Introduction to Atmospheric Science

Summary of notes and materials
related to University of Washington introductory course Atm S 301,
taught Fall 2010 by Professor Robert A. Houze (RAH),
and compiled by Michael C. McGoodwin (MCM). Content last updated 1/4/2011

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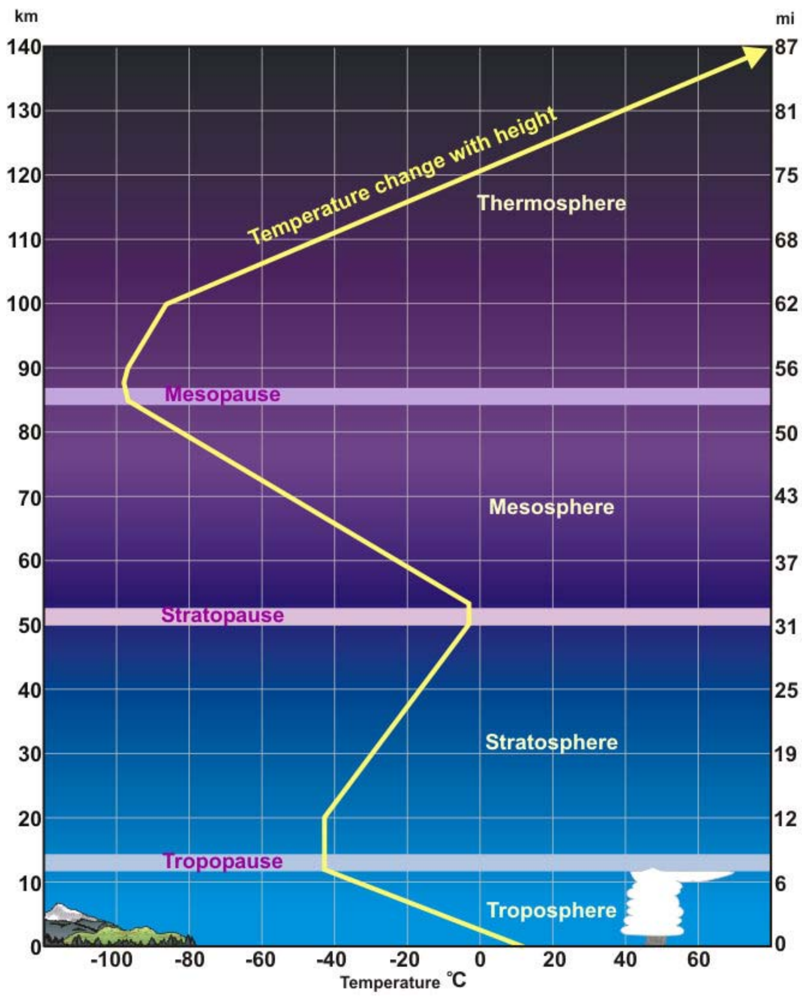

Atmosphere Layers and Their Mean Temperatures:
"Standardized Temperature Profile: An average temperature profile through the lower layers of the atmosphere. Height (in miles and kilometers) is indicated along each side. Temperatures in the thermosphere continue to climb, reaching as high as (3,600°F) 2,000°C."[1] (per NOAA)
The precise model used in this graph is not stated.

[1] Atmospheric Structure (NOAA): http://www.srh.noaa.gov/srh/jetstream/atmos/images/atmprofile.jpg

Introduction

I have compiled this summary to assist in learning materials relevant to the introductory study of Atmospheric Science—the subject of University of Washington course Atm S 301, as presented in fall 2010. This course is taught by Professor Robert A. Houze ("RAH").[2] I appreciate Professor Houze's remarkable expertise and his willingness to allow me to audit his course.

Sources : The materials in this summary represent selected course-related concepts assembled for the most part from various Web sources as well as the lecture notes, the textbook, the assigned materials, and other books. When I quote or paraphrase RAH, I am referring to his oral lectures, the excellent PDF outlines of his lectures which he has provided, and his website.[3] For students with password access, see also the professor's PDF class notes.[4] With one exception (a UW-derived weather map), no image in my summary comes directly from his PDFs. No assumptions are made regarding the ultimate authoritativeness of Web sources utilized such as Wikipedia, although I believe such sources can frequently provide helpful overview perspectives and links to more definitive scholarly materials. Note that links (URLs) shown in footnotes and elsewhere are "live" and can be followed by clicking on them in PDF documents such as this.

Textbooks and Key Book Resources: The main textbook used in this course in 2010 is *Atmospheric Sciences: An Introductory Survey (2nd Edition)*, J. M. Wallace and P. V. Hobbs, Academic Press, 2006. This is abbreviated below as *ASI*, so that *ASI*-7 is page 7 from this book. Professor Houze is a co-author of parts of this textbook's Chapter 8, "Weather Systems", and the authors are or were UW Atm S professors (Prof. Hobbs died in 2005). The current course does not discuss a number of the chapters of this rather advanced textbook (some of which are used in a graduate level course, Atm S 501). Specifically we did not study the following chapters or chapter sections in any detail: Chapter 2. The Earth System; Chapter 3.7. The Second Law of Thermodynamics and Entropy; parts of Chapter 4 (listed below); Chapter 5. Atmospheric Chemistry; Chapter 6. Cloud Microphysics; Chapter 8. Weather Systems, sections 8.1 Extratropical Cyclones and 8.2 Orographic Effects; Chapter 9. The Atmospheric Boundary Layer, and Chapter 10. Climate Dynamics.

Prof. Houze also references for this course his own 1993 advanced textbook, *Cloud Dynamics*,[5] in particular Chapter 1, as well as Chapter 1 ("The Butterfly Effect") of James Gleick's excellent 1987 popular book, *Chaos*.

The beginning student just starting out in atmospheric sciences, perhaps struggling to make progress in Wallace and Hobbs, might also wish to look over a truly introductory college textbook in meteorology, such as C. Donald Ahrens, *Meteorology today: an introduction to weather, climate, and the environment 8th Ed*, Belmont, California, Thomson/Brooks/Cole, 2007.[6] After reviewing this textbook, I learned from Prof. Houze

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[2] RAH webpage brief excerpts:
http://www.atmos.washington.edu/~houze/ :
"At the UW Professor Houze teaches classes on cloud physics and dynamics, thermodynamics, and general meteorology. His research interests are mesoscale meteorology, radar meteorology, tropical meteorology, precipitation processes, cloud dynamics, cloud microphysics, and storm dynamics.... Professor Houze leads a research team at the UW called the Mesoscale Group. He and his group have participated in many international field projects employing weather radar and aircraft in the tropics and midlatitudes... Professor Houze's approach integrates observations, models, and theory, and utilizes data sets collected in both the tropics and midlatitudes. In 1999 ... tropical precipitation at Kwajalein Atoll ... and storms producing heavy rains and floods in the Alps in northern Italy... In 2001 ... winter storms over the Oregon Cascades. From 1985-present, ... Tropical Rainfall Measuring Mission Satellite (TRMM)... He is now also on the NASA Science Team for CloudSat, another satellite that uses a radar to study clouds. He is also on the Science Team for the Department of Energy's Atmospheric Radiation Program. In 2005, ... Hurricane Rainband and Intensity Change Experiment (RAINEX) in which he co-directed flights of aircraft into Hurricanes Katrina, Ophelia, and Rita."

[3] http://www.atmos.washington.edu/~houze/301/

[4] http://www.atmos.washington.edu/~houze/301/protected/Notes2009/CompObsMaps.pdf

[5] *Cloud Dynamics*, Robert A. Houze, Jr., Academic Press, 573 pp., 1993. Described as a graduate textbook.

[6] It is unfortunate that textbooks have become so expensive, as otherwise it would in my opinion be useful to also use a textbook dealing specifically with meteorology, which is a major focus of this introductory class. Starting out learning meteorology using Wallace and Hobbs and Web resources was for me quite difficult. The Wallace and Hobbs textbook currently sells at Amazon for $50, whereas the Ahrens textbook is $100 at Amazon.com.

that he uses it in his 100 level introductory course. I will refer to this unassigned, descriptive, and comfortably basic—sometimes too basic—text in what follows as *MT8*.

Etymology and definitions in part derive from the newly released *Oxford English Dictionary, Third edition*, August 2010; online version November 2010, accessed online October – December 2010, hereafter abbreviated *OED3*.

Acknowledgements, Copyrights, and Disclaimers: When I have taken material or diagrams from Wikipedia or other Web sources, I have always shown a URL citation, usually in a footnote. (URLs are of course expected to go out-of-date with time, and I will not attempt to keep the links current.) However, I may not have always remembered to set off extracted materials with quotation marks. In many cases, I have adapted or paraphrased the material extracted from these external sources, and have in some cases added emphasis of my own such as italics. Readers incorporating any of these materials into their own writings for class or publication are advised to consult the sources and citations provided to obtain exact quotes so that the sources can be properly attributed. Despite their high value in teaching this subject matter, I have included only a modest number of diagrams and images, due to space limitations and copyright concerns. Most of these are from Web resources at NASA, NOAA, NWS, and other US governmental sources, or from Wikipedia. However, I have tried to point out where the interested reader might find other useful diagrams and multimedia materials. Where I have embedded editorial comments, clarifications, and questions of my own inside quoted material, I have enclosed these in [square brackets]. I have also tried to mention areas about which I remain personally unclear.

The Author: I am a retired physician and an auditing student, and claim no expertise in this field. I have not taken the time and/or do not have the background to understand fully all of the mathematics and details underlying this subject matter. Atmospheric Science is a huge and complex discipline, interfacing with earth science, astronomy, physics, chemistry, mathematics, etc., and this introductory single trimester course can only expose the student to a small subset of the potentially relevant material. Some of the important physics has not yet been discussed in the current course, and will be taken up in later courses. My personal goal has been to assimilate many of the important points, qualitatively if not always quantitatively. Many of the mathematical details that have been omitted from this summary may be found in some of the references I have provided, and certainly in the textbook and/or the course PDFs. This course flies by very fast! As I am only a beginner, I hope the reader will forgive me for my incomplete understanding of many of the materials presented. There is much more to be learned!

Constructive corrections and clarifications would always be appreciated. Send these to:
MCM at McGoodwin period NET (please convert to standard format when using)

Useful Web Links and Abbreviations Encountered

Abbreviations, Acronyms, and Symbols

(see also Glossary topics and other summaries of symbols employed in this document)

♦ = WebPages of greater interest and/or utility; ♦♦ = the very best or most useful
Δ = time increment between loop images (indicated where I have found it can be changed in the URL etc.)
–5 d (–5 days or 120 hrs) = recent actual observations in model
+7.5 d (+7.5 days or 180 hrs) = forecasts (predictions) in model;
0 days = Today's most recent observation for initialization or first image of forecast
(sometimes ambiguous exactly which is intended)
CAPE = Convective Available Potential Energy[7] (J kg-1, Higher values → atmospheric convective instability)
CDC = Climate Diagnostics Center
CIN = Convective inhibition[8] (J kg-1, energy that will prevent an air parcel from rising, higher → more stable);
also, in weather maps, cin = centiinches (or centi-inches, i.e., lengths of 1/100 inch)

[7] http://en.wikipedia.org/wiki/Convective_available_potential_energy
[8] http://en.wikipedia.org/wiki/Convective_inhibition

CIRES = Cooperative Institute for Research in Environmental Science (NOAA + CU Boulder)
CONUS = continental United States, (i.e., the 48 contiguous states, here including DC)
dam = decameters/dekameters
ECMWF = European Centre for Medium-Range Weather Forecasts
ENS = Environment News Service
EPS = Ensemble Prediction Systems
ESRL|PSD = Earth System Research Laboratory | Physical Sciences Division
Fcst = Forecast (prediction of future states)
GFS = Global Forecast System (global numerical weather prediction computer model of NCEP/NWS/NOAA)[9]
GMT = Greenwich Mean Time
GOES = Geostationary Operational Environmental Satellites (of NOAA/NESDIS/NASA)
GVAR = GOES Variable Format[10] (scaled 10-bit Infrared image data, convertible to Scene Radiance or Temp.)
hPa = hectoPascals (1 hPa = 100 Pascals, hPa are equivalent to millibars and are the preferred SI term)
IPCC = Intergovernmental Panel on Climate Change
IR = Infrared (highest clouds are coldest & appear brightest; lowest clouds or surface are warmer & darker)
McIDAS = Man computer Interactive Data Access System[11] (file format and package for processing of satellite images data, including GOES and geophysical data)
MM5 = Mesoscale, short-range (0-2 d) forecasts. (A 5th-generation mesoscale model[12] from Penn State/NCAR, partly replaced in favor of the WRF mesoscale model by the NRMC.)
(This appears to be a very complex subject about which I need to learn much more.)
NAM/NMM = North American Mesoscale Model (of the NCEP)[13]
NCEP = National Centers for Environmental Prediction
NCAR = National Center for Atmospheric Research
NESDIS = National Environmental Satellite, Data, and Information Service (of NOAA)
NH/SH = Northern Hemisphere/Southern Hemisphere
NMC = National Meteorological Center (US)
NMM = Non-hydrostatic Mesoscale Model
NOAA = National Oceanic and Atmospheric Administration
NP/SP = North Pole/South Pole
NRMC = Northwest Regional Modeling Consortium[14]
NSSDC = National Space Science Data Center
NWS = National Weather Service
Obs = Observations usu. recent (actual measurements and images as opposed to model forecasts)
OSDPD = Office of Satellite Data Processing and Distribution (of NOAA)
PST/PDT = Pacific standard time/Pacific daylight time
SLP = Sea-level pressure (MSLP=mean SLP)
SPC = Storm Prediction Center (NOAA/NWS)
SST = Sea Surface Temperature (NOAA sometimes extends to land surface)
TPW = Total Precipitable Water
UTC = Coordinated Universal Time (akin to Greenwich Mean Time)
UW = UW Atmospheric Science department
UWME = University of Washington Mesoscale Ensemble[15] (mesoscale 72-hr ensemble forecasts w MM5)
WMO = World Meteorological Organization

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9 GFS:
• http://www.emc.ncep.noaa.gov/gmb/moorthi/gam.html
• http://en.wikipedia.org/wiki/Global_Forecast_System
10 http://www.oso.noaa.gov/goes/goes-calibration/gvar-conversion.htm
11 McIDAS:
• Overall: http://www.ssec.wisc.edu/mcidas/
• File Format: http://amsu.cira.colostate.edu/Swath_format.html
12 MM5 model: http://www.mmm.ucar.edu/mm5/
13 NAM/NMM: "Currently, the Weather Research and Forecasting Non-hydrostatic Mesoscale Model (WRF-NMM) model is run as the NAM, thus, three names (NAM, WRF, or NMM) typically refer to the same model output."
http://en.wikipedia.org/wiki/North_American_Mesoscale_Model
14 http://www.atmos.washington.edu/~cliff/consortium.html
15 http://www.atmos.washington.edu/~ens/uwme_info.html

WRF = Weather Research & Forecasting Mesoscale Model. (The Advanced Research WRF (WRF-ARW) core of the Weather Research and Forecasting Model (WRF) is used by the NRMC and is partly replacing the MM5.[16] However, there is some confusion in labeling as to—what is still MM5?
WV = Water Vapor (in satellite views, brighter = moister)
Z = UTC "Zulu Time" (GMT, zero longitude, time adjustment 0, see also Glossary); also, (usu. capitalized) Geopotential Height above mean sea level in m; also radar reflectivity (see dBZ)

Global/Planetary or Synoptic Scale Earth Weather

- ♦♦500 mb Pressure Heights (dam isohypse contours & color) [0 to +7.5 d]
  UW; Centered on NP; –7 days obs. to +7.5 days (180 hr) forecast (GFS Global Spectral Model)
- ♦250 mb Pressure Heights (dam isohypse contours) & Wind Speeds (kts, color) [0 to +7.5 d]
  UW; Centered on NP; –7 days obs. to +7.5 days (180 hr) forecast (GFS Global Spectral Model)
- ♦Canadian 4-Panel: 500 hPa Z (dam, contours), 700 hPa Z (dam, contours), 850 hPa T (°C, color), MSLP (hPa, color), Wind (barbs at 500 hPa), Vorticity (s^{-1}, color), 1000-500 DZ (dam, color), 700 hPa Humidity (color)
  NP to Texas; 0 to +6 days (144 hr) forecast (GEM model 15-km res.) (click "anim", then "Play")
- ♦Ensemble Forecasts (NOAA/ESRL/PSD/NCEP/NMC):
  (NOAA/ESRL/PSD/NCEP/NMC) combining[17] 2 or more model forecasts for assessing reliability, etc.
- GOES Satellite Infrared IR view (°C, grayscale, whiter=colder)
  UW: of NA, East Pacific, W Atlantic, latest 6 hours obs., not color enhanced

Washington, North America, and Eastern Pacific Ocean Weather

- ♦♦GOES Weather Satellite, Infrared IR view of NE Pacific and West Coast US [past 4 d, Δ=3 h]
  UW: obs. latest 12 hours, Δ=30 min (extensible in URL,);
  GOES-11 satellite (?Imager ?Ch 4) GVAR→T Kelvin, color–enhanced for ~195–245 K.[18]
- ♦♦SLP (hPa, contours), Total Precipitation (centi-inches predicted in previous 3 hours, color)
  UW/NOAA, Pacific NW, 0 obs. to +72 hr forecast, WRF-GFS model 36-km res[19]
  [no past precipitation images are available]
- ♦♦500 mb Pressure Heights (dam isohypse contours & color) [0 to +7.5 d]
  UW: "Seattle View" (N Pole, N Pacific, NH, Mexico); –7 days obs. to +7.5 day (180 hr) forecast (GFS Global Spectral Model)
- ♦500 mb Pressure Height (m, isohypse contours), T (°C, color), Wind barbs at 500 mb [0 to +3 d]
  UW/NOAA, Pacific NW, -3 days obs. to +72 hr forecast, WRF-GFS model 36-km res
- 850 mb Pressure Heights (dam isohypse contours) & Temp (°C color) [0 to +7.5 d]
  UW: "Seattle View" (N Pole, N Pacific, NH, Mexico); –7 days obs. to +7.5 days (180 hr) forecast (GFS Global Spectral Model)
- ♦Surface SLP (mb isobar contours) & 500 mb Pressure Heights (dam, color) [0 to +7.5 d]
  UW: "Seattle View" (N Pole, N Pacific, NH, Mexico); - 7 days obs. to +7 days (180 hr) forecast (GFS Global Spectral Model)
- Surface SLP (mb isobar contours) and 1000-500 mb Thickness (dam, color) [0 to +3 d]
  UW: "Seattle View" (N Pole, N Pacific, NH, Mexico); –3 days to +3 days (72 hr) forecast (ETA model)
- Surface SLP (mb isobar contours) & Precipitation (inches/6 hour, color) [0 to +3 d]
  UW: "Seattle View" (N Pole, N Pacific, NH, Mexico); -3 days to +3 days (72 hr) forecast (ETA model)
- ♦SLP (hPa, contours), T °C at 925 mb (contours & color), Wind barbs @ surface [0 to +3 d]
  UW/NOAA: Pacific NW, -3 days to +72 hr forecast, WRF-GFS model 36-km res.
- Radar CONUS base reflectivity obs. and surface map
  UW: CONUS; latest 6 hours obs.
- Radar—selectable displays from CONUS
  NCAR: requires enabled Java plug-in (Firefox: "Next Generation Java Plug-In for Mozilla Browsers")
- Radar—Northwest
  UW: WA+OR+ID+BC, no specific technical info on this; erratic display, activate w loop length

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[16] WRF at the UW:
• http://www.atmos.washington.edu/~cliff/consortium.html [2003 paper]
• http://www.atmos.washington.edu/mm5rt/info.html
[17] "The Use of Ensemble Forecasts to Produce Improved Medium Range (3-15 days) Weather Forecasts" http://www.esrl.noaa.gov/psd/spotlight/12012001/
[18] Similar to NOAA Satellite view: http://www.ssd.noaa.gov/goes/west/nepac/flash-ir2.html
[19] http://www.atmos.washington.edu/mm5rt/descript/pages/pcp24.html

- ♦Radar—Washington
  NOAA/NWS: composite short-range reflectivity
- ♦Radar—Seattle
  NOAA/NWS: Seattle ATX station, composite short-range reflectivity
- ♦Soundings and upper-air maps for US and world regions, many levels
  U Wyoming: obs. for current day or any past day back to 1973 in 12 h intervals
- ♦Severe Weather Over the U.S. Map of Current US NWS Weather Hazards
  NOAA/NWS (Storm Prediction Center, sometimes not available presumably due to overusage)
- ♦GOES Weather Satellite image server
  NOAA: mult. animations of IR, Visible, & Water Vapor of East CONUS, West CONUS, Alaska, & Hawaii
- GOES Weather Satellite Western US Imagery loops
  NOAA: GOES and Polar satellites, multiple wavelengths available
- ♦GOES Weather Satellite Water Vapor view of NE Pacific and US West Coast [past 4 d Δ=3 h]
  UW: Eastern Pacific & Western US; obs. past 48 hour, Δ=30 min
- ♦Seattle Forecast (text-based)
  NOAA/NWS: 7 day forecast.

Tropics

- Tropical Cyclones and Atlantic hurricanes
  Prof. Houze's links

General Atmospheric Science, Weather, and Climate

- ♦♦University of Washington Atm S Index of Weather Loops
  Lists many of the specific views and "loops" given above.[20] Some limitations on access.
- ♦University of Washington Atm S "Data & Forecasts"
- European Centre for Medium-Range Weather Forecasts (ECMWF)
  European weather, limited access. Also includes extensive multi-year climate data.[21]
- Weathergraph Observation and Plotting (weather symbols for observations, etc.)
- Wallace and Hobbs ASI Textbook companion website

Space Weather (Earth–Solar Interactions)

- ♦Spaceweather.com[22]
- ♦NOAA Space Weather Prediction Center[23]
- NOAA National Geophysical Data Center page on Solar-Terrestrial physics[24]

Mathematical Symbols; Meteorological Coordinate Systems

See *here*[25] for a limited summary of mathematical topics including vector calculus.

Some handy characters and symbols used in writing this summary:

Greek letters:	αβγδΔ∏πζεηνθκΛλμρ∑στφΦχψΩω
Mathematical & Misc. Symbols:	°≈≠≡∂√•∫±¶⇒∠∝∇∗×^⊥‖⊙⊕♦

The text *ASI*-3 utilizes a simplified spherical coordinate system which is centered at the Earth's center (thus it is *geocentric*) and that rotates with the Earth's rotation (thus it is *Earth-fixed*, rotating like the Earth counterclockwise as viewed above the NP). It assumes for simplicity that the Earth is a sphere having radius R_E, thus ignoring the ellipsoidal shape of the Earth assumed in *Geodetic coordinates*.[26] In this coordinate system, a point on or above the Earth's surface may be expressed by coordinates

[20] The Help file (http://www.atmos.washington.edu/~ovens/loops/wxloop.cgi) is quite technical and difficult to understand, and I have not yet mastered navigating these loop files.
[21] http://www.ecmwf.int/research/era/ERA-40/ERA-40_Atlas/index.html
[22] http://spaceweather.com/
[23] http://www.swpc.noaa.gov/SWN/
[24] http://www.ngdc.noaa.gov/stp/
[25] http://www.mcgoodwin.net/pages/spacephysics_ess471.pdf
[26] http://www.spenvis.oma.be/help/background/coortran/coortran.html#GEOD

• **radius r** ≡ radius from the Earth's center to the point,
• **geocentric latitude φ** ≡ angle in degrees formed between a line passing from the Earth's center to the point and the equatorial plane, with values defined as positive measured north of the equator), and
• **longitude λ** ≡ angular distance in degrees of the point's meridian from the Prime (aka International or Greenwich) Meridian, with positive values measured eastward from the Prime Meridian.

For example, downtown Seattle (near 6th and University) is at

φ = 47°36′35″N (47.609722 degrees N)
λ = –122°19′59″E (–122.333056 degrees E), equivalent to 122°19′59″W

Points may also be expressed with x, y, and r coordinates, where
• x ≡ distance east of the Prime Meridian along a latitude circle
(computed by integration of $dx = r\, d\lambda \cos\varphi$),
• y ≡ distance north of the equator
(computed by integrating $dy = r\, d\varphi$, where φ is expressed in radians), and
• r ≡ same as above.

Note that at the Earth's surface, a degree of latitude corresponds to ~111 km. This reference[27] discusses the extent of deviation of the Earth's surface from sphericity. A reasonable mean value for R_E is 6.371 x 10^6 m = 6,371 km = 3,959 miles. Using the same R_E, the mean Earth circumference is 40,030 km = 24,870 miles. As more than 99.9% of the Earth's atmosphere lies below 50 km, we may say that the thickness of Earth's atmosphere is effectively less than 0.8% of R_E, thus less than 1%.

Velocities of atmospheric motions have magnitudes given by:
• $u \equiv dx/dt = R_E \cos\varphi\, d\lambda/dt$ (the zonal velocity component magnitude along an E-W zone defined by a given latitude circle, parallel to the Earth's idealized spherical surface, positive eastward or westerly),
• $v \equiv dy/dt = R_E\, d\varphi/dt$ (the meridional velocity component magnitude along a N-S meridian at a given longitude circle, parallel to the Earth's idealized spherical surface, positive northward or southerly), and
• $w \equiv dz/dt = dr/dt$ (the vertical velocity magnitude, perpendicular to the plane of the Earth's idealized spherical surface, positive upward)

The full velocity vector **V** may be represented by $\mathbf{V} \equiv u\mathbf{i} + v\mathbf{j} + w\mathbf{k}$, where **i**, **j**, and **k** are unit vectors in the same directions as defined just above. The horizontal velocity vector $\overrightarrow{V_h} = u\vec{\mathbf{i}} + v\vec{\mathbf{j}}$ ignores the vertical velocity component w**k**, which is typically quite small and negligible relative to horizontal motion.

The **total time derivative** (aka material or Lagrangian derivative, derivative following the motion) is defined as

$$d/dt\ (\text{“Lagrangian”}) = \partial/\partial t + u\, \partial/\partial x + v\, \partial/\partial y + w\, \partial/\partial z$$

and is used to express the rate of change in an air parcel as it moves along in its 3-D trajectory, thus not at a fixed point.[28]

The **local time derivative** (the "Eulerian" derivative or rate of change) is defined at a fixed point (x,y,z) in rotating space as

$$\partial/\partial t\ (\text{“Eulerian”}) = d/dt - u\, \partial/\partial x - v\, \partial/\partial y - w\, \partial/\partial z$$

In these expressions, the terms which include velocities are *advection terms*, which describe bulk transport of a quantity with flow of the fluid (as with a wind, river, or pipeline).[29] For a conserved tracer scalar quantity ψ, the total derivative $d\psi/dt$ is 0, and the Eulerian or local derivative $\partial\psi/\partial t$ is given solely by the advection terms.

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[27] http://en.wikipedia.org/wiki/Earth_radius
[28] http://en.wikipedia.org/wiki/Material_derivative
[29] http://en.wikipedia.org/wiki/Advection

Basic Facts about the Sun ⊙ Compared to the Earth ⊕

This section was compiled in 2009 for a Space Physics course, separately described, thus some information presented here is not essential to atmospheric science. However, it is all interesting! The values and references were correct as of 2009.

Radius of Sun $R_\odot$ (at equator)[30]— 6.9599x10⁸ m = 695,990 km = 432,470 mi = 109 $R_\oplus$

Radius of Earth (R_E or $R_\oplus$ per WGS-84)[31]

Mean at Equator: $6.378137\text{x}10^6$ m = 6,378.137 km
Mean at Poles: $6.356752\text{x}10^6$ m = 6,356.752 km

Ellipticity of Sun (Flattening or oblateness)[32] = 9×10^{-6} (thus nearly a perfect sphere)

Ellipticity of Earth = 0.00335 = ~0.3% (expressed inverted: 1:298)

Distance from Sun to Earth, average (1 Astronomical Unit = AU):[33]

1.496×10^{11} m = 92.96 million mi = 8.32 lm (light minutes) = 499 ls = 4.8481×10^{-6} parsec = 215 $R_\odot$

Mass of Sun $M_\odot$ = $1.989\text{x}10^{30}$ kg = 333,000 $M_\oplus$

Mass of Earth $M_\oplus$ = $5.9742\text{x}10^{24}$ kg

Density of Sun $\rho_\odot$: [note that 1 gm/cm³ = 10³ kg/m³]

Mean: 1.408 gm/cm³ = 1.408×10^3 kg/m³ = 0.255 mean ρ_E
Central or Core: up to 150 g/cm³ = $150\text{x}10^3$ kg/m³ (the core extends to 0.2 to 0.25 $R_\odot$)
Photosphere[34]— $2\text{x}10^{-7}$ g/cm³ = $2\text{x}10^{-4}$ kg/m³ [~$1.6\text{x}10^{-4}$ times the Earth sea level atmos. density[35]]
Particle density = ~10^{23} particles m^{-3}
Corona Mean[36]— 1×10^{-15} g/cm³ = 1×10^{-12} kg/m³
Lower Corona[37]— $1\text{x}10^{-16}$ g/cm³
Particle density[38]— 10^{15} – 10^{16} particles m^{-3}

Density of Earth ρ_E:[39]

Mean:	5.515 gm/cm³	= $5.515\text{x}10^3$ kg/m³
Inner Core:	12.8 – 13.1 gm/cm³	= $12.8\text{x}10^3$ - $13.1\text{x}10^3$ kg/m³
Mantle:	3.4 – 5.6 gm/cm³	= $3.4\text{x}10^3$ - $5.6\text{x}10^3$ kg/m³
Crust:	2.2 – 2.9 gm/cm³	= $2.2\text{x}10^3$ - $2.9\text{x}10^3$ kg/m³
Atmosphere (at sea level)[40]—	$1.2\text{x}10^{-3}$ gm/cm³	= 1.2 kg/m³

[MCM crude estimate cf. Sun: ~$6\text{x}10^{26}$ particles m^{-3}]

Temperature of Sun[41]

Surface (effective black body temperature) = 5770 K = 9,930 °F (*ISP*: 5785 K)
Central or Core = 15,600,000 K = 28,000,000 °F

Luminosity of Sun $L_\odot$[42,43] = 3.846×10^{26} W = 3.846×10^{33} erg/s

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30 http://solarscience.msfc.nasa.gov/
31 http://en.wikipedia.org/wiki/World_Geodetic_System
32 Ellipticity:
http://en.wikipedia.org/wiki/Flattening:
Ellipticity is defined for an ellipsoid with equatorial radius a and polar radius b as (a-b)/a
33 http://en.wikipedia.org/wiki/Astronomical_unit
34 http://en.wikipedia.org/wiki/Sun
35 http://solarscience.msfc.nasa.gov/
36 http://en.wikipedia.org/wiki/Sun
37 http://solar-center.stanford.edu/vitalstats.html
38 http://en.wikipedia.org/wiki/Sun
39 http://en.wikipedia.org/wiki/Earth
40 http://en.wikipedia.org/wiki/Earth%27s_atmosphere
41 http://solarscience.msfc.nasa.gov/
42 http://solarscience.msfc.nasa.gov/
43 Luminosity:
http://en.wikipedia.org/wiki/Solar_luminosity:

Spectral Stellar Classification of Sun (Morgan-Keenan)[44,45]: G2V

Magnitude of Sun:
Absolute: +4.83
Visual (Apparent): -26.74

Elemental Composition of Sun by Mass % or ppm
Photosphere[46] = H 91.0%, He 8.9%; O 774 ppm, C 330 ppm, Ne 112 ppm, N 102 ppm, Fe 43 ppm …
Central[47]= 35% H, 63% He, 2% (C, N, O, etc.)

Age of Sun[48] = 4.57×10^9 yr (cf. 4.54×10^9 yr for Earth)[49]

Rate of Mass Conversion to Energy of Sun through Fusion[50]— 4.4×10^9 kg s^{-1} or 9.2×10^{37} protons s^{-1}

Rotation Periods of the Surface of the Sun:[51]

Sidereal equatorial: 24.47 d (rotation period in days to same apparent location as viewed in star frame)

Synodic equatorial: 26.24 d (rotation period in days to same apparent location as viewed from Earth)

Sidereal Carrington (~26 degrees latitude): 25.38 d

Synodic Carrington (~26 degrees latitude): 27.2753 d

Solar Rotation period (an empiric formula by latitude at the surface for data collected 1967 – 1987):[52]
$\omega = 14.713 - 2.396\sin^2(\varphi) - 1.787\sin^4(\varphi)$, where
ω = deg/d sidereal
φ = solar latitude (deg)
This gives sidereal days: 0°→24.47 d, 26°→25.38 d, 30°→25.71 d, 60°→30.22 d, 90°→34.19 d

Total Solar Irradiance (TSI, the not-so-constant "Solar Constant") is the irradiance (W m^{-2}) at all wavelengths of photons (effectively from about 10,000 nm to about 10 nm) at exactly 1 A.U.[53]
on a surface perpendicular to the incoming rays:
Mean is about 1366 W m^{-2}
Actual solar irradiance[54] varies due to changing Earth-Sun distance and solar fluctuations from 1,412 to 1,321 W m^{-2}

Tilt of Sun's rotational axis with respect to the plane of Earth's orbit: ~7.25 degrees[55]
Tilt of Sun's magnetic dipole field axis with respect to rotation axis: varies during solar cycle but up to ±(10° to 20°).[56]

Luminosity here is total bolometric (wide spectrum) photon radiant energy output, and does not include neutrino radiant energy, which adds 0.1×10^{26} W
[44] Star Spectral classification:
http://en.wikipedia.org/wiki/Spectral_classification:
For the Sun classified as G2V in the Morgan-Keenan classification,
- Letter G indicates a yellowish star with surface T 5,200–6,000 K
- Number 2 indicates two tenths of the range between star classes G and adjacent star class K (orangish)
- Roman Number V indicates the width of certain absorption lines, which correlates with stellar size, so that V indicates a Main Sequence star.

[45] http://en.wikipedia.org/wiki/Hertzsprung%E2%80%93Russell_diagram
[46] http://nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html
[47] http://solarscience.msfc.nasa.gov/
[48] http://en.wikipedia.org/wiki/Sun and http://solarscience.msfc.nasa.gov/
[49] http://en.wikipedia.org/wiki/Age_of_the_Earth
[50] http://en.wikipedia.org/wiki/Sun
[51] http://en.wikipedia.org/wiki/Solar_rotation
[52] Solar differential rotation:
Snodgrass, H. B. & Ulrich, R. K., "Rotation of Doppler features in the solar photosphere", *Astrophysical Journal*, Part 1 vol. 351, 1990, p. 309-316
[53] ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_IRRADIANCE/COMPOSITE.v2.PDF
[54] http://en.wikipedia.org/wiki/Solar_irradiation
[55] http://solarscience.msfc.nasa.gov/sunturn.shtml

Sun rotation direction: Counterclockwise (when viewed from the north)
(this is the same direction that the planets including Earth rotate and orbit around the Sun).

Sun Escape Velocity: Escape velocity[57] in general is given by $v_e = (2GM/r)^{1/2}$, where M is the mass of the massive body being escaped from starting at distance from the body's center r, and v_e is the minimum speed required when propulsion ceases at that distance. (This idealized formula ignores the drag of the atmosphere.) For the Sun's surface, the idealized escape velocity is calculated at 617.5 km/s, whereas for the Earth' surface, it is calculated at 11.2 km/s. However, there appears to be a complex relationship between this simplistic solar escape velocity estimate and the velocities actually attained in solar wind. The latter is found to be below v_e at least using estimates from actual measurements near the Sun (at $4R_\odot$ – $7R_\odot$) using data from the Ulysses probe,[58] and certainly solar wind speed is often < v_e (see below) by the time the solar wind has decelerated in travelling to Earth orbit.

Atmospheric Sciences Introduction

See also topics summarized in the Glossary.

Scope of Atmospheric Sciences

"*Atmospheric sciences* is an umbrella term for the study of the atmosphere, its processes, the effects other systems [such as the oceans] have on the atmosphere, and the effects of the atmosphere on these other systems. *Meteorology* includes atmospheric chemistry and atmospheric physics with a major focus on weather forecasting. *Climatology* is the study of atmospheric changes (both long and short-term) that define average climates and their change over time, due to both natural and anthropogenic climate variability. *Aeronomy* is the study of the upper layers of the atmosphere, where dissociation and ionization are important. Atmospheric science has been extended to the field of planetary science and the study of the atmospheres of the planets of the solar system.... The term *aerology* ... is sometimes used as an alternative term [to atmospheric sciences] for the study of Earth's atmosphere."[59]

Major Subdivisions of Atmospheric Sciences

- Atmospheric Physics
- Atmospheric Chemistry
- Atmospheric Dynamics
- Climatology
- Meteorology and Forecasting
- Extraterrestrial Planetary Atmospheric Science

Meteorology and Forecasting

As opposed to *climatology*, *meteorology* focuses on weather and short term forecasting. The name "Meteorology" derives from Aristotle's *Meterologica*, which purported to describe weather and climate. The term *meteor* referred to things that fell from the sky or were found in the sky, and the Greek word meteoros meant "high in the air" (*MT8*-17*)* or "*raised, lofty, an alteration*" (*OED3*).

"Meteorology and climatology are rooted in different parent disciplines, the former in physics and the latter in physical geography. They have, in effect, become interwoven to form a single discipline known as the atmospheric sciences, which is devoted to the understanding and prediction of the evolution of planetary atmospheres and the broad range of phenomena that occur within them."[60] It often combines
• *observation* (discrete measurements of actual conditions (T, dew point, P, wind, cloud cover, precipitation, etc.) using surface station measurements, radiosonde soundings, radar, satellite data, etc.). These discrete observations are depicted on weather maps using compact weather symbols.[61]

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[56] http://www.nso.edu/press/newsletter/Tilted_Solar_Magnetic_Dipole.pdf
[57] http://en.wikipedia.org/wiki/Escape_velocity
[58] Efimova AI et al. "Solar wind velocity measurements near the sun using Ulysses radio amplitude correlations at two frequencies". *Advances in Space Research*. Volume 35, Issue 12, 2005, Pages 2189-2194
[59] http://en.wikipedia.org/wiki/Atmospheric_sciences
[60] John M. Wallace, "Meteorology," in AccessScience, ©McGraw-Hill Companies, 2008, online
[61] http://www.weathergraphics.com/dl/wxchart.pdf

• *analysis*[62] (including, for example, inference of continuous distributions of pressure and temperature for weather maps), and
• *forecasting* (*predicting weather*).
Meteorology includes atmospheric chemistry and physics but has a major focus on weather forecasting.

Accurate long-range weather prediction has proven to be virtually impossible, due to chaotic non-linear phenomena and extreme sensitivity to initial conditions (as first discovered by Edward N. Lorenz and depicted in the Lorenz Attractor diagram).[63]

Weather-related observations (measurements) are currently made with:
Surface stations (including the ASOS systems)
Upper-air stations (using radiosondes, rawinsondes, and rocketsondes)[64]
Ground-based weather surveillance Radar (WSR)[65]
Satellite imaging (GOES system, etc.)

In addition to T °C, Dew Point °C, Wind barb (speed in kts and direction), sky cloud cover, and pressure (SLP mb) or pressure height (dam or m) indicators, weather map observations may include some of the following commonly used symbols:[66]

Weather reporting in its raw form can be quite cryptic. The METAR system is "the international standard code format for hourly surface weather observations which is analogous to the SA coding currently used in the US."[67] Text weather reports use METAR symbols including the following (ASOS reports are somewhat more restrictive) for "WX" =weather:[68]

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62 http://amsglossary.allenpress.com/glossary/search?p=1&query=aerological&submit=Search etc.
63 http://en.wikipedia.org/wiki/Lorenz_attractor
64 http://www.ncdc.noaa.gov/oa/upperair.html
65 http://en.wikipedia.org/wiki/Weather_radar
66 http://www.hpc.ncep.noaa.gov/html/stationplot.shtml
67 http://www.ncdc.noaa.gov/oa/wdc/metar/index.php?name=faq
68 METAR WX symbols:
• http://wx.erau.edu/reference/text/metar_decode_key.pdf
• http://www.ofcm.gov/fmh-1/pdf/N-APNDXB.pdf

For precipitation, intensity is prefixed: light (–), moderate (no sign), heavy (+)

BC	Patches
BL	Blowing
BR	Mist
DU	Dust
DZ	Drizzle
FC	funnel cloud/tornado/waterspout
FG	Fog
FZ	Freezing
FZFG	freezing (FZ) + fog (FG, temperature below 0°C)
FZRA	freezing (FZ) + rain (RA)
GR	hail
GS	small hail and/or snow pellets <1/4 inch
HZ	haze
MI	Shallow
RA	Rain (liquid precipitation that does not freeze)
SJ	Showers
SN	Snow (frozen precipitation other than hail; –SN = light snow)
SQ	squalls
TS	thunderstorm
UP	precipitation of unknown type
VA	volcanic ash

Weather and Climate

Climate change is touched on in the Radiation section below, *ASI* chapters 2.5 and 10.4, and in *MT8* chapter 16.

Weather

Weather describes the simultaneous state of certain atmospheric bulk conditions and phenomena in the Earth's troposphere—temperature, humidity or moisture, precipitation, cloud pattern, fog, wind velocity, barometric pressure, etc.—at a given place (or over broad areas of the Earth), and at a given time or on a day-to-day basis, or with timescales of at most a few weeks.[69] "When such a collection of weather elements is part of an interrelated physical structure of the atmosphere, it is termed a *weather system*, and includes phenomena at all elevations above the ground."[70]

In contrast, such atmospheric phenomena on much longer timescales are described by *climate*. Neither of these terms include other atmospheric properties and phenomena such as cosmic rays, other radiations, and chemical constituents.

Climate

NOAA states:[71]

> "*Climate* refers to the average daily and seasonal weather conditions (such as air temperature, humidity, wind, and precipitation). Seasonal climate prediction is the process of estimating the most probable condition of the average surface temperature and precipitation for the future. Climate prediction is typically expressed as the departure from a long-term average, or so-called normal climate. It is expressed in terms of the probability that subsequent seasonally averaged U.S. temperature and precipitation will be below, above, or near this normal climate state. Climate prediction is different from weather prediction in that it forecasts the most probable averaged state of the environment, rather than the daily sequence of environmental changes."

[69] Definition combined from MCM plus:
- http://en.wikipedia.org/wiki/Weather
- http://www.nws.noaa.gov/ndfd/definitions.htm
- http://www.thefreedictionary.com/weather
- http://www.accessscience.com.offcampus.lib.washington.edu/content.aspx?searchStr=weather&id=742500

[70] Philip F. Clapp, "Weather," in AccessScience, ©McGraw-Hill Companies, 2008, online

[71] http://www.research.noaa.gov/climate/t_prediction.html

The IPCC defines climate as follows:[72]

> "*Climate* in a narrow sense is usually defined as the 'average weather', or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period is 30 years, as defined by the World Meteorological Organization (WMO). These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system."

Climate history and the Earth System, the Hydrologic Cycle, the Carbon Cycle, and Oxygen are taken up in *ASI* chapter 2, and Climate Dynamics is the subject of *ASI* chapter 10, but we did not take up these topics in any detail. Global climate is also presented extensively in *MT8* chapter 17.

Climate Variability versus Climate Change

Climate Change and *Variability* describe phenomena affecting the atmosphere (and related effects in the oceans) that are seen over particular time periods lasting months, a few years, or longer. (For climate change, see the Radiation section of this summary; also *ASI* chapters 2.5 and 10.4 and *MT8* chapter 16)

The phrase *climate change*, a linguistically neutral term though politically somewhat controversial subject, appears to be applied to what has been deduced to be human-caused climate changes including *global warming*. It may be termed *anthropogenic climate change* to the extent that this causation has been established[73]—certainly a large fraction of the recent global warming appears anthropogenic.

In contrast, *climate variability* seems to be applied to natural causes of climate changes, which are often cyclical. Climate variability includes the *Pacific Decadal Oscillation PDO* and the *El Niño/Southern Oscillation ENSO.*[74] NOAA states:

> "The Earth's climate is dynamic and naturally varies on seasonal, decadal, centennial, and longer timescales. Each "up and down" fluctuation can lead to conditions which are warmer or colder, wetter or drier, more stormy or quiescent. Analyses of decadal and longer climate records and studies based on climate models suggest that many changes in recent decades can be attributed to human actions; these decadal trends are referred to as *climate change*. The effects of *climate variability* and change ripple throughout the environment and society—indeed touching nearly all aspects of the human endeavor and the environment.... Perhaps the most well understood occurrence of *climate variability* is the naturally occurring phenomenon known as the *El Niño-Southern Oscillation* (*ENSO*), an interaction between the ocean and the atmosphere over the tropical Pacific Ocean that has important consequences for weather around the globe. The ENSO cycle is characterized by coherent and strong variations in sea-surface temperatures, rainfall, air pressure, and atmospheric circulation across the equatorial Pacific. El Niño refers to the warm phase of the cycle, in which above-average sea-surface temperatures develop across the east-central tropical Pacific. La Niña is the cold phase of the ENSO cycle. The swings of the ENSO cycle typically occur on a time scale of a few years. These changes in tropical rainfall affect weather patterns throughout the world... Climate variability is manifested in other ways as well. Decadal and seasonal shifts in wind patterns and sea surface temperatures in the Atlantic cause changes in hurricane frequency, for example. Sometimes climate varies in ways that are random or not fully explainable. The Dust Bowl of the 1930s in the United States is one such example... Many of the longer period fluctuations are linked to the ocean."[75]

Chemical Composition of Air (Fixed and Variable Components):

Tables here are derived from Wikipedia[76] and from RAH. See also Standard Atmospheres in Glossary. Atmospheric Chemistry is presented in detail in Chapter 5 of *ASI*, but we did not read this chapter.) Pollutants are discussed in *MT8* chapters 18.

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[72] http://www.grida.no/publications/other/ipcc_tar/?src=/climate/ipcc_tar/wg1/518.htm
[73] http://www.ipcc.ch/publications_and_data/publications_and_data_reports.htm
[74] Climate variability:
See for example "Climate Variability in the Pacific" regarding the PDO and ENSO, downloadable at http://www.clivar.org/ as the PDF pacific.pdf
[75] http://www.research.noaa.gov/climate/t_observing.html
[76] http://en.wikipedia.org/wiki/Atmosphere_of_Earth

Fixed Gases

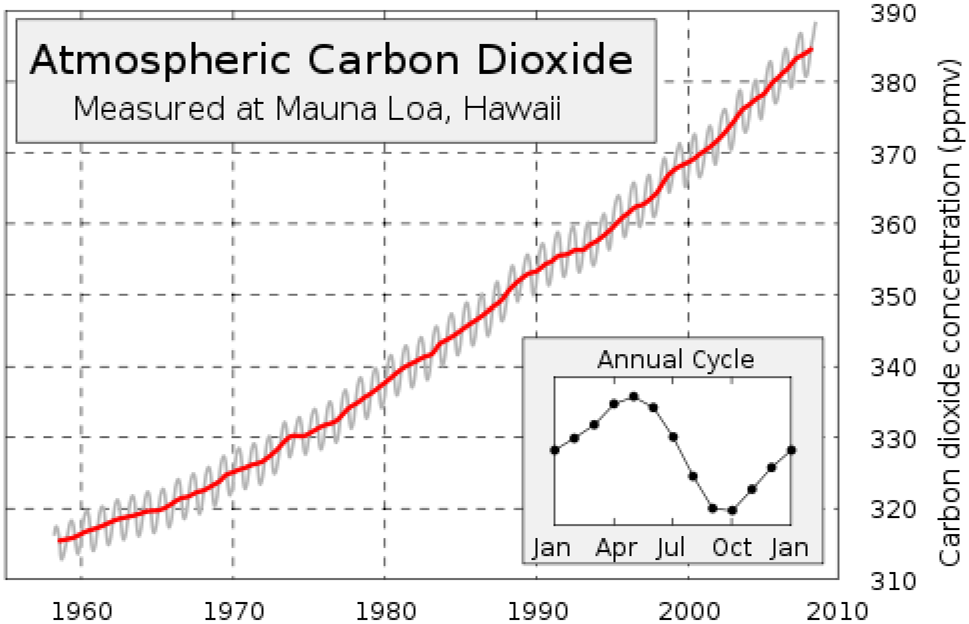
Gas	Concentration by Volume	
Nitrogen (N_2)	780,840 ppmv	78.084%)
Oxygen (O_2)	209,460 ppmv	20.946%)
Argon (Ar)	9,340 ppmv	0.9340%)
Carbon dioxide (CO_2)	390 ppmv[77]	0.039%)
Neon (Ne)	18.18 ppmv	0.001818%)
Helium (He)	5.24 ppmv	0.000524%)
Methane (CH_4)	1.79 ppmv	0.000179%)
Krypton (Kr)	1.14 ppmv	0.000114%)
Hydrogen (H_2)	0.55 ppmv	0.000055%)
Nitrous oxide (N_2O)	0.3 ppmv	0.00003%)
Carbon monoxide (CO)	0.1 ppmv	0.00001%)
Xenon (Xe)	0.09 ppmv	9×10^{-6}%)
Ozone (O_3)	0.0 to 0.07 ppmv	0 to 7×10^{-6}%)
Nitrogen dioxide (NO_2)	0.02 ppmv	2×10^{-6}%
Iodine (I)	0.01 ppmv	1 × 10−6%
Ammonia (NH_3)	trace	

Variable Components

Gas or Other Component	Concentration by Volume
Water vapor (H_2O)	0.40% over full atmosphere, typically 1%–4% at surface
Particulates: dust, pollen and spores, sea spray and salt, volcanic ash	0.01 - 0.15 ppmv
Chlorofluorocarbons (CFCs).	0.0002 ppmv
Misc. industrial and anthropogenic pollutants causing air pollution: Cl_2 and other chlorine compounds, fluorine compounds, Hg, NO (nitric oxide), SO_2 (sulfur dioxide), SO_3 (sulfur trioxide), other sulfur compounds, etc. (see also *MT8* chapter 18)	variable

[77] Keeling Curve: http://en.wikipedia.org/wiki/Carbon_dioxide_in_Earth%27s_atmosphere

Of course, the atmospheric composition of carbon dioxide (CO_2) is steadily rising (as shown in the following "Keeling Curve" of Charles David Keeling), an indisputable fact central to the politically charged debate on global warming:



Keeling Curve (from http://en.wikipedia.org/wiki/Carbon_dioxide_in_Earth%27s_atmosphere)

Other atmospheric constituents, such as the stratospheric ozone, are also changing due to anthropogenic effects.

Atmospheric Scales

Atmospheric Horizontal Scale

The horizontal scales of the atmosphere for description of clouds, horizontal motion, and other phenomena are variously and loosely defined as follows:

Planetary Scale: **> 20,000 km** (*ASI*-376)

Synoptic Scale (aka *large scale* or *cyclonic* scale): 1000[78] or 2000 km (*ASI*-376, RAH[79]) to 20′000 km (*ASI*-376)

Mesoscale: **2 km** (*ASI*-376) or 10 km (Wikipedia) or 20 km (RAH) **to** 1000 km (Wikipedia) or **2000 km** (*ASI*-376, RAH)

Meso-α	200 km to 2000 km	(*ASI*-376)
Meso-β	20 km to 200 km	(*ASI*-376)
Meso-γ	2 km to 20 km	(*ASI*-376)

[Convective Scale for clouds: **0.2 km to 20 km** (RAH)]

Microscale: **2 mm** (*ASI*-376) **to 2 km** (*ASI*-376)

Micro-α	200 m to 2 km	(*ASI*-376)
Micro-β	20 m to 200 m	(*ASI*-376)
Micro-γ	2 m to 20 m	(*ASI*-376)
Micro-δ	2 mm to 2 m	(*ASI*-376)
Molecular	Molecular size	(*ASI*-376)

78 http://en.wikipedia.org/wiki/Synoptic_scale_meteorology
79 RAH, *Cloud Dynamics*, p. 65

Atmospheric Layers and Relation to Temperature

Note that the vertical subdivisions of the atmosphere pertaining to clouds and termed Étages are discussed under Clouds.

Text that follows is excerpted from NOAA[80] and Wikipedia.[81] For an image of atmosphere vertical structure, see the beginning of this document. Layers are listed beginning with the lowest.

Troposphere (0 to 6–20 km)

NOAA: "The troposphere begins at the Earth's surface and extends up to 4-12 miles (6-20 km) high. This is where we live. As the density of the gases in this layer decrease with height, the air becomes thinner. Therefore, the *temperature in the troposphere also decreases with height*. As you climb higher, the temperature drops from about 62°F (17°C) to -60°F (-51°C). Almost all weather occurs in this region… The height of the troposphere varies from the equator to the poles. At the equator it is around 11-12 miles (18-20 km) high, at 50°N and 50°S, 5½ miles and at the poles just under four miles high. The transition boundary between the troposphere and the [stratosphere] … is called the tropopause. Together the tropopause and the troposphere are known as the lower atmosphere."

Wikipedia: "The troposphere begins at the surface and extends to between 7 km (23,000 ft) at the poles and 17 km (56,000 ft) at the equator, with some variation due to weather. The troposphere is mostly heated by transfer of energy from the surface, so on average the lowest part of the troposphere is warmest and temperature decreases with altitude. This promotes vertical mixing (hence the origin of its name in the Greek word "τροπή", trope, meaning turn or overturn). The troposphere contains roughly 80% of the mass of the atmosphere. The tropopause is the boundary between the troposphere and stratosphere."

Stratosphere (6–20 km to ~50–55 km)

NOAA: "The Stratosphere extends from the tropopause up to 31 miles above the Earth's surface. This layer holds 19 percent of the atmosphere's gases but very little water vapor… *Temperature increases with height* as radiation is increasingly absorbed by oxygen molecules leading to the formation of Ozone. The temperature rises from an average -76°F (-60°C) at tropopause to a maximum of about 5°F (-15°C) at the stratopause due to this absorption of ultraviolet radiation. This increase is temperature with height means no "convection" occurs since there is no vertical movement of the gases... The transition boundary which separates the stratosphere from the mesosphere is called the stratopause. The regions of the stratosphere and the mesosphere, along with the stratopause and mesopause, are called the middle atmosphere by scientists."

Wikipedia: "The stratosphere extends from the tropopause to about 51 km (32 mi). Temperature increases with height, which restricts turbulence and mixing. The stratopause, which is the boundary between the stratosphere and mesosphere, typically is at 50 to 55 km (31 to 34 mi). The pressure here is 1/1000th of sea level."

Mesosphere (~50–55 km to 80–85 km)

NOAA: "The mesosphere extends from the stratopause to about 53 miles (85 km) above the earth. The gases, including the oxygen molecules, continue to become thinner and thinner with height. As such, the effect of the warming by ultraviolet radiation also becomes less and less leading to *a decrease in temperature with height*. On average, temperature decreases from about 5°F (-15°C) to as low as -184°F (-120°C) at the mesopause. However, the gases in the mesosphere are still thick enough to slow down meteorites hurtling into the atmosphere, where they burn up, leaving fiery trails in the night sky."

Wikipedia: "The mesosphere extends from the stratopause to 80–85 km (50–53 mi). It is the layer where most meteors burn up upon entering the atmosphere. Temperature decreases with height in the mesosphere. The mesopause, the temperature minimum that marks the top of the mesosphere, is the coldest place on Earth and has an average temperature around −85 °C (−121 °F; 188.1 K). Due to the cold temperature of the mesosphere, water vapor is frozen, forming ice clouds (or Noctilucent clouds). A type of lightning referred to as either sprites or ELVES, form many miles above thunderclouds in the troposphere."

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[80] http://www.srh.noaa.gov/srh/jetstream/atmos/layers.htm

[81] Atmosphere layers: http://en.wikipedia.org/wiki/Atmosphere_of_Earth

Thermosphere (80–85 km to 690 km)

NOAA: "The Thermosphere extends from the mesopause to 430 miles (690 km) above the earth. This layer is known as the upper atmosphere... The gases of the thermosphere are increasingly thinner than in the mesosphere. As such, incoming high energy ultraviolet and x-ray radiation from the sun, absorbed by the molecules in this layer, causes a large temperature increase... Because of this absorption, the *temperature increases with height* and can reach as high as 3,600°F (2,000°C) near the top of this layer; however, despite the high temperature, this layer of the atmosphere would still feel very cold to our skin because of the extremely thin air. The total amount of energy from the very few molecules in this layer is not enough to heat our skin."

Wikipedia: "...The temperature of this layer can rise to 1,500 °C, though the gas molecules are so far apart that temperature in the usual sense is not well defined. The International Space Station orbits in this layer, between 320 and 380 km (200 and 240 mi). The top of the thermosphere is the bottom of the exosphere, called the exobase. Its height varies with solar activity and ranges from about 350–800 km."

NOAA: "Located within the thermosphere, the **ionosphere** is made of electrically charged (ionized) gas particles. The ionosphere extends from 37 to 190 miles (60-300 km) above the earth's surface. It is divided into three regions or layers; the F-Region, E-Layer and D-layer. During the daytime the F-Layer splits into two layers then recombines at night."[82] The ionosphere overlaps all layers of the atmosphere except the troposphere.

Exosphere (690 km to 10,000 km)

NOAA: "The Exosphere is the outermost layer of the atmosphere. It extends from the thermopause—the transition boundary which separates the exosphere from the thermosphere below—to 6,200 miles (10,000 km) above the earth. In this layer, atoms and molecules escape into space and satellites orbit the earth."

Wikipedia: "... extends from the exobase upward. Here the particles are so far apart that they can travel hundreds of kilometres without colliding with one another. Since the particles rarely collide, the atmosphere no longer behaves like a fluid. These free-moving particles follow ballistic trajectories and may migrate into and out of the magnetosphere or the solar wind. The exosphere is mainly composed of hydrogen and helium."

Global Air Circulation and Winds

Although many regions have special winds of their own (partially discussed below), there are certain generalizations that can be made about global wind patterns. Such discussion invariably start with an idealized model of an ocean planet having no land surfaces and with rotation in the same direction of the Earth but with no rotational axis tilt with respect to the sun. Computations using this model predict the following patterns:

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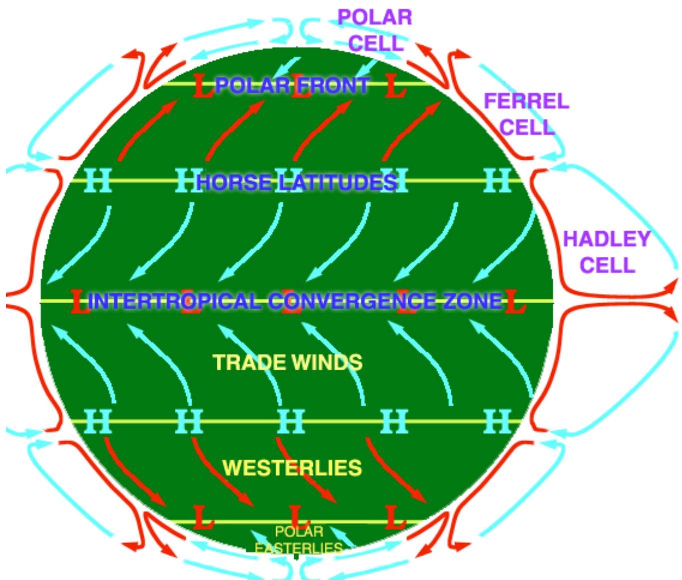
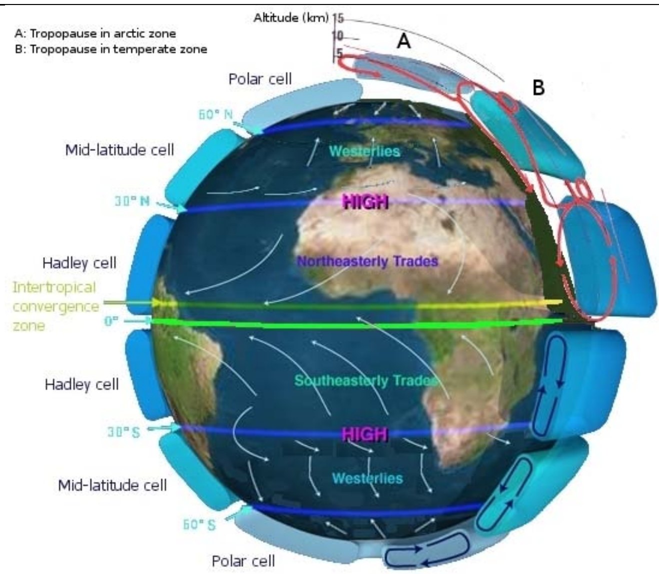
[82] http://www.srh.noaa.gov/srh/jetstream/atmos/ionosphere_max.htm

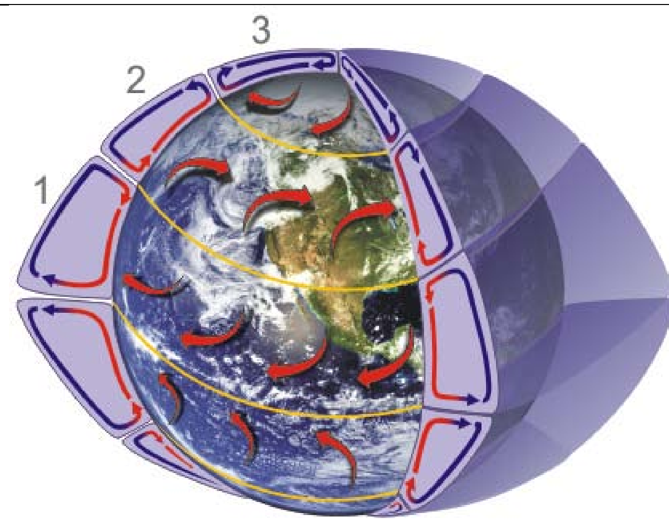


Idealized ocean planet model surface winds and vertical circulations
fr. http://en.wikipedia.org/wiki/Global_winds

With the addition of the Earth's major land masses, which are much more extensive in the NH than the SH, plus the planetary tilt of 24.4° (varying from 22.1° to 24.5°)[83], we get a more typical model of Earth pattern of winds (still ignoring in this diagram any seasonal or local wind variations):



More realistic averaged global air circulations
from Wikipedia http://en.wikipedia.org/wiki/Global_winds



More realistic averaged global air circulations
from NOAA http://www.srh.noaa.gov/jetstream/global/circ.htm

These diagrams show the directions prevailing for surface winds, including the trades and the mid-latitude westerlies (in both hemispheres). The Intertropical Convergence Zone is discussed below. The Hadley cell (named after George Hadley) and the Mid-latitude cell depict major vertical and upper level components of normal global atmosphere circulation. The Polar cell is indicated but not discussed in detail. The Mid-latitude cell here is also called a *Ferrel cell* (named after William Ferrel). The decrease in height of the tropopause going from Equator to Pole is depicted in exaggerated scale. Various aspects of this global circulation are mentioned throughout this summary. Of course this wind pattern also affects precipitation.

NOAA summarizes some of these features (slightly edited),

[83] http://en.wikipedia.org/wiki/Axial_tilt

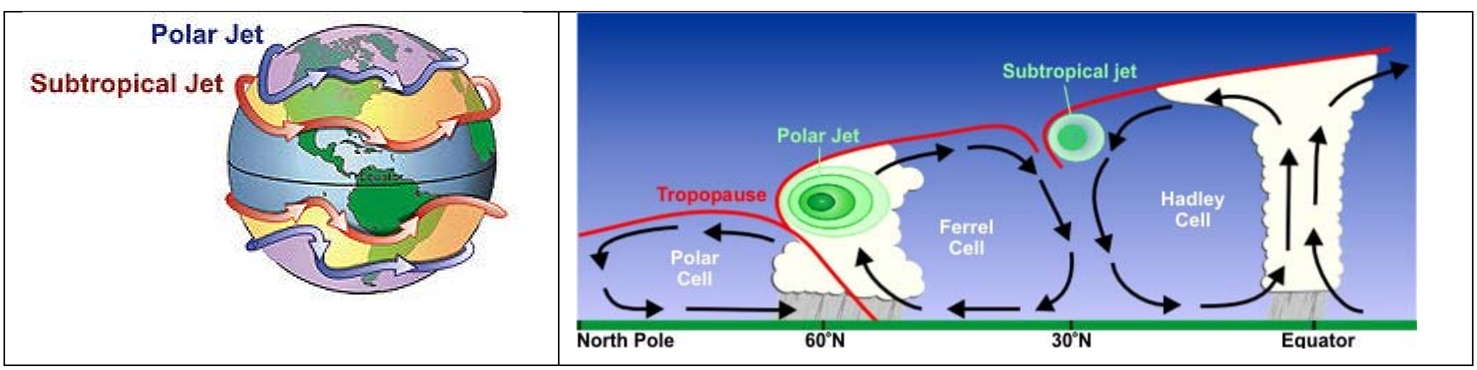
"Instead of one large circulation between the poles and the equator, there are three circulations…
1. Hadley cell—Low latitude air movement toward the equator that with heating, rises vertically, with poleward movement in the upper atmosphere. This forms a convection cell that dominates tropical and sub-tropical climates.
2. Ferrel cell—A mid-latitude mean atmospheric circulation cell for weather named by [William] Ferrel in the 19th century. In this cell the air flows poleward and eastward near the surface and equatorward and westward at higher levels.
3. Polar cell—Air rises, diverges, and travels toward the poles [at about 60º]. Once over the poles, the air [converges aloft and] sinks, forming the polar [surface] highs. At the surface, air diverges outward from the polar highs. Surface winds in the polar cell are easterly (polar easterlies).

Between each of these circulation cells are bands of high and low pressure at the surface. The [surface] high pressure band is located about 30° N/S latitude and at each pole. [These are all sites of convergence aloft.] [Surface] low pressure bands are found at the equator and 50°-60° N/S. [These are all sites of divergence aloft].

Usually, fair and dry/hot weather is associated with high pressure, [while] rainy and stormy weather [are] associated with low pressure. You can see the results of these circulations on a globe. Look at the number of deserts located along the 30°N/S latitude around the world. Now, look at the region between 50°-60° N/S latitude. These areas, especially the west coast of continents, tend to have more precipitation due to more storms moving around the earth at these latitudes."

Jet Streams

The jet streams are important upper air circulations. The *northern polar jet* is at the northerly limit of the Ferrel cells but is not actually so polar, being found between latitudes 50°N and 60°N (sometimes as low as 30°N), and is therefore also called the *mid-latitude jet stream* or simply the *jet stream*. The northern *subtropical jet stream* is located close to latitude 30°N. (Thus the two jet streams can approach fairly close to each other or even merge at times.) The northern polar jet is the most important for aviation and weather forecasting in the NH. "The westerly subtropical jet is at the poleward limit of the Hadley cell, around 30° N and S; the northern subtropical jet is strongest at the 200 mb level [~11785 m], and above the Indian subcontinent. This is one of the most powerful wind systems on earth, at times reaching speeds of 135 m s^{-1}, and it follows a more fixed pattern than the polar-front jet. It results from the poleward drift of air in the Hadley circulation and the conservation of angular momentum."[84] The wind speed in the jet stream can be compared to that of a river, for which speed "is generally the strongest in the center with decreasing strength as one approaches the river's bank. It can be said that jet streams are 'rivers of air'."[85] The actual jet stream versus slower nearby air moving in the same direction are apparently differentiated as follows: "Although often erroneously applied to all upper-level winds, by definition jet stream wind speeds are *in excess of [50 knots]* 57 mph (92 km/h)." "The highest wind speed ever recorded on the surface of the Earth was 231 mph on April 12 1934, atop Mt. Washington, New Hampshire. This high-elevation weather station experienced the winds of an extremely strong jet stream that had descended to the top of the mountain."[86]



Global diagram view and NH meridional cross sectional diagram
from http://www.srh.noaa.gov/jetstream/global/jet.htm

[84] http://science.jrank.org/pages/45960/jet-stream.html
[85] http://www.srh.noaa.gov/jetstream/global/jet.htm
[86] http://www.weatherquestions.com/What_causes_the_jet_stream.htm

Per Wikipedia:

> "Jet streams are fast flowing, narrow air currents found in the atmospheres of some planets. The main jet streams are located near the tropopause... The major jet streams on Earth are westerly winds... Their paths typically have a meandering shape; jet streams may start, stop, split into two or more parts, combine into one stream, or flow in various directions including the opposite direction of most of the jet. The strongest jet streams are the polar jets, at around 7–12 km (23,000–39,000 ft) above sea level, and the higher and somewhat weaker [presumably due to thinner air] subtropical jets [are] at around 10–16 km (33,000–52,000 ft). The northern hemisphere and the southern hemisphere each have both a *polar jet* and a *subtropical jet*. The northern hemisphere polar jet flows over the middle to northern latitudes of North America, Europe, and Asia and their intervening oceans, while the southern hemisphere polar jet mostly circles Antarctica all year round...
>
> Jet streams are caused by a combination of a planet's rotation on its axis and atmospheric heating (by solar radiation and, on some planets other than Earth, internal heat). The Coriolis effect describes how a planet's surface and atmosphere rotate fastest relative to each other at the planet's equator while virtually not rotating at all at the poles. While this speed difference generally has very little effect on a planet's surface, it plays an important role in atmospheric air currents because air at higher levels of the atmosphere, especially near the equator, must travel very fast to keep up with the planet's rotation. Thus there is a tendency for air at higher levels of the atmosphere to 'slip' and fall behind the speed of the air below. This results in a pressure buildup behind the 'slipped' air, and so some air will have to catch up by moving in the same general direction as the planet's rotation (west to east on Earth); however, this air does not follow a simple pattern but instead is also influenced by its temperature and water content compared to that of surrounding air regions. In essence, instead of the atmosphere moving along with the planet consistently, parts of the atmosphere travel faster than others via jet streams.
>
> Jet streams form near boundaries of adjacent air masses with significant differences in temperature, such as the polar region and the warmer air towards the equator... Meteorologists use the location of some of the jet streams as an aid in weather forecasting...
>
> Polar jet streams are typically located near the 250 hPa pressure level, or 7 kilometres (4.3 mi) to 12 kilometres (7.5 mi) above sea level, while the weaker subtropical jet streams are much higher, between 10 kilometres (6.2 mi) and 16 kilometres (9.9 mi) above sea level. In each hemisphere, both upper-level jet streams form near breaks in the tropopause, which is at a higher altitude near the equator than it is over the poles, with large changes in its height occurring near the location of the jet stream. The northern hemisphere polar jet stream is most commonly found between latitudes 30°N and 60°N, while the northern subtropical jet stream located close to latitude 30°N. The upper level jet stream is said to 'follow the sun' as it moves northward during the warm season, or late spring and summer, and southward during the cold season, or autumn and winter. The width of a jet stream is typically a few hundred miles and its vertical thickness often less than three miles.
>
> Associated with jet streams is a phenomenon known as *clear air turbulence* (CAT), caused by vertical and horizontal windshear connected to the jet streams. The CAT is strongest on the cold air side of the jet [stream], next to and just underneath the axis of the jet [stream]. Clear air turbulence can cause aircraft to plunge and so present a passenger safety hazard that has caused fatal accidents, such as the death of one passenger on United Airlines Flight 826 (1997)."[87]

Polar views of NH and SH jet streams, showing the direction in which they flow, may be seen *here*.[88]

Pressure, Flows, and Fronts

Pressure P is the force per unit area applied in a direction perpendicular to the surface of an object.[89] *Gauge pressure* is the pressure relative to [i.e., in excess of] the local atmospheric or ambient pressure... The SI unit for pressure is the *pascal* (Pa), equaling one newton per square meter (N m^{-2} or $kg \cdot m^{-1} \cdot s^{-2}$)... Non-SI measures such as pounds per square inch and bar are used in some parts of the world, primarily in the USA...

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[87] http://en.wikipedia.org/wiki/Jet_stream

[88] Flow direction of jet streams in NH vs. SH:
- View from NP: http://www.atmos.washington.edu/~ovens/loops/wxloop.cgi?npole_h250_wind+/-168//
- View from SP: http://www.atmos.washington.edu/~ovens/loops/wxloop.cgi?spole_h250_wind+/-168//

[89] http://en.wikipedia.org/wiki/Pressure

Pressure is sometimes expressed in grams of force cm^{-2}, or as kg cm^{-2} without properly identifying the force units. Using the names kilogram, gram, kilogram-force, or gram-force (or their symbols) as units of force is expressly forbidden in SI units.[90] Many meteorologists prefer units of hectopascals (hPa) for atmospheric air pressure, as hPa is equivalent to the widely used millibar (mbar or mb). In other fields, where the hecto- prefix is rarely used, pressures of similar magnitude are given in kilopascals (kPa). Inches or millimeters of mercury are also used in the United States. In medicine, blood pressure is commonly measured in millimeters of mercury, and lung-related pressures in centimeters of water.

Because pressure is commonly measured by its ability to displace a column of liquid in a manometer, pressures are often expressed as a height of water or mercury (Hg) in the manometer column (e.g., centimeters of water, inches of water, inches of Hg, or millimeters of Hg). The pressure exerted by a column of liquid of height h and uniform density ρ is given by the hydrostatic pressure equation $p = \rho g h$. This assumes ρ and g are constant over the height of the column, but in fact fluid density and local gravity can vary with height and locale, so the height of a fluid column does not define pressure precisely. The units millimeters of mercury or inches of mercury are not based on a physical column of mercury—rather, they have been given precise definitions expressed in terms of SI units. Thus, one mm Hg (millimeter of mercury) is equal to one Torr = 1/760 std atm (see below). The water-based units still depend on the density of water, a measured rather than defined quantity."[91]

Atmospheric Pressure Variation with Altitude (Geopotential Height)

The standard atmosphere (atm) is a defined constant: **One std atmosphere**[92] is an international reference pressure defined as 101,325 Pa, reflecting the true mean sea level pressure at the latitude of Paris, and is equal to

101325 Pa
101.325 kPa
1013.25 hPa (hPa are equivalent to millibars=mb=mbar)
1.01325 bar
760 Torr (mm Hg; by definition)
14.696 psi

While the average sea level atmospheric pressure is 1013.25 mb (29.92 mm Hg), the lowest recorded sea level pressure was 870 mb, and the highest recorded was 1084 mb (per RAH notes). According to *ASI*-7, the globally averaged surface pressure is 985 hPa (this of course encompasses latitudes other than that of Paris, and apparently includes land surfaces that are above sea level). (see also *MT8*-197)

[90] http://www.newworldencyclopedia.org/entry/Pressure
[91] http://en.wikipedia.org/wiki/Pressure
[92] http://en.wikipedia.org/wiki/Atmosphere_%28unit%29

At any given location on Earth, atmospheric pressure always decreases with height above sea level[93] in approximately exponential fashion, and is estimated (according to standard models) as follows:

Fraction of 1 Atm.	Pressure (mb)	Geopotential Height (m) and Approximate Layer US Std Atmosphere[94]	Geopotential Height (m) ICAO Std Atmosphere[95]
1 atm	1013.25 mb	0 m (sea level)	0 m (sea level)
	1000 mb	110 m	111 m
	850 mb	1,457 m	1,457 m
	700 mb	3,012 m	3,012 m
1/2 atm	506.625 mb	5,477 m (troposphere)	
	500 mb	5,574 m (troposphere)	5,574 m
1/4 atm	253.313 mb	10,278 m (upper troposphere or lower stratosphere)	
	250 mb	10,363 m (upper troposphere or lower stratosphere)	10,363 m
	200 mb	11,784 m	11,784 m
1/10 atm	101.325 mb	16,096 m (upper troposphere or lower stratosphere)	
	100 mb	16,180 m (upper troposphere or lower stratosphere)	16,180 m
1/100 atm	10.13 mb	30,967 m (stratosphere)	
1/1000 atm	1.01 mb	47,716 m (upper stratosphere)	

Thus more than 99.9% of the atmosphere lies below 50 km. It is also apparent that the 500 mb level is a good approximation to the 0.5 atm level, and the 250 mb level is a good approximation to the 0.25 atm level.

Mathematical estimates of the mean atmospheric pressure (and other quantities such as mean free path) as a function of altitude are given by simple or quite complex models.[96] It is extensively described in "U.S. Standard Atmosphere 1976"[97] of NASA/NOAA, which presents a model consisting of two submodels: one extending from 0 to 86 km and the second extending from 86 km to 1000 km. Part 4 Table I gives pressure, temperature T, and density ρ as a function of geometric and geopotential height up to 1000 km. The *barometric formulas* described *here*[98] are usable formulas for estimating mean pressure by altitude using the U.S. Standard Atmosphere 1976 model (though I have not confirmed the details).

Constant Pressure Geopotential Height (Isohypse) Contour Charting

Variations of pressure can be mapped with Constant Pressure geopotential height (isohypse) contour line charts, in which the heights, usually geopotential heights, to a virtual surface of constant pressure (such as

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[93] http://en.wikipedia.org/wiki/Atmospheric_pressure#Altitude_atmospheric_pressure_variation
[94] U.S. Standard Atmosphere 1976: interpolated from Part 4 table I, see below.
[95] ICAO Std Atmosphere: http://www.aviation.ch/tools-atmosphere.asp and Skew T Log P diagram
[96] Modeling of the atmosphere pressure vs. altitude:
• http://www.engineeringtoolbox.com/air-altitude-pressure-d_462.html
• http://www.regentsprep.org/Regents/math/algtrig/ATP8b/exponentialResource.htm
[97] U.S. Standard Atmosphere 1976 (see also Glossary):
• NASA/NOAA full description October 1976: http://www.pdas.com/refs/us76.pdf
• Hydrostatic equations (which I have not yet studied): http://www.pdas.com/hydro.pdf
[98] http://en.wikipedia.org/wiki/Barometric_formula

850 mb) are plotted. "…In the mountainous terrain of the western United States and Mexican Plateau, the 850 hPa pressure surface can be a more realistic depiction of the weather pattern than a standard surface analysis. [Presumably mappers of isohypse contours for mountainous terrain as in Colorado that is already above the 850 hPa level must interpolate fictitious values as best they can.] Using the 850 and 700 hPa pressure surfaces, one can determine when and where warm advection (coincident with upward vertical motion) and cold advection (coincident with downward vertical motion) is occurring within the lower portions of the troposphere. Areas with small dewpoint depressions and are below freezing indicate the presence of icing conditions for aircraft. The 500 hPa pressure surface can be used as a rough guide for the motion of many tropical cyclones. Shallower tropical cyclones, which have experienced vertical wind shear, tend to be steered by winds at the 700 hPa level… Use of the 300 and 200 hPa constant pressure charts can indicate the strength of systems in the lower troposphere, as stronger systems near the Earth's surface are reflected as stronger features at these levels of the atmosphere… Minima in the wind pattern aloft are favorable for tropical cyclogenesis. Maxima in the wind pattern at various levels of the atmosphere show locations of jet streams."[99]

An aircraft flying into colder air along a low constant pressure surface set by the altimeter is actually descending in geometric height and may fly into the ground unless the altimeter is adjusted for the temperature—thus a preference for radio altimeters rather than pressure altimeters. (*MT8*-200)

Atmospheric Pressure Variation with Latitude, Longitude, and Season

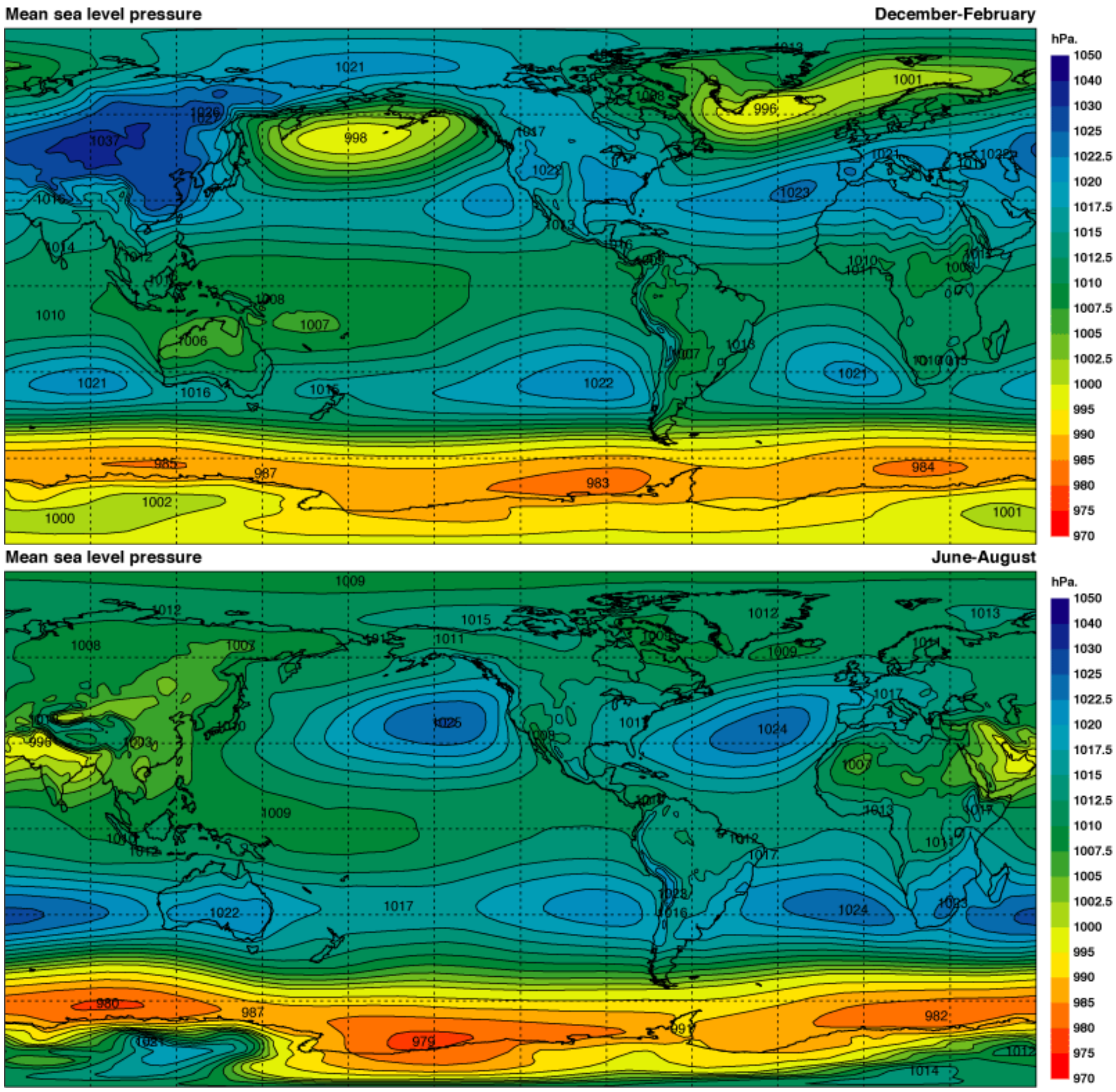
The relation of atmospheric pressure with latitude, locale, and season is complex.

Averaged Observations of Pressure

The actual pattern of long-range average atmospheric pressure is complex, and varies with the latitude, longitude, and season. Discussions of atmospheric pressure versus latitude etc. can be confusing unless one carefully specifies the elevation (geopotential height, etc.) for which the discussion applies.

[99] http://en.wikipedia.org/wiki/Weather_maps#Constant_pressure_charts

Sea Level Pressures (SLP)



Source: ECMWF: ERA-40 Atlas: Surface climatologies: Mean sea level pressure, Latitude-Longitude, December-February and June-August (using averaged data from 1979 - 2001)[100]

These maps show in the NH winter the subpolar *Icelandic Low* and the *Aleutian Low*, as well as the *Siberian High*, the *Canadian High*, and the *Bermuda High*, etc. In the NH summer, a thermal low forms over the US desert SW and over Iran and India, the *Bermuda High* moves to the W closer to Bermuda and the US, and the *Pacific High* moves to the N and becomes more prominent. (*MT8*-260) Other more detailed statements can be inferred from this diagram.

It has been stated, "In the summer [sea level pressure] is higher at the equator [compared to the poles] but in the winter it is not."[101] Another source on polar region pressure states, "Changing patterns of high pressure [presumably at the surface] are found in both polar regions. In the north polar region, the Northern Annular Mode is an area of high atmospheric pressure that moves between a location over the North Pole and a ring around the Pole at 45°N latitude. The changing location of the high-pressure zone causes changes in wind patterns and affects weather patterns from year to year such as how cold it will get in North America and Europe during a winter. In the south polar region, the Southern Annular Mode is similar. It involves a zone

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[100]ECMWF ERA-40 atlas:
• Website 2006: http://www.ecmwf.int/research/era/ERA-40_Atlas/docs/section_B/parameter_mslp.html
• Paper 2005 (68 MB):
http://www.ecmwf.int/publications/library/ecpublications/_pdf/era/era40/ERA40_PRS19_rev.pdf
[101] http://en.allexperts.com/q/Meteorology-Weather-668/Sea-level-atmospheric-pressure.htm

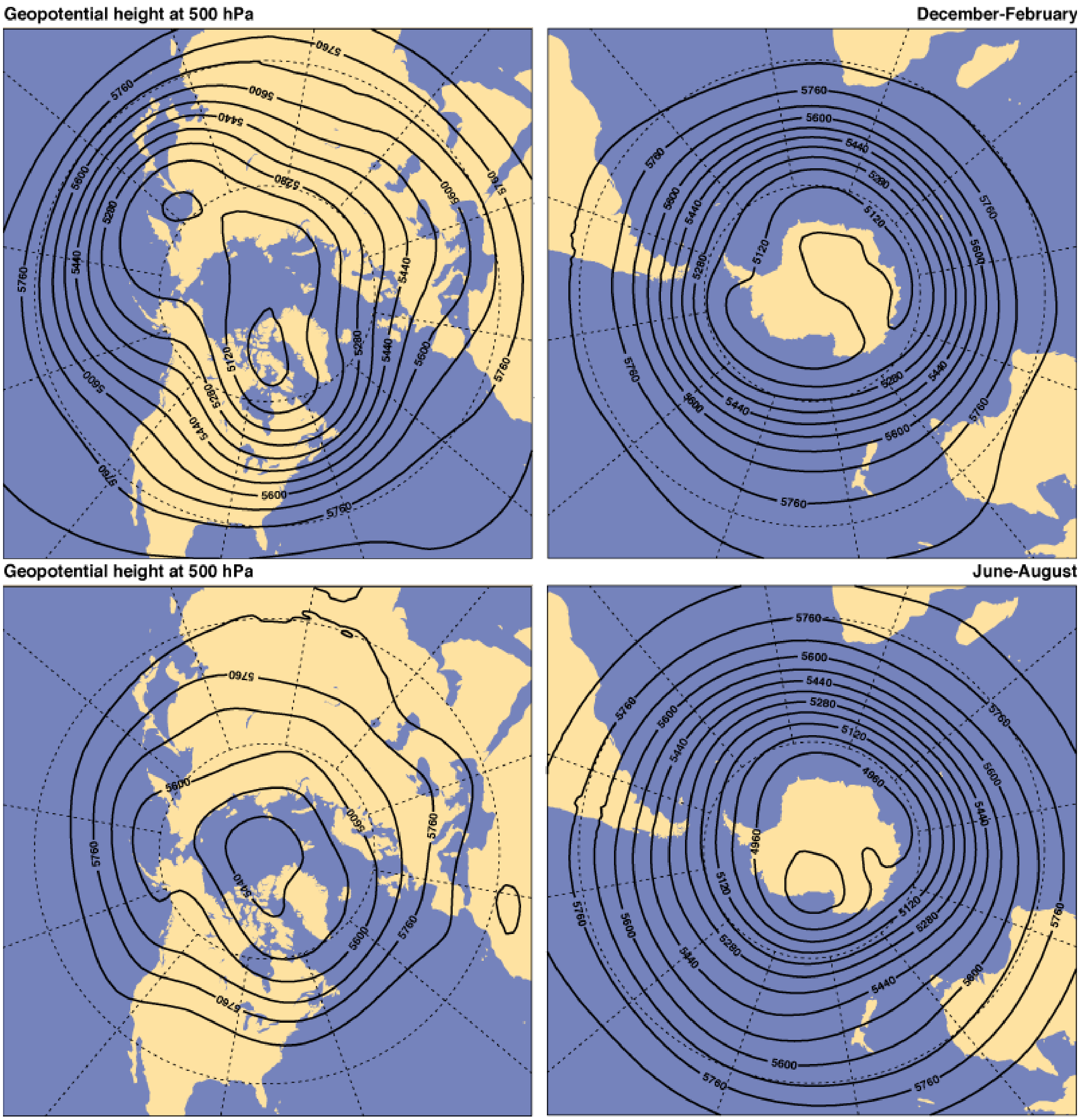
of high pressure that moves its location between the South Pole and a ring around the pole at 45°S latitude."[102]

However, for me it is difficult to generalize on this pattern, and inspection of the actual surface climatologies is the best approach.

Sea level pressure charts (for which actual surface pressures are adjusted to sea level) are also termed "Surface maps". (*MT8*-196)

500 mb Pressure Heights

In general, the atmosphere is colder and therefore denser in the polar than in the equatorial regions, and correspondingly, the 500 mb surface for polar regions is attained at (or lies at) a lower height than for the equator:



modified slightly from http://www.ecmwf.int/research/era/ERA-40_Atlas/images/full/D18_PS_JJA.gif and http://www.ecmwf.int/research/era/ERA-40_Atlas/images/full/D18_PS_DJF.gif

[102] http://www.windows2universe.org/earth/polar/polar_atmosphere.html

Superimposed on this general trend of isohypse contours circling the poles are long wavelength (LW) and shorter wavelength (SW) ridges and troughs of higher and lower pressure (corresponding to higher and lower heights of the 500 mb surface), the so-called *baroclinic* or *Rossby waves*. These LW and SW waves are associated with significant weather systems, discussed under troughs and ridges.

A Role for Gravity?

One might guess that surface atmospheric P would be lower at the equator than at the poles due to greater centrifugal force counteracting gravity at the equator and also to the effect of the equatorial bulge (which also reduces local gravity due to greater distance from the Earth center). "In combination, the equatorial bulge and the effects of centrifugal force mean that sea-level gravitational acceleration increases from about 9.780 $m \cdot s^{-2}$ at the equator to about 9.832 $m \cdot s^{-2}$ at the poles, so an object will weigh about 0.5% more at the poles than at the equator."[103] Judging by the observed patterns above, gravity variation plays little role.

Upper Level Atmospheric Pressures and Flows; Atmospheric Tides

(Many of the terms and concepts presented here are discussed in greater detail in the glossary.)

Upper level flow parameters such as pressure are observed with probes such as the rawinsonde system launched from upper-level stations[104] and by other means. Upper level pressure is typically mapped using *pressure surfaces*, such as the 500 mb surface (or level—i.e., the virtual surface representing the height above sea level, often expressed in decameters, at which the atmospheric pressure has fallen to 500 mb). The discrete observational data obtained from these probes is interpolated to yield a *Constant pressure geopotential height chart* for various pressure levels such as 500 mb.

It is not useful to call the pressure height contour lines *isobars*—after all, these contours lines are all at the same pressure but they have varying pressure surface geopotential heights. Such contour lines may be termed *isoheights* or *isoheight contours* (terms which are ambiguous), or better, *isohypses* or *isohypse contours*.[105] (The suffix *-hypse* derives from Greek *hypsos* = *height*.)[106] However, I note that some authors (*MT8*-199) refer to constant pressure height surfaces as *isobaric surfaces*, and their maps as *isobaric charts*, an undesirable usage in my opinion. This terminology appears to be a ready source of confusion.

A higher pressure height surface corresponds to a warmer higher pressure region, a lower height to a colder lower pressure region. Note that 5600 meters is the average height of the 500 mb surface. When air is heated, it expands, becomes less dense and more buoyant, and rises. When air is cooled, it contracts, becomes denser and less buoyant, and sinks. As air warms and rises, more air molecules will be found above 5600 meters than normal. Thus *above warmer air below, the 500 mb surface is found at a higher pressure height*. Where cold air has contracted and sunk toward the surface, fewer air molecules than normal are found above 5600 meter. Thus *above colder air below, the 500 mb surface is found at a lower pressure height*.[107] Stated another way, "It takes a shorter column of cold, more dense air to exert the same surface pressure as a taller column of warm less dense air." (*MT8*-192)

However, and rather confusingly, "warm air aloft is normally associated with high atmospheric pressure [at the geometric height where 'aloft' is defined], and cold air aloft is associated with low atmospheric pressure [at the same geometric height where 'aloft' is defined]." (*MT8*-192 and 199) A column of warm air next to a column of cold air will therefore have a pressure gradient across the plane of the same geometric height level, going from warm to cold. "Heating or cooling a column of air can establish horizontal variations in pressure that cause the air to move. The net accumulation [i.e., increase] of air above the surface causes air pressure to rise, whereas a decrease in the amount of air above the surface causes the air pressure to fall." (*MT8*-193)

As a result of these horizontal flows from hotter air aloft toward cooler air aloft at the same geometric height, the heated surface air of a heated air column is accompanied by a lower surface pressures, especially apparent for example in the SW desert US in summer. This is termed a *thermal (warm-core) low*. (*MT8*-236, 260) Likewise, cold arctic surface air in winter is accompanied also by flows from hotter air aloft toward cooler air aloft at the same geometric height, resulting in higher surface pressure over the column of colder air

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[103] http://en.wikipedia.org/wiki/Gravity_of_Earth
[104] http://weather.uwyo.edu/upperair/
[105] http://en.wikipedia.org/wiki/Contour_line
[106] http://www.yourdictionary.com/hypso-prefix
[107] Paraphrased from
http://www.uwsp.edu/geo/faculty/ritter/geog101/textbook/circulation/analyzing_pressure_patterns.html

compared to the nearby warmer column. This is termed a *thermal (cold-core) high*. (*MT8*-236). The lateral flowing or air resulting from day/night heating variation results in a diurnal variation of pressure. In the mid-latitudes, the surface pressure peaks at about 1013 mb around 2 PM and reaches its lowest of about 1007 mb at around 7 AM, an excursion of about 7 mb. (This excursion is smaller at higher latitudes.) In the tropics, the surface pressure peaks at around 1010 mb around 10 AM and 10 PM and reaches a nadir of about 1008 mb at around 4 PM and 4 AM. These smaller but semidiurnal excursions are about 2.5 mb maximum and are termed *thermal* or *atmospheric tides*. (*MT8*-193, see also *here*[108])

Sea and large lake breezes are another type of thermal circulation. At mid-latitudes these are strongest in spring and summer. When land warms during the day, air rises over this land, a pressure gradient develops, and cooler sea breezes blow inland to replace the air. At night, when the land cools faster than the sea surface, the air rises more over the sea and is replaced by offshore winds from land. (*MT8*-237)

Tropic to Polar variation: "In general constant pressure [geopotential height] surfaces slope downwards from the tropics to the poles."[109] This means that the warmer temperatures of the tropics cause expansion of the air, thus causing a given pressure height surface to be at a higher altitude compared to the colder air in the polar regions, for which the contracted cold air attains the given pressure height surface at a lower altitude.

Pressure Height Isohypse vs. Constant absolute altitude Isobar pressure contours: The isohypse contour lines (e.g., in m for the 500 mb pressure height surface) follow the same pattern and appear nearly identical compared to the isobar pressure contour lines (in mb) of a constant absolute height map (e.g., the 5600 m surface).[110] The latter type of graph does not appear to be commonly encountered in routine weather mapping.

Convergence and Divergence: *Convergence* aloft (a net inflow of air molecules into a region of the atmosphere) is associated with increasing surface pressure, since the mass overhead per unit surface area, or weight of the column, will increase with time. In contrast, *divergence* aloft (a net outflow of air molecules from a region of the atmosphere) is always associated with decreasing surface pressure, since the mass per unit surface area, or weight of the column, will decrease with time. A high surface pressure develops under a region of maximum convergence aloft. A low surface pressure develops under a region of maximum divergence aloft. In general, rising air motion is associated with decreasing (*Low*) pressure (at least at the surface), adiabatic cooling, increasing relative humidity, condensation, clouds and precipitation. In contrast, sinking air motion is associated with increasing (*High*) pressure (at the surface), adiabatic warming, decreasing relative humidity, and relatively clear skies.[111]

Troughs and Ridges, Normal and Cut-off Lows and Highs, Blocking Highs: These are most easily understood as phenomena defined on constant pressure surfaces. The large-scale (synoptic) pattern of the 500 mb surface apparent in views centered on the N Pole (for example *here*[112]), shows concentric pressure height contours corresponding with westerlies which encircle the pole (geostrophic wind flow direction is along the pressure height contours). Typically the pressure height isohypse contours are circumpolar contours which decrease in height value with increased latitude (see above). There are large wave-like perturbations in the circularity of these pressure height contours. These waves, called *baroclinic or Rossby waves*, are associated with *troughs* (which are elongated regions of relatively low or depressed pressure height surfaces, often associated with weather fronts) and *ridges* (which are elongated regions of relatively high or elevated pressure height surfaces). In the NH, a trough on a constant pressure height map appears as a southward extension or meander of the pressure height contour lines, whereas a ridge appears as a poleward extension or meander of these lines. The axis of symmetry of the trough or ridge is often tilted, in the NH from SW to NE. A strong meander can become detached and evolve to an enclosed cut-off rotating region (forming a high or low pressure *center*). The cut-off pressure height contour lines, which are often elliptical in shape, may be poleward of the westerly current and contain a closed *high (H)* pressure region,[113] or they may be equatorward

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[108] Atmospheric tide:
- http://en.wikipedia.org/wiki/Atmospheric_tide
- http://amsglossary.allenpress.com/glossary/search?id=atmospheric-tide1

[109] http://atoc.colorado.edu/~cassano/atoc1050/Lecture_Notes/Chapter03/chapter3.pdf

[110] ibid. (compare diagrams "A" and "B")

[111] Paraphrased partially from http://atoc.colorado.edu/~cassano/atoc1050/Lecture_Notes/Chapter08/chapter8.pdf

[112] http://www.atmos.washington.edu/~ovens/loops/wxloop.cgi?npole_h500+/-168//

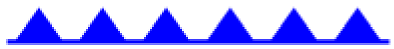
[113] http://amsglossary.allenpress.com/glossary/search?p=1&query=cut-off&submit=Search

of the westerly current and enclose a *low (L)* pressure region.[114] Such a cut-off high may act as a blocking high or blocking anticyclone, defined as "any high (or anticyclone) that remains nearly stationary or moves slowly compared to the west-to-east motion 'upstream' from its location, so that it effectively 'blocks' the movement of migratory cyclones across its latitudes... A blocking high may comprise a smaller-scale effect than that associated with large-scale blocking."[115]

Wind Response to Pressure Gradients: Wind direction is not usually perpendicular to the isohypse (pressure height) contours (as one might naively expect, assuming air flow were simply directed along the pressure gradient, but this is true only at the Equator where Coriolis effect is absent, or would also be true for a non-rotating Earth). Rather, under the influence of the Coriolis Effect and a low Rossby number for large-scale flows, it is everywhere nearly parallel to isohypse contours. For example, the polar jet streams, which flow nearly parallel to pressure height contours for which pressure height and temp is decreasing toward the poles, are westerly winds in both hemispheres.

Fronts and Their Relation to Baroclinic Waves

According to RAH: "A *front* is always the warm edge of a zone of strong temperature contrast." (Other sources define a front as the transition zone between [or boundary separating] two air masses of different densities.)[116] Cold air always underlies warmer air, due to its greater density. Apparently, fronts are weather phenomena at and near the surface.

Cold Front: A *cold front*, symbolized by  is a front in which cold air behind the front is advancing toward receding warm air.[117] Cold fronts have a steeply sloping interface with the less dense warm air. They lift the warm air below which they advance abruptly, and cause a more concentrated formation of clouds and precipitation above the advancing front.

Warm Front: A *warm front* , symbolized by  moves toward and over colder air, retreating from warm air behind it.[118] The interface between a warm front and the cold air it is overriding has a more gradual slope along which the warm air gradually rises, causing more horizontally widespread cloud formation and precipitation.

Occluded Front: An *occluded front*, symbolized by  is one in which the cold air front has caught up with (overtaken) and partly overridden a warm front, forcing warm air aloft. It exhibits a gradually lowering cloud base, followed by precipitation and then a rapidly rising cloud base. "An occluded front is formed during the process of *cyclogenesis* [the development or strengthening of cyclonic circulation in the atmosphere about a low pressure area] when a cold front overtakes a warm front. When this occurs, the warm air is separated (occluded) from the cyclone center at the Earth's surface. The point where the front and the occluded front meet (and consequently the nearest location of warm air to the center of the cyclone) is called the triple point... There are two types of occlusion, warm and cold. In a cold occlusion, the air mass overtaking the warm front is cooler than the cool air ahead of the warm front, and plows under both air masses. In a warm occlusion, the air mass overtaking the warm front is not as cool as the cold air ahead of the warm front, and rides over the colder air mass while lifting the warm air... A wide variety of weather can be found along an occluded front, with thunderstorms possible, but usually their passage is associated with a drying of the air mass. Additionally, cold core funnel clouds are possible if shear is significant enough along the cold front. Occluded fronts are indicated on a weather map by a purple line with alternating semicircles and triangles pointing in direction of travel. Occluded fronts usually form around mature low pressure areas."[119] According to RAH, occluded fronts often represent a line of relative maximum temperature surrounded horizontally by cooler air. Occluded fronts are common in the Seattle area, especially in the winter.

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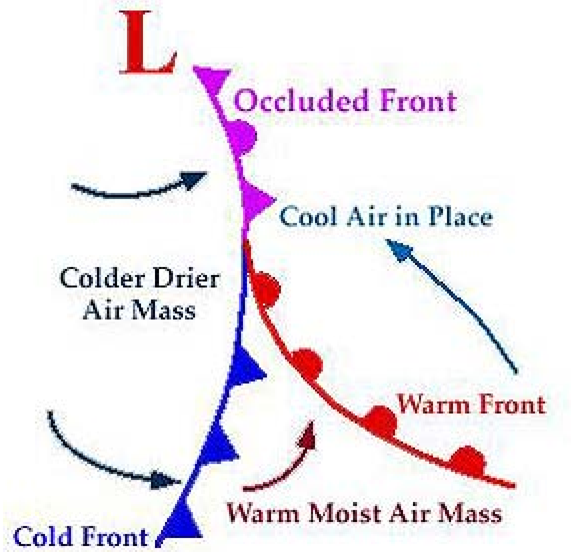
[114] http://amsglossary.allenpress.com/glossary/search?id=cut-off-low1
[115] http://amsglossary.allenpress.com/glossary/search?id=blocking-high1
[116] Fronts:
• http://ww2010.atmos.uiuc.edu/%28Gh%29/guides/mtr/af/frnts/home.rxml
• http://en.wikipedia.org/wiki/Weather_front
[117] http://en.wikipedia.org/wiki/Cold_front
[118] http://en.wikipedia.org/wiki/Warm_front
[119] http://en.wikipedia.org/wiki/Occluded_front

The following diagram[120] illustrates a typical configuration of an occluded front that has formed in association with a Low pressure center having counterclockwise rotation (in the NH):



"Cold fronts and occluded fronts in the Northern Hemisphere usually travel from the northwest to southeast, while warm fronts move more poleward with time."[121]

Relationship of Surface Fronts and Baroclinic Waves Aloft; Northers; Air Masses: According to RAH, cold fronts (which are experienced at the surface) tend to form beneath the leading edge of an upper level pressure trough (as seen for instance at the 500 mb level), a region exhibiting divergence aloft and therefore uplift. In other words, they form below the zone of transition in a baroclinic wave, going from W to E, from somewhat forward of the trough peak (point of greatest excursion of the trough) to somewhat before reaching the ridge peak or crest. Let us call this region the leading edge of the trough. This is a region with typically strong winds and a strong temperature gradient. On the other side of upper level troughs, there is typically convergence aloft, and sinking air, and fronts beneath typically do not have much surface weather, aside from possible high winds.

A deep ridge and trough may carry cold air as far as Texas, the so-called *Texas norther*. (*MT8*-249) "In the southern United States, especially in Texas…, the norther is a strong cold wind [cold front] from between northeast and northwest. It occurs between November and April, freshening during the afternoon and decreasing at night. It is a cold air outbreak associated with the southward movement of a cold anticyclone. It is usually preceded by a warm and cloudy or rainy spell with southerly winds. The norther comes as a rushing blast and brings a sudden drop of temperature of as much as 25°F in one hour or 50°F in three hours in winter…"[122]

RAH presented a surface and upper level 3-D diagram[123] which correlates the upper level baroclinic wave location with surface fronts and weather effects associated with development of a mid-latitude cyclone. The following summarizes this complex diagram (which I can't reproduce here) as best I can . Beneath the leading limb of the trough is a cold front with showers and a nearby surface Low (having surrounding cyclonic rotation, and moving in the same overall direction as the flow in the overhead leading edge of the trough). Surface air in the region under the leading edge of the trough is rising toward the overhead divergence aloft (expected when surface pressure is Low), causing precipitation including even winter snow. Forward of the direction of movement of the surface cold front there are increasing clouds and falling pressure, and behind the cold front are clearing skies and rising pressure. The trailing limb of the trough, which is associated with convergence aloft, leads back to a ridge peak aloft, and upper level ridge is associated below with rising surface pressure (a High), anticyclonic rotation, sinking air, clear skies, and cold surface temperatures. This model for developing mid-latitude cyclones includes the *conveyor belt model:* warm air originating in the warm

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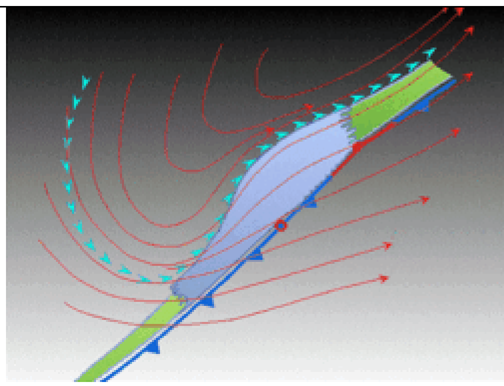
[120] Image taken from http://rst.gsfc.nasa.gov/Sect14/Sect14_1c.html
[121] http://en.wikipedia.org/wiki/Weather_front
[122] http://amsglossary.allenpress.com/glossary/search?id=norther1
[123] *MT8* fig. 12.12, p. 322

sector ahead of the cold front rises on the warm conveyor belt and cold air descends on the cold conveyor belt behind the cold front. The mechanism includes formation of a characteristic *comma cloud*[124] (which indicate that the storm is still developing and intensifying, *MT8*-323) and the dry conveyor belt, which may produce a dry clear area. I must defer discussing the role of vorticity, which we have not studied.

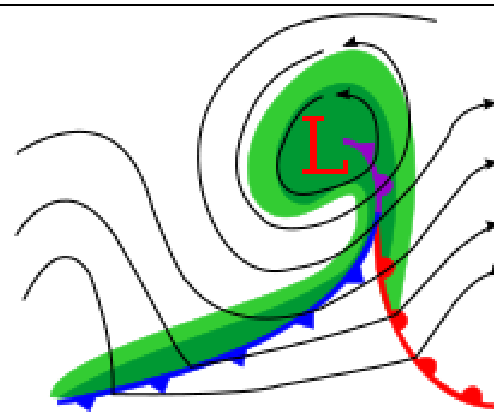
According to RAH, the analysis of weather patterns in terms of *air masses* (such as cP = *continental polar* air mass, mT = *marine tropical* air mass) has been traditional in weather reporting (and is still emphasized in *MT8*-286 as well as in popular weather map presentations). As I understand his position, RAH suggests that analysis by air mass movements is being de-emphasized in preference to the analysis (at least in the mid-latitudes) based on evaluation of upper level westerly winds and baroclinic waves, etc. However, *fronts* are still a useful concept. (*MT8*-296)

Formation of Frontal Extratropical Cyclones

The following diagrams illustrate how frontal cyclones form in association with fronts. These systems can be quite large, according to RAH, extending with synoptic scale over 1000 km or more. I have not mastered why these cyclones form, although it appears to be a complex three dimensional process. (See also discussion in section just above.) Extratropical cyclones are discussed extensively in *ASI* chapter 8 "Weather Systems"—though we did not read this chapter—as well as *MT8*-309.

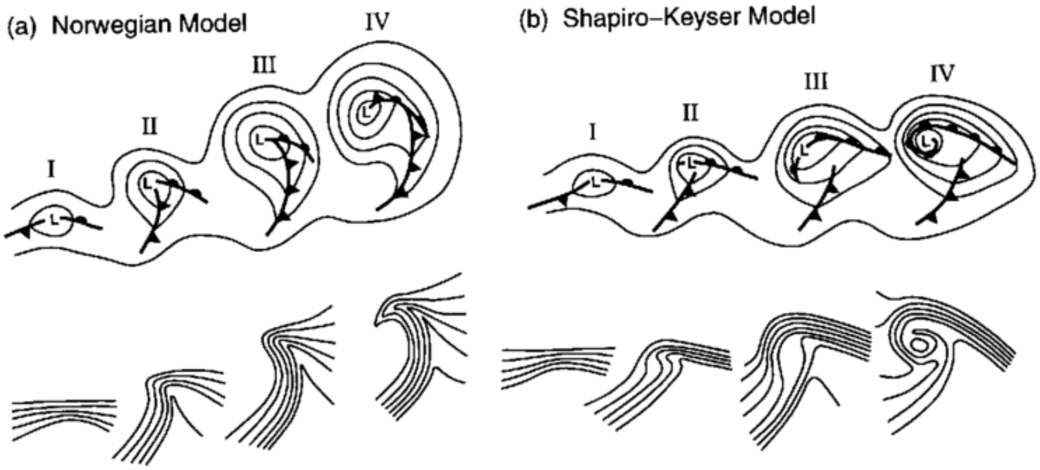


"The initial frontal wave (or low pressure area) forms at the location of the red dot on the image…" The direction of the upper level jet stream, which is nearly parallel to the pressure contours, and therefore nearly geostrophic, is shown in light blue.
(from http://en.wikipedia.org/wiki/Cyclogenesis)



Occluded cyclone example. The triple point is the intersection of the cold, warm, and occluded fronts. The low pressure cyclone that has formed, marked with "L", is associated with cyclonic winds (rotating counterclockwise in the NH).
A comma cloud is probably present
(from http://en.wikipedia.org/wiki/Surface_weather_analysis)

124 http://msx4.pha.jhu.edu/ssip/asat_int/cyclogen.html



Proposed models of mid-latitude (extratropical) cyclogenesis, the Norwegian model being on the left.
From http://en.wikipedia.org/wiki/Extratropical_cyclone

Mid-latitude extratropical cyclones form in association with [polar] fronts separating colder polar air from warmer subtropical air. (*MT8*-310 etc.) "Of the two theories on extratropical cyclone structure and life cycle, the older is the Norwegian Cyclone Model, developed during World War I. In this theory, cyclones develop as they move up and along a frontal boundary, eventually occluding and reaching a barotropically cold environment. It was developed completely from surface-based weather observations, including descriptions of clouds found near frontal boundaries. This theory still retains merit, as it is a good description for extratropical cyclones over continental landmasses… A second competing theory for extratropical cyclone development over the oceans is the Shapiro-Keyser model, developed in 1990. Its main differences with the Norwegian Cyclone Model are the fracture of the cold front, treating warm-type occlusions and warm fronts as the same, and allowing the cold front to progress through the warm sector perpendicular to the warm front. This model was based on oceanic cyclones and their frontal structure, as seen in surface observations and in previous projects which used aircraft to determine the vertical structure of fronts across the northwest Atlantic."[125]

Thermodynamics, Physics of Gases, Water Vapor, Lifting, and Misc.

The following presents a few highlights of this extensive topic, the subject matter of *ASI* Chapter 3 and the course Unit 2 PDF by RAH entitled "ch3-thermo.pdf".[126] For the most part, I have included only final important equations without showing their derivations. Chapter 3 of the textbook also discusses the 2nd Law of Thermodynamics, but the current course does not take up this topic.

Skew-T, Log-P diagram (STLPD) and Other Thermodynamic Diagrams

Reference will be made where appropriate to utilization primarily of the *Skew-T, Log-P diagram* (STLPD, described elsewhere) for computations. Other thermodynamic diagrams, including the *Stüve diagram*[127] (for which P and T are perpendicular, isotherms being vertical), and plots of P against V have also been useful.

The *Skew-T, Log-P Diagram* (*STLPD*) is also known as the *Skew-T Ln(P) Diagram* or *Skew-T Log(P) Diagram*. It is so named because the ordinate is scaled to log or ln P, whereas the T isotherms slant from lower left to upper right (thus are "skew"). "The Skew-T, Log-P diagram is very useful and preferred for showing sounding and other weather state data and for making analog calculations because:
(a) most of the important isopleths are straight rather than curved [specifically, the isobars, isotherms, and the saturation mixing ratios [w_s],
(b) the angle between the adiabats [dry and moist adiabats $\mathbf{\Gamma_d}$ and $\mathbf{\Gamma_m}$] and the isotherms is large enough to

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[125] http://en.wikipedia.org/wiki/Extratropical_cyclone
[126] MCM local file Thermodynamics_AtmS301_2010.pdf
[127] http://en.wikipedia.org/wiki/St%C3%BCve_diagram

facilitate estimates of the stability,
(c) the ratio of area on the chart to thermodynamic energy [used for instance in estimating CAPE] is the same over the whole diagram,
(d) the vertical in the atmosphere approximates the vertical coordinate of the diagram (i.e. the isobars are plotted to a logarithmic scale and pressure in the atmosphere decreases nearly logarithmically with height), and
(e) an entire sounding to levels in the stratosphere can be plotted on one chart."[128]
This quote, modified and expanded by me, is from the detailed PDF titled *Skew-T, Log-P Diagram Analysis Procedures*, listed on the course website, widely available elsewhere on the Web, and locally.[129] See also other references in this webpage to this diagram.

Symbols and Constants Employed in Equations

Symbol	Typical Units	Name and Description
α (alpha)	m^3 per 1 kg	**Specific Volume** ≡ volume per unit mass at a specified pressure P and temp T). α_d = specific volume of dry air α_v = specific volume of water vapor
C_p	$J\ K^{-1}\ kg^{-1}$	**Specific heat (mass-specific heat capacity) of a gas at constant pressure** = $C_v + R$. = 1005.7 ± 2.5 for dry air.[130]
C_v	$J\ K^{-1}\ kg^{-1}$	**Specific heat (mass-specific heat capacity) of a gas at constant volume** 719 ± 2.5 for dry air.[131]
e e_s e_{si}	Pa	**Partial Pressure of water vapor =** $\rho_v R_v T$ e_s = Saturation vapor pressure of water over plane surface of liquid water e_{si} = Saturation vapor pressure of water over plane surface of ice
ε	<none>	**Ratio of R_d to R_v** = M_w/M_d = 0.622 (*ASI*-66)
g_0 $g = g(\varphi,z)$	$m\ s^{-2}$ or $N\ kg^{-1}$	**Gravitational acceleration**, "standard" approximately average = 9.80665 m/s^2 (ref.[132]) **Gravitational acceleration**, local, varies at least w height and latitude (also minimally with terrain), ranging at sea level fr. 9.789 at the equator to 9.832 m/s^2 at the poles (ref.[133]) Varies with altitude: 9.31 m/s^2 at *z*=0, 9.77 m/s^2 at 10 km, 9.5 m/s^2 at 100 km, and 8.43 m/s^2 at 500 km (*ASI*-69)

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[128] Skew-T, Log-P Diagram:
• Quoted from http://www.met.tamu.edu/class/atmo251/Skew-T.pdf
See also:
• http://airsnrt.jpl.nasa.gov/SkewT_info.html
• Air Weather. Service Technical Report (AWS/TR-79/006):
http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA221842&Location=U2&doc=GetTRDoc.pdf
[129] MCM local file SkewT_AtmS301_2010.pdf
[130] http://amsglossary.allenpress.com/glossary/search?id=specific-heat-capacity1
[131] ibid.
[132] http://en.wikipedia.org/wiki/Standard_gravity
[133] http://en.wikipedia.org/wiki/Earth%27s_gravity

Symbol	Typical Units	Name and Description
Γ Γ_d Γ_s	K km^{-1}	**Lapse rate** $\Gamma = -dT/dz$ or $-dT/dZ$ **Γ_d ≡ Dry Adiabatic lapse rate**, approximately $-(-9.8$ K $km^{-1}) = +9.8$ K km^{-1} (defined below). Here T decreases with increasing Z, but the minus sign makes the lapse rate positive. When defined in pressure coordinates, the "lapse rate in pressure coordinates" dT/dp is also positive (T decreases with decreasing p). **Γ_s = Saturated Moist Adiabatic lapse rate** ≈ – (–4 to –7) K km^{-1} = +4 to +7 K km^{-1} (discussed below) The term "*Lapse rate*" is used to refer to (1) the *environmental lapse rate* [the actual prevailing conditions] & also, (2) *adiabatic lapse rates* [the dry and moist lapse rates exhibited by rising parcels that have specified starting conditions that often differ from the environment in which they start and rise.]
$\bar{H}$	m	**Scale height** (see hypsometric equation in *ASI*-70)
I or U	J	**Internal Energy**
k or k_B	J K^{-1}	**Boltzmann's constant** = R / N_A = 1.38065 × 10^{-23} J K^{-1} (ref.[134])
L_v L_m	J kg^{-1}	**Latent heat of vaporization and evaporation** = L_v L_m = **Latent heat of melting and freezing**
m m_d m_v m_{vs}	kg or g	**Mass** of a sample m_d = mass of dry air m_v = mass of water vapor m_{vs} = mass of water vapor at saturation
M M_d M_w	g mol^{-1}	**Gram Molecular Weight** ≡ atomic mass units or Daltons Da (for which 1 amu = 1 Da = 1/12 of the rest mass of an unbound atom of ^{12}C in its nuclear and electronic ground state, or 1.6605388×10^{-27} kg), but expressed as g. (ref.[135]) For ^{12}C: M = 12 g mol^{-1} For H_2O: M_w = 18.016 g mol^{-1} (*ASI*-66) or 18.015 g mol^{-1} (ref.[136]) For dry air, M_d = **apparent Gram Molecular Weight of Dry Air** = 28.97 g (textbook) or 28.9644 g/mol (US Std Atmosphere 1976 (ref.[137])
n	<none>	**Number of Moles = Molar quantity** of gas(es), for which n (moles) = m/M
N_A	entities mol^{-1}	**Avogadro Constant** = 6.02214×10^{23} entities mol^{-1}. (ref.[138])
p p_d p_v p_0 p_g	Pa ≡ N m^{-2} ≡ J m^{-3}	**Pressure** of a sample p_d = partial pressure of dry air p_v = partial pressure of water vapor p_0 = pressure adjusted to sea level p_g = pressure at actual ground surface level
Φ	J kg^{-1}	**Geopotential** (defined below)
ϕ	degrees	**Latitude**
q q	<none> J	**Specific Humidity** ≡ w / (1 + w) (Ref. *ASI*-80) Heat

[134] http://en.wikipedia.org/wiki/Boltzmann%E2%80%99s_constant
[135] http://en.wikipedia.org/wiki/Mole_%28unit%29
[136] http://en.wikipedia.org/wiki/Properties_of_water
[137] http://en.wikipedia.org/wiki/Density_of_air
and http://www.atmosculator.com/The%20Standard%20Atmosphere.html
[138] http://en.wikipedia.org/wiki/Avogadro_constant

Symbol	Typical Units	Name and Description
R R_d R_v	$J\ K^{-1}\ kg^{-1}$	**Specific Gas Constant** (applicable to a mass of a particular gas molecule) R_d = 287.0 $J\ K^{-1}\ kg^{-1}$ (*ASI*-66) or 287.058 $J\ K^{-1}\ kg^{-1}$ (ref.[139]) R_v = SGC for water vapor = 461.51 $J\ K^{-1}\ kg^{-1}$ (*ASI*-66)
R*	$N\ m\ kmol^{-1}\ K^{-1}$, or $N\ m\ mol^{-1}\ K^{-1}$ = $J\ K^{-1}\ mol^{-1}$	**Universal Gas Constant** (applicable to moles of any idealized molecular gas or mixtures of gases) = 8.3145 $J\ K^{-1}\ mol^{-1}$ or $m^3\ Pa\ K^{-1}\ mol^{-1}$ or 8.31432x10^3 $N\ m\ kmol^{-1}\ K^{-1}$ (US Std Atm 1976)[140]
RH	%	**Relative Humidity**
ρ (rho)	$kg\ m^{-3}$ or $g\ m^{-3}$	**Density** of a sample
T	K (Kelvin) or °C	**Temperature** of a sample
T_V	K (Kelvin) or °C	**Virtual Temperature** (defined below)
θ θ_e θ_w	K	**Potential temperature θ** (defined below) **Equivalent potential temperature θ_e** for air containing water vapor **Wet-bulb potential temperature θ_w**
V	m^3	**Volume** of a sample
w w_s	g (H_2O) kg^{-1} (dry air)	**Mixing Ratio w** ≡ m_v/m_d = mass of water vapor / mass of dry air **Saturation mixing ratio w_s for water vapor** = m_{vs}/m_d
z Z Z_g	m m	**Height** above mean sea level **Geopotential height** (defined below) Z_g=Geopotential height of ground surface

Gas Laws, Equation of State (Ideal Gas Law), Boyle's and Charles's Laws

pV = mRT   Ideal gas equation (Equation of State) for a specific gas using mass & Specific Gas Constant R

pV = nR*T   Ideal gas equation (Equation of State) for any ideal gas using moles & the Universal Gas Const. R*

Boyle's Law: If only T and m are held constant, V is inversely proportional to P.

Charles's Law I: If only P and m are held constant, V is proportional to T.

Charles's Law II: If only V and m are held constant, P is proportional to T.

Virtual Temperature and Equations of State for Dry and Moist Air

$p_d = \rho R_d T$ Equation of State for dry air

The *virtual temperature T_v* is a fictitious temperature allowing expression of the Equation of State with moisture present using overall density ρ, R_d, and T_v:

Given

$\rho = (m_d + m_v) / V$ [overall density is sum of dry air density component + water vapor component)

and T_v (Virtual Temperature), defined as

$$\mathbf{T_v} \equiv \frac{\mathbf{T}}{\left(\mathbf{1} - \frac{\mathbf{e}}{\mathbf{p}}(\mathbf{1}-\boldsymbol{\varepsilon})\right)} = \frac{\mathbf{T}}{\left(\mathbf{1} - \mathbf{0.378}\,\frac{\mathbf{e}}{\mathbf{p}}\right)}$$

then

$$\mathbf{p} = \boldsymbol{\rho}\mathbf{R_d}\mathbf{T_v}$$

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139 http://en.wikipedia.org/wiki/Gas_constant

140 http://en.wikipedia.org/wiki/Gas_constant

[thus the total pressure is given by gas law for dry air using the virtual temperature]

Note that since $e/p < 1$, $T_v \geq T$, and $\rho = p/R_dT_v$, then *moist air has lower density and is therefore lighter than dry air*. (See also *MetTod-101* for more about this non-intuitive fact.)

Hydrostatic Equation, Geopotential Φ(z) and Height Z, Hypsometric Equation

For equilibrium (static, nonconvecting) conditions in which downward gravitational force is nearly balanced by pressure, **The Hydrostatic Equation**, giving rate of change of pressure with density and local gravity g, is:

$$\frac{\partial p}{\partial z} = -\rho g(\phi, z)$$

Geopotential, defined as work required to raise 1 kg to geometric height z (units in J kg^{-1}):

$$\Phi(z) = \int_0^z g(\phi, z)\, dz$$

thus, it is a function of height and the non-constant local g.

Geopotential Height, using globally averaged standard acceleration g_0 and geopotential is defined as:

$$\mathbf{Z = \Phi(z)/g_0}$$

Note that the definition uses constant $g_0 \equiv 9.80665$ m s^{-2} (defined exactly) rather than varying g.

Because g decreases with height (i.e., for elevations above mean sea level, g is $< g_0 \equiv 9.80665$ m s^{-2}), the geopotential height Z at higher elevations is lower than (or underestimates) the actual geometric height z, a discrepancy that becomes more pronounced at much greater distances from the Earth than found in the troposphere.

Geopotential thickness of a layer between pressure levels]

$$Z_2 - Z_1 = \frac{R_d}{g_0} \int_{p_2}^{p_1} T_v \frac{dp}{p}$$

Hydrostatic Equation using geopotential height Z and g_0:

$$\frac{\partial \mathbf{p}}{\partial \mathbf{Z}} = -\boldsymbol{\rho} \mathbf{g_0}$$

or

$$\frac{\partial \mathbf{Z}}{\partial \mathbf{p}} = -\frac{\mathbf{1}}{\boldsymbol{\rho} \mathbf{g_0}}$$

Hypsometric Equation (HE): The Geopotential thickness of a layer between 2 pressures using mean virtual temperature T_v is given by:

$$\mathbf{Z_2 - Z_1 = \frac{R_d}{g_0} \overline{T}_v \ln \frac{p_1}{p_2}}$$

The hypsometric equation is used for mapping pressure surfaces and/or layer thicknesses, which serve as a forecasting tool. (*MT8*-343) Note that as $\overline{T}_v$ increases, the layer becomes thicker—thickness of a layer is greater where air is warmer.

Warm cores lows (lows with warmer center than periphery, as seen in hurricanes) exhibit near the ground depression of isohypse pressure height surfaces and greater thickness of layers (wider spacing of isohypse contours), corresponding to greatest intensity winds near the ground. These may underlie a high aloft.

"Upper level lows, as seen with occlusions, may be cold core lows that do not always extend downward to the ground. In these cases, "It follows from the HE that these lows must be cold core below the level at which they achieve their greatest intensity and warm core above that level…" (*ASI*-72, RAH)

Reduction of Pressure to Sea Level

This adjustment of pressure to a common reference elevation at sea level is done to make reporting of pressure meaningful with respect to weather effects over terrain that varies in surface elevation. Note that despite the name, "reduction" of a higher station pressure to sea level involves increasing the computed pressure value. Comparing computed sea level pressure p_0 and the actual surface ground level pressure p_g of the non-sea level station at geopotential height Zg (*ASI*-32):

$$\boldsymbol{p_0 = p_g \exp\left(\frac{g_0 Z_g}{R_d\,\overline{T}_v}\right)}$$

or, for small Z_g and $Z_g/H \ll 1$:

$$\boldsymbol{p_0 - p_g \cong p_g \left(\frac{g_0 Z_g}{R_d\,\overline{T}_v}\right)}$$

where and R_d = 287.0 J K^{-1} kg^{-1}

For surface locations that are at substantially high elevation (such as Leadville, CO, at 3096 m or about 700 mb), a small error in actual surface pressure determination leads to a large discrepancy in pressure reduced to sea level. Therefore, it is common to smooth the surface isobars in drawing surface maps, particularly for such high-altitude stations and other stations that might have pressure reporting errors. (*MT8*-198)

First Law of Thermodynamics (FLT) and Specific Heats

This expresses the conservation of energy. For an ideal gas (working substance) of mass m, fully enclosed in an insulated cylindrical container bounded at one end by a moveable piston and at the other with a fixed wall, when heat dQ (in J) is added to the gas, the heat may increase the internal energy of the gas dU (in J) and/or do work dW on or by the environment (in J, in this case interacting with the piston). The first law states:

First Law of Thermodynamics FLT (1):

$$dQ - dW = dU$$

These variables change independent of the manner in which the system moves between the two states. The work performed may be visualized on a p-V thermodynamic diagram.

Specific heat (mass-specific heat capacity) of a gas at constant volume is defined as:

$$C_V = \left(\frac{dQ}{dT}\right)_{V\ \mathrm{constant}}$$

per unit mass (units are therefore J K^{-1} kg^{-1})

Specific heat (mass-specific heat capacity) of a gas at constant pressure is defined as:

$$C_P = \left(\frac{dQ}{dT}\right)_{P\ \mathrm{constant}}$$

per unit mass (J K^{-1} kg^{-1})

Then the First Law FLT (2) is alternatively, for α = specific volume, given by

$$dQ = dU + pd\alpha$$

First Law FLT (3) for ideal gas, expressed per unit mass:

$$dQ = C_v dT + pd\alpha$$

FLT (4) for ideal gas, expressed per unit mass, useful as it uses P and T:

$$\mathbf{dQ = C_p dT - \alpha dp}$$

Dry Adiabatic Processes and Potential Temperature

Adiabatic processes are processes for which dQ = 0, no heat is added or removed. When dry parcels of air are "lifted" rapidly so that there is no condensation or evaporation and no radiation, then the process is "dry–adiabatic". Note: Until condensation forms at the LCL—see below—moist unsaturated parcels that are lifted also follow a dry adiabat and for them the process is also "dry-adiabatic" (*ASI*-84).

For dry adiabatic conditions,

$$p\alpha = R_d T$$

Per RAH, the *Dry adiabatic lapse rate in p-coordinates* (note this somewhat confusing terminology) is:

$$\frac{dT}{dp} = \frac{\alpha}{C_p} > 0$$

Presumably it is this definition of lapse rate which justifies the labeling by some[141] of the dry adiabats on the STLPD as Γ_d, although in other contexts Γ_d seems to pertain to height.

The dry adiabatic lapse rate Γ_d (per *ASI*-12, 77 and *here*[142]) is given by

$$\Gamma_d \equiv -\left(\frac{\partial T}{\partial z}\right)_{\text{dry parcel}} = -\rho g_0$$

Note that the differential ∂z is replaced by ∂Z by RAH, quantities that are apparently nearly interchangeable for troposphere heights.

Also, for adiabatic process,

$$0 = C_p\, dT - \alpha\, dp$$

The standard **Dry adiabatic lapse rate** Γ_d in standard Z-coordinates = 9.8 K km^{-1}:

$$\Gamma_d \equiv -\frac{dT}{dZ} = \frac{g_0}{C_p} = \frac{9.80665}{1005.7}\,\mathrm{K\,m^{-1}} = 9.75\frac{\mathrm{K}}{\mathrm{km}} = 3.25\ \frac{\mathrm{K}}{1000\ \mathrm{ft}} = 5.85\ \frac{°\mathrm{F}}{1000\ \mathrm{ft}}$$

where the differential dZ is in ASI expressed as dz.

Therefore, *T as a function of Z* is:

$$T_2 = T_1 - \frac{g_0}{C_p}(Z_2 - Z_1)$$

which makes the assumption of hydrostatic balance

A more exact alternative form expressing *T as a function of P*:

$$\mathbf{T_2 = T_1\left(\frac{p_2}{p_1}\right)^{R_d/C_p}}$$

which is exact, as does not assume hydrostatic balance. Note that the exponent is ≈ 0.286.

Potential temperature θ and equivalent potential temperature θ_e

θ is the temperature of a parcel of air with initial pressure p after being brought adiabatically (by compression or expansion) to a standard reference pressure p_0, usually 1000 hPa.[143] RAH states the definition of θ requires *dry* adiabatic, but this requirement is not explicitly stated in *ASI*-77. However, the use of *equivalent potential temperature* θ_e for moist air (*ASI*-85), clarifies this point (see below).

From dq = 0 and the FLT, we can derive *Poisson's equation* for the potential temperature of an air parcel at pressure p and temperature T compared to the reference pressure p_0:

$$\theta = T\left(\frac{p_0}{p}\right)^{R_d/C_p}$$

The exponent is ≈ 0.286, so given T and p, we can compute θ.

dθ = 0 for dry adiabatic processes, and θ is a *conserved quantity* under these conditions.

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[141] PDF: *Skew-T, Log-P Diagram Analysis Procedures*
[142] http://en.wikipedia.org/wiki/Lapse_rate#Dry_adiabatic_lapse_rate
[143] http://en.wikipedia.org/wiki/Potential_temperature

θ can be estimated with the Skew-T Log-P diagram (STLPD) by locating the data point A(P,T) of the parcel on the STLPD, then reading off the T on the *Dry Adiabat* (orange line slanting up and to the left) that is closest to the point, interpolating as needed. The θ value of dry adiabats are shown just below the 1000 mb horizontal isobar.

The **equivalent potential temperature** for a parcel is given exactly here[144] but approximately by (*ASI*-85):

$$\theta_e \cong \theta \exp\left(\frac{L_v w_s}{c_p T}\right)$$

where L_v is the latent heat of vaporization
T is the temperature of the parcel
θ is the potential temperature (of what?)

According to *ASI*-86, "The air is expanded (i.e., lifted) pseudo-adiabatically until all the [water] vapor has condensed, released its latent heat [of condensation], and fallen out. The air is then compressed dry adiabatically to the standard pressure of 1000 hPa, at which point it will attain the temperature θ_e." In order to use this formula for air that it not initially saturated, "w_s and T are the saturation mixing ratio and temperature at the point where the air first becomes saturated after being lifted dry adiabatically."

"The lifting of a parcel from its original pressure level to the upper levels of the troposphere will release the latent heat of condensation and freezing in that parcel. The more moisture the parcel contains the more latent heat that can be released. Theta-e [θ_e] is used operationally to map out which regions have the most unstable and thus positively buoyant air. The Theta-E [θ_e] of an air parcel increases with increasing temperature and increasing moisture content. Therefore, in a region with adequate instability, areas of relatively high Theta-e (called Theta-e ridges) are often the burst points for thermodynamically induced thunderstorms and MCS's [Mesoscale convective systems] . Theta-e ridges can often be found in those areas experiencing the greatest warm air advection and moisture advection."[145]

NOAA states, "The equivalent potential temperature is the temperature a parcel at a specific pressure level and temperature would have if it were raised to 0 mb [?], condensing all moisture from the parcel, and then lowered to 1000 mb."

The θ in the equation for θ_e above appears to be determined from the starting parcel conditions by simply following the interpolated dry adiabat down to 1000 mb (even though the parcel is not actually "dry").

I wonder, how is it possible for a parcel to lose all its water vapor, not retaining even a trace. However, I believe that what is meant in practical terms is that, at least when using the STLPD, one simply starts at the parcel conditions and follows the moist adiabat for the starting parcel conditions up to such a high altitude (on the standard graph to 200 mb where these curves end) that the residual moisture has become extremely low and the moist and dry adiabats are essentially parallel. One then selects the dry adiabat Γ_d which coincides with the intersection of the 200 mb level with the moist adiabat, interpolating as necessary, and follows that dry adiabat back down to the 1000 mb level, where the equivalent potential temperature is read off.

Moist Air Processes

These are processes in which air parcels contain water vapor and typically attain saturation at some point. Variables and quantities expressing or relating to presence of water vapor include mixing ratio w and w_s, dew point T_d, water vapor partial pressure $e = p_v$, virtual temperature T_v, equivalent potential temperature θ_e, etc.

The **(mass) mixing ratio** $\mathbf{w \equiv m_v/m_d}$, is usually expressed in units of g water vapor per kg dry air. It is conserved for processes in which there is no condensation or evaporation (*ASI*-80 and RAH).

Specific humidity q is defined above.

The **vapor pressure of water e** in a sample is given (*ASI*-80) by:

$$e = p_v = \left(\frac{w}{w + \varepsilon}\right) p$$

144 http://amsglossary.allenpress.com/glossary/search?id=equivalent-potential-temperatur1
145 http://www.theweatherprediction.com/habyhints/162/

where $\varepsilon = 0.622$.

The virtual temperature T_v can be derived from w as follows:

$$T_v = T\frac{w+\varepsilon}{\varepsilon(1+w)} \cong \frac{1-\varepsilon}{\varepsilon}\mathrm{wT} = \mathrm{T}(1+0.61\mathrm{w})$$

The **saturation vapor pressure of water e_s** (*ASI*-81) applies when water is evaporating and condensing at equilibrium rates, and is defined for conditions in which the liquid water-air interface is a flat plane surface (thus not in droplet or snow crystal form, etc.) The e_{si} = **Saturation vapor pressure of water over plane surface of ice** is also discussed in *ASI*-81. See *here*[146] for comparison of liquid water and the slightly lower ice saturation vapor pressures, including empiric equations (not given here) fitting the data of the *Clausius-Clapeyron relations*[147] for these phase transitions for $e_s = f(T)$. Note that $\mathbf{e_s}$ increases exponentially with T, almost doubling with every 10 °C increase. The difference $e_s - e_{si}$ is maximal at -12 °C, reaching ~0.26 hPa. *ASI*-81 states this leads to deposition of water vapor on ice particles in water-saturated air.

The **saturation mixing ratio for water vapor w_s** is

$$w_s \equiv \frac{m_{vs}}{m_d}$$

For a given temp T,

$$\mathrm{w_s} = 0.622\frac{\mathrm{e_s}}{\mathrm{p}}$$

Thus, for typical Earth atmosphere temperatures, w_s is a function of T and p, specifically is inversely proportional to total pressure.

Relative humidity RH is defined as

$$\mathrm{RH} = \frac{\mathrm{w}}{\mathrm{w_s(T,p)}} \times 100\%$$

Calculating RH: We can use the STLPD to compute T_d and RH given measured data point A(p, T, w). Locate this point on the STLPD. We calculate RH = $w/(w_s(p,T)$, where w is as measured and $w_s(p,T)$ is the saturation mixing ratio (green dashed line) passing through A(p, T, w), interpolated as necessary.

Calculating T_d graphically using the STLPD: Slide left along horizontal isobar to the point at which for the same pressure the w_s (green dashed line) is equal to the measured w (this point is therefore B(p, T_d, $w_s(T_d,p)$). We therefore have the T_d, interpolated as needed.

Lifted Moist Air Parcels, LCL, and LFC

When a parcel of air is "lifted" from initial state A(p_1,T_1,w) to state B(p_2,T_2,w), the process is often at least initially adiabatic, for which dQ = 0. The P and T values therefore follow a dry adiabat contour (which is applicable, even though the parcel actually contains water), and the mixing ratio w of the parcel remains constant. (Dry adiabats appear as gently curved nearly straight lines on the STLPD, slightly convex down and to the left). With sufficient lifting, the pressure of the parcel attains a level on the dry adiabat at which relative humidity is 100% and condensation begins to form (in the form of clouds or fog, the level defining the cloud base). This occurs at the **lifting condensation level** (**LCL**), a pressure level expressed as pressure in Pa. I emphasize that the LCL for a parcel depends on the initial moisture in the parcel (given by w or T_d) as well as its starting T. This is "the level to which an unsaturated moist parcel of air can be lifted [dry] adiabatically before it becomes saturated." (*ASI*-83) The rising air parcels are usually not visible below the LCL. In the US, the cloud base tends to rise as one moves westward from the East Coast toward the Central Plains and on to the desert West, i.e., toward increasingly drier terrain and air. (*MT8*-153)

Calculating LCL Graphically: The location of the LCL for a specified parcel can be estimated using the STLPD as an analog calculator as follows. For a starting unsaturated parcel state A(p_1,T_1,w), find on the same isobar (horizontal line) the dewpoint B(p_1,T_{d1},w=w_s) as above, using the intersection with the green dotted s*aturation mixing ratio* line, and interpolating as needed. Move along the green dotted saturation mixing ratio

[146] http://www.its.caltech.edu/~atomic/snowcrystals/ice/ice.htm

[147] http://en.wikipedia.org/wiki/Clausius%E2%80%93Clapeyron_relation

line as it heads up and to the right until it intersects with the dry adiabat coming up and toward the left from [A(p_1,T_1,w). The p level where these two lines intersect is the LCL (let us call this intersection point [p_{LCL},T_{LCL}]). Note that if the parcel is already saturated at its starting point, it is already at its LCL, but the term LCL makes the most sense when applied to parcels that are not yet saturated.

Lifting Above the LCL: For parcels that rise or are lifted higher than the LCL, condensation begins which releases heat as latent heat of vaporization and evaporation L_v. Thus, dq is no longer = 0, so dq ≠ 0. The STLPD assumes that any condensed moisture falls out of the lifted parcel immediately.[148] The heat released into the parcel offsets some of the decrease in T arising from lifting, so T for a saturated parcel falls off more slowly than it would along a dry adiabat for an unsaturated parcel. This is equivalent to stating that $\mathbf{\Gamma_s} < \mathbf{\Gamma_d}$ (i.e., –dT/dZ ≈ 7 is less than –dT/dZ = 9.8 K km^{-1}), where $\mathbf{\Gamma_d}$ = **Dry Adiabatic lapse rate** and $\mathbf{\Gamma_s}$ = **Saturated Moist Adiabatic lapse rate**, here expressed in height coordinates. (Even when expressed in pressure coordinates, lapse rates for dry adiabats are more positive and thus greater than for moist adiabats.) Graphically (using the STLPD), the moist adiabat tilts less to the left than the dry adiabat for ascent to higher Z (lower p), which is equivalent to saying that the moist adiabat decreases less in T with rising Z or with decreasing p compared to the dry adiabat. The lapse rates $\mathbf{\Gamma_s}$ for saturated adiabats are not constant but curve up and to the left so that they appear convex to the upper right, but at higher levels their slopes more closely parallel the dry adiabats, especially at lower temperatures. (*ASI*-85, including more discussion of how values vary with latitude and elevation.) The STLPD does not extend the Saturated Moist Adiabatic curves above 200 mb because they are parallel to the dry adiabats.

Calculating Moist Adiabatic Lifting Graphically: (*ASI*-85) After attaining the LCL at point (p_{LCL},T_{LCL}), a rising parcel follows a *moist adiabat* or *saturation adiabat* (aka *saturated adiabat* from that point. (The curve is actually for a *pseudoadiabat* because of the removal of condensed water assumed for the STLPD). On the STLPD, these saturation adiabats are solid green lines arcing up and to the left, convex upward and toward the right. The lifted parcel initially arrives at the LCL as calculated above—if the parcel is initially saturated, the LCL is at the initial starting point. The initial dew point T_d calculation allows determination of the actual initial mixing ratio, or w may be give explicitly (example: 4.4 g kg^{-1}). For lifting above the LCL, the parcel will follow a saturated adiabat (interpolated as needed) starting at [p_{LCL},T_{LCL}]. If the endpoint of lifting is expressed as a pressure, the final T and final w_s (example: 1.9 g kg^{-1}) can be read off the graph. We may conclude that the amount of condensation that has fallen out of the parcel in this example is 4.4 – 1.9 = 2.5 g kg^{-1} as a result of the lifting above the LCL.

Level of Free Convection (**LFC**): If the moist adiabat for the parcel above its LCL crosses above and to the right of the environmental sounding curve (p,T), so that it is now warmer than the surrounding environmental air, it becomes buoyant. (Depending on environmental conditions, this does not always occur.) The level at which this crossing occurs is termed the *Level of Free Convection* (*LFC*), and as implied the parcel can further rise rapidly due to its buoyancy in the colder air around it. Let us call the point on the moist adiabat at which the LFC is graphically determined (p_{LFC},T_{LFC}). Both (p_{LCL},T_{LCL}) and (p_{LFC},T_{LFC}) lie on a moist adiabat defined for a particular parcel.

Stability of Air Parcels With Respect to Convection: U, CU, and S

The stability of an air parcel with respect to convection at a particular level in the atmosphere can be visualized in a "Pseudo-adiabatic Chart" by comparing:
(1) The lapse rate $\mathbf{\Gamma_e}$ of the environment (i.e., of ambient air conditions), as revealed by the actual rawinsonde soundings, etc., and
(2) the adiabatic lapse rates $\mathbf{\Gamma_d}$ and $\mathbf{\Gamma_s}$ applying to the rising air parcel. These values are of course determined by the (p,T,w) processes and positions on the STLPD described above .

Unstable (Absolute Instability): If $\mathbf{\Gamma_d} < \mathbf{\Gamma_e}$ (or $\mathbf{\Gamma_e} > \mathbf{\Gamma_d}$, so that $\mathbf{\Gamma_e}$ slopes more to the left with increasing level than $\mathbf{\Gamma_d}$), the parcel is absolutely *Unstable*. If displaced upward, it will continue to rise, and if displaced downward, it will continue to fall. This behavior is analogous energetically to that of a ball falling in either direction off a rounded potential peak. It is rarely found in nature due to its extreme instability. "Meteorologists call this a 'super-adiabatic lapse rate' since heat loss with elevation is so rapid."[149]

Neutral (Neutral Stability): This term is briefly mentioned and somewhat confusing in the textbook, but other sources clarify this. The textbook states that when $\mathbf{\Gamma_e} = \mathbf{\Gamma_s}$ for saturated air parcels (*ASI*-91), the parcel has no tendency to rise or fall, and this state is termed neutral with respect to vertical displacements. This is

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[148] PDF G-1
[149] http://www.piercecollegeweather.com/stability.html

analogous energetically to a ball lying on a flat horizontal plane. Another source states, "Neutral stability occurs when ELR [environmental lapse rate $\mathbf{\Gamma_e}$] and DALR [dry adiabatic lapse rate $\mathbf{\Gamma_d}$] are equal. That is, when ELR is 9.8°C/1km. It is called 'neutral' because the thermal keeps its initial momentum and does not accelerate or slow down."[150] Another source states, "[neutral stability is] the state of an unsaturated or saturated column of air in the atmosphere when its environmental lapse rate of temperature is equal to the dry-adiabatic lapse rate or the saturation-adiabatic lapse rate respectively; under such conditions a parcel of air displaced vertically will experience no buoyant acceleration. Also known as indifferent equilibrium; indifferent stability. "[151] Yet another source states, "In the absence of saturation, an atmospheric layer is neutrally stable if its lapse rate is the same as the dry-adiabatic rate. Under this particular condition, any existing vertical motion is neither damped nor accelerated… In the case of a saturated parcel, the same stability terms apply. In this case, however, the comparison of atmospheric lapse rate is made with the moist-adiabatic rate appropriate to the temperature encountered."[152] Another states, "When the environmental lapse rate is the same as the dry adiabatic lapse rate, the atmosphere is in a state of neutral stability (Figure 4-9). Vertical air movement is neither encouraged nor hindered. The neutral condition is important as the dividing line between stable and unstable conditions. Neutral stability occurs on windy days or when there is cloud cover such that strong heating or cooling of the earth's surface is not occurring."[153]

Stable (Absolute Stability): If $\mathbf{\Gamma_s} > \mathbf{\Gamma_e}$ (or $\mathbf{\Gamma_e} < \mathbf{\Gamma_s}$, so that $\mathbf{\Gamma_e}$ slopes less to the left with increasing level than $\mathbf{\Gamma_s}$), the parcel is always *absolutely* s*table*, and if displaced it will tend initially to return toward the starting level. In fact, such a parcel will overshoot the starting level and undergo buoyancy gravity wave oscillations about an equilibrium level at a characteristic buoyancy frequency (having the *Brunt-Vaisala period*, typically about 10 minutes in the troposphere) and with gradually decreasing amplitude. This phenomenon can be observed with cloud gravity waves. At the top of the wave excursion, the parcel has become cooler than its surroundings (the environment) and therefore denser, and begins to descend. At the bottom of its excursion, it is warmer than the environment and begins to ascend.[154] This behavior is analogous energetically to that of a ball lying in a rounded potential well.

Conditionally Unstable (Conditional Instability): If $\mathbf{\Gamma_d} > \mathbf{\Gamma_e} > \mathbf{\Gamma_s}$ (or $\mathbf{\Gamma_s} < \mathbf{\Gamma_e} < \mathbf{\Gamma_d}$, so that the slope of $\mathbf{\Gamma_e}$ falls between $\mathbf{\Gamma_s}$ and $\mathbf{\Gamma_d}$), the parcel is *Conditionally Unstable* (with respect to convection). If it rises sufficiently, first along a dry adiabat and then, above the LCL, along a moist adiabat, it may eventually(depending on the prevailing environmental conditions) attain a point where the parcel is warmer than the ambient air. (Graphically, this is when the moist adiabat crosses above the environmental T sounding curve on the STLPD.) The point where the parcel crosses above the moist adiabat is the *Level of Free Convection* (*LFC*), a level which depends on the starting parcel temperature and moisture as well as the environmental lapse rate $\mathbf{\Gamma_e}$ or soundings. Crossing above the LFC leads to instability and vigorous convective overturning if vertical motions are large enough (*ASI*-92). Energetically, this situation is analogous to a ball lying in a relative potential well as in a metastable state with a low side wall over which it can escape and therefore roll without restraint to a much lower energy level.

Conditional stability develops (*MT8*-146) when either air aloft is cooled by
(1) winds bringing in colder air (cold advection), or
(2) the emitting IR to space by clouds or air,
or surface air is warmed by
(3) daytime solar heating of the surface, or
(4) an influx of warm air brought in by the wind, or
(5) the movement of air over a warm surface.

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150 ibid.
151 http://www.answers.com/topic/neutral-stability
152 http://fam.nwcg.gov/fam-web/pocketcards/reference_cd_2009/10_miscellaneous/pms_425_Fire_Wx_ch_04.pdf
153 http://yosemite.epa.gov/oaqps/EOGtrain.nsf/fabbfcfe2fc93dac85256afe00483cc4/1c9d492b7ccef4fe85256b6d0064b4ee/$FILE/Lesson%204.pdf
154 Buoyancy Gravity Waves:
http://amsglossary.allenpress.com/glossary/search?id=gravity-wave1
http://en.wikipedia.org/wiki/Lee_waves
http://www.physics.uwo.ca/~whocking/p103/grav_wav.html

Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN)

Convective Available Potential Energy (**CAPE**): is a measure of the degree of convective instability that can potentially lead to "*deep convection*". It is expressed in J kg^{-1} for a reference air parcel. In what follows, EL is the *equilibrium level*, located above the LFC along the moist adiabat and defined as the level at which the reference parcel undergoing free convection above the LFC is no longer warmer than its environment. CAPE is given by (*ASI*-345):

$$\mathrm{CAPE} = \int_{EL}^{LFC} (\alpha' - \alpha)\, dp$$

where α' = specific volume (volume per unit mass for give p and T) of the rising air parcel, and
α = specific volume of the environmental air at the same level

Using $p = \rho R_d T_v$ (this step is somewhat unclear to me)

$$\mathrm{CAPE} = R_d \int_{EL}^{LFC} (T'_v - T_v)\, d\ln p$$

where T'_v = virtual temperature of the rising air parcel, and
T_v = virtual temperature of the environmental air at the same level

According to *ASI*-345, "if we ignore the small virtual temperature correction, the integral in this expression is simply the area, on the skew-T ln p plot, extending from LFC to EL, and bounded by the environmental temperature sounding on the left and a moist [saturation] adiabat on the right." This is one of the useful features of the STLPD, the fact that the subject area that is readily visualized on the diagram is proportional to the potential energy available for convection. The moist adiabat referred to, as mentioned before, is the one passing through the point (p_{LCL},T_{LCL}) at which the LCL is determined (as above). "Observed values [of CAPE] in thunderstorm environments often may exceed 1000 joules per kilogram (J/kg), and in extreme cases may exceed 5000 J/kg."[155]

Convective Inhibition (**CIN** or **CINH**): If there is *Convective Inhibition* (*CIN*) present, there is a (low level) capping inversion region (a "lid") which can prevent an air parcel from rising from the surface to the level of free convection.[156] This lid can prevent storms from forming, even with high instability aloft. Like CAPE, CIN has units of J kg^{-1} and if non-zero is expressed as a positive quantity. It represents the amount of energy needed to initiate convection—that is, to lift the reference air parcel to its LFC (*ASI*-346). It thus may be viewed as a negative CAPE (*ASI*-346, though CIN is positive in value). CIN values "are obtained on a sounding by computing the area enclosed between the environmental temperature profile and the path of a rising air parcel, over the layer within which the latter is cooler than the former. (This area sometimes is called *negative area*.)"[157] CIN values greater than 200 J/kg are sufficient enough to prevent convection in the atmosphere."[158] "For CIN > 100 J kg^{-1}, deep convection is unlikely to occur in the absence of external forcing such as might be provided by daytime heating or the approach of a strong front." (*ASI*-346)

Overcoming a capping inversion: In the presence of a capping inversion, some additional mechanism is required to initiate convection. In the absence of mesoscale lifting, there are three *common mechanisms for overcoming a capping inversion*. (The following discussion largely derives from this website,[159] which has unusually good animated diagrams of convective phenomena):

1. *Heating* : "In the case of heating, the presence of a lid can prevent convection while the surface temperature climbs... The instability, measured by CAPE, continues to grow until daytime heating eliminates the capping inversion. The ensuing convection can be much stronger than if it had occurred earlier, before significant heating had occurred. For example, an analysis of data from the central U.S. determined that the stronger the lid, the less likely convection was. However, if storms did form, they were more likely to be severe if the

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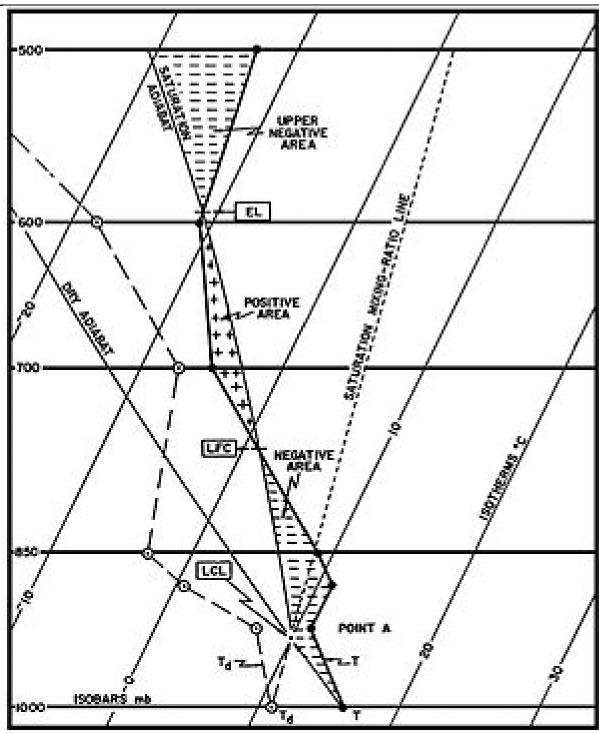
[155] http://www.weather.gov/glossary/index.php?letter=c
[156] http://en.wikipedia.org/wiki/Convective_inhibition
[157] http://www.weather.gov/glossary/index.php?letter=c
[158] http://en.wikipedia.org/wiki/Convective_inhibition
[159] http://www.atmos.albany.edu/daes/atmclasses/atm301/CAPE.htm

CIN was high."[160] As the animation on the referenced website illustrates, warming shifts the low level sounding to the right, eliminating the capping inversion.

2 . *Moistening* : Here, a rising dew point shifts the LCL down and to the right, so that the moist adiabat that is then followed lies to the right of and circumvents the capping inversion in the sounding. "Another way to overcome a capping inversion is to add moisture to the lower atmosphere… Moistening the lower atmosphere increases the dewpoint of a low-level air parcel. On the skew-T diagram, this moistening shifts the ascent path far enough to the right that rising air parcel remains buoyant throughout its ascent, eliminating convective inhibition… Moistening in the lower atmosphere can occur through either low-level advection of moister air into the region or locally through evaporation from a local moisture source such as a lake or irrigated field. Low-level moist advection can produce large changes in a short time to overcome relatively large amounts of CIN… Advection can be important even when the air is moist initially. Evaporation is more effective when the conditions are dry initially or only a small change is needed to overcome the CIN."[161]

3. *Synoptic-scale lifting/ascent*: "One other common mechanism for overcoming convective inhibition is synoptic-scale ascent caused by passage of a short wave or front. These processes act to lift and weaken the inversion layer. On the skew-T diagram, this effectively eliminates the inversion, shifts the inversion to the left, or some combination of the two. In either event, the inversion no longer acts to cap the ascent path of a rising air parcel. Because this process acts fairly slowly on its own, it will be most effective if it coincides with daytime heating and/or moistening of the boundary layer."[162]

The following STLPD[163] shows an environmental sounding and a starting parcel (at 1000 mb), and demonstrates:



Probably conditionally unstable starting conditions (for which $\Gamma_d > \Gamma_e > \Gamma_s$) for the parcel at 1000 mb
The LCL at which condensation can begin to form: Intersection of Sat. Mixing ratio passing through (1000 mb, Td) & Dry Adiabat passing through (1000 mb, T)
A low-level capping inversion beginning at point A, which with the Negative Area prevents convection. (This appears close to but does not precisely correspond with the LCL)
A non-zero Convective Inhibition CIN related to the capping inversion and with value proportional to the area of the lower "Negative Area". CIN here represents the energy that must be supplied to lift the reference air parcel starting at 1000 mb to its LFC.
The LFC for the parcel, at which point free convection could begin, if the CIN were overcome.
The CAPE ("Positive area") above the LFC, with area representing the potential energy available for free convection.
The EL and upper negative area, a region at the tropopause inhibiting further convection.

[160] ibid.
[161] ibid.
[162] ibid.
[163] http://en.wikipedia.org/wiki/Convective_inhibition

Clouds (Unit 3)

This is a large subject and I only touch on selected topics. It was the subject of the course Unit 3. RAH presents a cloud atlas *here*[164] and of course his major textbook is on Cloud Dynamics—but we only studied the first chapter. See Atmospheric Horizontal Scale section for scales pertaining to clouds. A useful cloud atlas for learning to identify clouds and classifying complex cloud patterns is given *here*.[165]

Clouds tend to form by air rising, expanding, and cooling. The occurs due to "1. surface heating and free convection, 2. uplift along topography [including mountains], 3. widespread ascent due to convergence of surface air, or 4. uplift along weather fronts. (*MT8*-149)

Cloud Classification by Atmosphere Étages

The French word *étage* (meaning floor, tier, or in this context, *layer*) is used to distinguish height of cloud base layers from the larger scale atmospheric layers (troposphere, stratosphere, etc.) The *étages* of the various genera of clouds are (per RAH):

Cloud Name (Genera)	Étage	Polar	Mid-Latitude	Tropics
Cumulus (Cu) **Cumulonimbus (Cb)** **Stratus (St)** **Stratocumulus (Sc)** **Nimbostratus (Ns)** [**Fog**—at ground level]	**Low C_L**	< 2 km	< 2km	< 2 km
Altostratus (As) **Altocumulus (Ac)**	**Middle C_M**	2 – 4 km	2 – 7 km	2 – 8 km
Cirrus (Ci) **Cirrostratus (Cs)** **Cirrocumulus (Cc)**	**High C_H**	3 – 8 km	5 – 13 km	6 – 18 km

Selected Cloud Terminology:[166]

These definitions include selected cloud genera, their species and supplementary features, and other cloud-related terms.

Alto- = [fr. L. altus] a prefix meaning high (but here in middle étage**,** thus not as high as cirrus)

Altocumulus: "One of the main cloud genera: a middle-level cloud [CM] that occurs as a layer or patch of more or less separate cloudlets in the form of heaps, rolls, or pancakes. The cloud elements have an apparent [ground observer's] width of 1–5° (by which they are distinguished from the higher cirrocumulus and the lower stratocumulus). They are white, or white and grey, normally with darker shading. Altocumulus clouds predominantly consist of water droplets, but ice crystals are often present. They display diffraction phenomena such as coronae and iridescence. Altocumulus clouds are extremely varied, and occur in the cloud species castellanus, floccus, lenticularis, and stratiformis; and the cloud varieties duplicatus, lacunosus, opacus, perlucidus, radiatus, translucidus, and undulatus."

Altostratus: "One of the main cloud genera: a middle-level cloud [C_M] that occurs as a grey or bluish-grey sheet that may be completely uniform or appear fibrous or striated. It may be thin enough for the disk of the Sun to be visible [though often only dimly visible], but does not exhibit halo phenomena. The edges of

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[164] http://www.atmos.washington.edu/Atlas/

[165] *International Cloud Atlas: Volume I* [1975] *and II* [1987].--*Manual on the Observations of Clouds and Other Meteors*. World Meteorological Organization. Several editions dating back to 1896, Volume I most recently published 1975, the image atlas was last updated 1987. http://en.wikipedia.org/wiki/International_Cloud_Atlas

[166] Quoted definitions are, unless otherwise noted, from *A Dictionary of Weather*. Storm Dunlop. Oxford University Press, 2008.Oxford Reference Online. Oxford University Press…

a layer may sometimes show a corona or iridescence. Altostratus may be either a water droplet or a mixed [droplet plus ice] cloud. It frequently produces precipitation, but this may not reach the ground. The main cloud varieties are: duplicatus, opacus, radiatus, translucidus, and undulatus."

Banner cloud: "A cloud that is restricted to the area immediately downwind of an abrupt, isolated mountain peak, and which resembles a banner or flag. Two mechanisms are possibly involved, the principal one being the presence of a lee eddy, which raises air behind the peak above the condensation level. A reduction in pressure behind the obstacle would also facilitate condensation, similar to the way condensation trails form in the central, low-pressure core of aircraft wing-tip vortices. The most famous banner cloud is that associated with the Matterhorn." RAH states that the pressure is reduced on the lee side of the peak, presumably from the Bernoulli effect, and this causes lower-lying air to rise. Unlike lenticular clouds, this type of cloud is not situated above the peak or at the peaks of a mountain wave.

Billow cloud (popular name for *undulatus): "*Some forms are the result of shear instability (Kelvin–Helmholtz instability clouds), and some result from gravity waves. Billow clouds are present when there is sufficient moisture present in the upward motion of the waves to make the wave structure visible by condensation of cloud droplets. Billows formed from gravity waves exhibit broad, nearly parallel, lines of cloud oriented normal to the wind direction, with cloud bases near an inversion surface. The distance between billows is on the order of 1000–2000 m." Billow clouds may appear as a series of breaking waves as with surf.

Calvus: "[Latin: 'bald'] A cloud species. A cumulonimbus cloud in which the tops of certain towers have started to lose their hard [i.e., sharp] cumuliform outline, but cirriform characteristics are not yet readily apparent. Some striations may be evident. This stage indicates that glaciation has begun in the top of the cloud."

Capillatus: "[Latin: 'hairy'] A cloud species. A cumulonimbus in which the tops of the cloud have developed into cirrus, with a distinct fibrous or striated structure. The cirrus may be in the form of virga, or appear as a massive plume or flattened anvil (incus)."

Castellatus: "[Latin: 'turreted'] is the correct term. *Castellanus* [from Latin castellum: 'castle'] appears to have … become the most commonly used form… A cloud species in which vertical cumuliform turrets arise from a lower line or layer of cloud. Many of the cloud turrets are higher than they are wide, giving a clear indication of instability at that level… "

Ceiling: The cloud ceiling is the height of the lowest layer (the base) of clouds above a surface, thus analogous to the ceiling of a room blocking viewing of higher structures.

Cirrus = "[Latin: 'curl', 'tuft', 'wisp'] One of the main cloud genera: a high-level [C_H] cloud … that occurs as white or mainly white patches or bands, generally with a fibrous appearance… Cirrus clouds consist of ice particles, and although they do not exhibit many halo phenomena (commonly seen in cirrostratus), may show other optical effects, especially a bright form of parhelion. Cirrus may occur as various cloud species (castellatus, fibratus, floccus, spissatus , and uncinus), cloud varieties (duplicatus, intortus, radiatus, and vertebratus), and as praecipitatio and virga. Dense cirrus, particularly the spissatus variety, may appear dark grey when seen against the light."

Cirrocumulus: "[Latin: 'wisp' + 'heap'] One of the main cloud genera: a high-level [C_H] cloud that occurs as a layer or patch of more or less separate cloudlets in the form of heaps, rolls, or pancakes. The cloud elements have an apparent [ground observer's] width of less than 1° (by which they are distinguished from the lower altocumulus). They are white, without shading. Cirrocumulus occurs in the cloud species castellatus, floccus, lenticularis, and stratiformis, and the cloud varieties lacunosus and undulatus."

Cirrostratus: "[Latin: 'wisp' + 'layer'] One of the main cloud genera: a high-level [C_H] cloud that occurs as a thin sheet, occasionally in the form of a thin featureless white veil, but normally showing some fibrous structure. Cirrostratus consists of ice crystals and is the cloud genus most prone to exhibit halo phenomena. It may occur as the cloud species fibratus and nebulosus, and the cloud varieties duplicatus and undulatus."

Congestus: "A cloud species, commonly known as towering cumulus. Cumulus cloud of considerable vertical extent, growing vigorously, with a firm cauliflower-like head that shows no sign of glaciation (which would cause the cloud to be classed as cumulonimbus). Cumulus congestus may produce precipitation through the coalescence process and their strong convection may sometimes give rise to funnel clouds, landspouts, or waterspouts."

Cumulus: "[Latin: 'heap'] One of the cloud genera. A cloud in the form of a relatively well-defined individual mound or heap, occasionally ragged, but generally with a flat, darkish base and rounded, white upper regions, often actively growing vertically. Cumulus clouds originate from convection in the form of thermals [*OED3*: A rising current of relatively warm air, used by gliders and birds to gain height], but orographic effects often contribute to their growth. Cumulus occurs in four cloud species: fractus, humilis, mediocris, and congestus."

Cumulonimbus: "[Latin: 'heap' + 'raincloud'] One of the cloud genera. A large, towering cloud of great vertical extent, with a dark, ragged base from which rain, hail, or snow is falling, often in the form of *virga* [thus not always reaching the ground]… The cloud usually shows signs of vigorous convection, and the tops (which appear brilliantly white when illuminated by the Sun) are glaciated [composed of ice crystals] and may appear smooth, fibrous, or striated, or be flattened into an anvil (incus)…"

Fibratus: "[Latin: 'fibrous'] A cloud species. Straight or slightly irregular, long streaks of cloud, without any obvious tufts (generating heads) or hooks. Generally applied to thin sheets or detached patches of cirrostratus or cirrus."

Floccus: "[Latin: 'tuft'] A cloud species. Cirrus, cirrocumulus, or altocumulus clouds in the form of small individual tufts, more or less rounded above but ragged below, frequently with trailing virga…"

Föhn wind: "A warm and often extremely dry wind that descends in the lee of a mountain barrier. Föhn winds occur under stable conditions that are conducive to the formation of large-amplitude lee waves. Air from very high levels (well above the mountain-tops) may be brought down to the surface and undergo considerable adiabatic heating. Föhn winds (such as the *chinook*) are noted for their rapid temperature rise, their desiccating effect, and the rapid disappearance of snow cover. Although originally applied to [southerly] winds in the Alpine region, the term is now used for all similar winds." Not the same as Santa Ana style katabatic winds.

Fractus: "[Latin: 'broken'] A cloud species: cumulus or stratus clouds that exhibit a ragged or shredded appearance"

Glaciation: "The process by which supercooled water droplets change into ice crystals."

Incus: "[Latin: 'anvil'] An accessory cloud specifically associated with cumulonimbus capillatus, where the upper portion of a cumulonimbus has spread out on reaching an inversion to give a large, overhanging layer of cloud… This may be smooth, striated, or fibrous in appearance."

Halo: "A halo (ἅλως; also known as a nimbus, icebow or Gloriole) is an optical phenomenon produced by ice crystals creating colored or white arcs and spots in the sky. Many are near the sun or moon but others are elsewhere and even in the opposite part of the sky. They can also form around artificial lights in very cold weather when ice crystals called diamond dust are floating in the nearby air…. There are many types of ice halos. They are produced by the ice crystals in cirrus clouds high (5–10 km, or 3–6 miles) in the upper troposphere. The particular shape and orientation of the crystals is responsible for the type of halo observed. Light is reflected and refracted by the ice crystals and may split up into colors because of dispersion. The crystals behave like prisms and mirrors, refracting and reflecting sunlight between their faces, sending shafts of light in particular directions."[167]

Humilis: "A cumulus cloud species that appears flattened and which, when viewed from the ground, has a greater horizontal than vertical extent." Typically, indicates a fair weather cloud.

Lee wave: "Also known as a *mountain wave*. A wave or series of waves that forms above and downwind of an obstacle, such as a range of mountains. A stationary ('standing') gravity wave [aka *buoyancy wave*] that develops in a stable layer between less stable higher and lower layers… In certain cases the wave train may extend hundreds of kilometres downwind, and be extremely persistent while conditions remain constant. The downward motion of the initial wave behind the obstacle may occasionally be very large and bring air from high levels down close to the surface, creating *föhn* conditions. The crests of the waves often exhibit *wave clouds*, such as altocumulus lenticularis." At their peaks, the lee waves to be visible have condensed droplets, whereas at their troughs, the droplets may have evaporated and no longer be visible. (*MT8*-155) *Rotor clouds* may form under an eddy peak or lenticular cloud of a lee cloud—these are extremely turbulent and present a hazard to aircraft (see separate entry).

Lenticularis: "A cloud species in which the elements are approximately lens or almond shaped (and commonly known as lenticular clouds). The cloud types most often encountered are altocumulus and cirrocumulus, although stratocumulus occurs occasionally. In most cases, the clouds are of orographic origin and lie at

[167] http://en.wikipedia.org/wiki/Halo_%28optical_phenomenon%29

the crests of lee waves, remaining essentially stationary in the sky while the conditions (including wind speed and direction) remain constant. Depending on circumstances, however, they may sometimes lie far downwind of any mountain range or obvious source of vertical motion."

Katabatic wind: "A wind consisting of dense air that has cooled by radiative cooling over upland areas or contact with snow and ice fields and which then drains down into the valleys. Also known as a drainage wind and a mountain breeze. Examples of strong katabatic winds are the bora [Adriatic], mistral [S France], and the extreme winds that drain from the Antarctic ice cap." "Sometimes also called *fall winds.* Katabatic winds can rush down elevated slopes at hurricane speeds… Examples of true katabatic winds include the Bora (or Bura) in the Adriatic, the Santa Ana in southern California [especially the Santa Ana Canyon], and the Oroshi in Japan. [This wind undergoes] warming adiabatically as it descends. The temperature of the wind depends on the temperature in the source region and the amount of descent. In the case of the Santa Ana, for example, the wind can (but does not always) become hot by the time it reaches sea level. [Santa Ana winds tend to blow strongest when there is a High to the NW producing strong anti-cyclonic flow to the SW in the canyon.] In the case of Antarctica, by contrast, the wind is still intensely cold."[168]

Mamma or Mammatus: "[Latin: 'udder'] A supplementary cloud feature consisting of bulges or pouches beneath the lower surface of a cloud. They are the visible signs of downdraughts bringing colder air into the lower layers…"

Meteor : originally the term *meteorology*, as directly transliterated from ancient Greek, referred to the study of celestial and Meteorological phenomena. The term *meteor* came to signify in English, "Any atmospheric or meteorological phenomenon" (*OED3*)—these included winds, rain, dew, rainbows, etc. Meteor used in this sense is now "An old-fashioned term (although one that is still used in World Meteorological Organization definitions) for any liquid or solid particles, apart from a cloud, that may be suspended in the atmosphere, precipitated from it, or deposited on the surface. It also applies to any electrical [e.g., lightning, St. Elmo's fire, thunder, aurora] or optical [e.g., parhelion] phenomena…" These additional categories are termed electrometeor, hydrometeor, and lithometeor, etc.

Nacreous (Polar stratospheric) clouds (PSCs): (from *Nacre=mother of pearl,OED3*) are clouds in the winter polar stratosphere at altitudes of 15,000–25,000 meters (50,000–80,000 ft). They are implicated in the formation of ozone holes; their effects on ozone depletion arise because they support chemical reactions that produce active chlorine which catalyzes ozone destruction, and also because they remove gaseous nitric acid, perturbing nitrogen and chlorine cycles in a way which increases ozone destruction.... The stratosphere is very dry; unlike the troposphere, it rarely allows clouds to form. In the extreme cold of the polar winter, however, stratospheric clouds of different types may form, which are classified according to their physical state and chemical composition. Due to their high altitude and the curvature of the surface of the Earth, these clouds will receive sunlight from below the horizon and reflect it to the ground, shining brightly well before dawn or after dusk [thus contributing to their mother of pearl appearance]… PSCs form at very low temperatures, below −78 °C. These temperatures can occur in the lower stratosphere in polar winter. In the Antarctic, temperatures below −88 °C frequently cause type II PSCs. Such low temperatures are rarer in the Arctic. In the Northern hemisphere, the generation of lee waves by mountains may locally cool the lower stratosphere and lead to the formation of PSCs. (Paraphrased from *here*[169])

Nimbostratus: "[Latin: 'rain' + 'layer'] One of the main cloud genera: a thick grey or dark grey, middle-level layer cloud that produces more or less continuous precipitation in the form of rain or snow. It is always thick enough to hide the Sun, and the bottom often appears diffuse because of the precipitation. Ahead of approaching warm fronts, altostratus normally lowers and thickens to become nimbostratus, which in turn may extend down almost to ground level." May have only virga which do not reach the ground.

Noctilucent clouds: "are tenuous cloud-like phenomena that are the 'ragged-edge' of a much brighter and pervasive polar cloud layer called polar mesospheric clouds in the upper atmosphere, visible in a deep twilight. They are made of crystals of water ice. The name means roughly night shining in Latin. They are most commonly observed in the summer months at latitudes between 50° and 70° north and south of the equator. They are the highest clouds in the Earth's atmosphere, located in the mesosphere at altitudes of around 76 to 85 kilometers (47 to 53 mi). They are normally too faint to be seen, and are visible only when illuminated by sunlight from below the horizon while the lower layers of the atmosphere are in the Earth's

[168] http://en.wikipedia.org/wiki/Katabatic_wind

[169] http://en.wikipedia.org/wiki/Polar_stratospheric_cloud

shadow… Noctilucent clouds can form only under very restrictive conditions; their occurrence can be used as a sensitive guide to changes in the upper atmosphere. Since their relatively recent classification, the occurrence of noctilucent clouds appears to be increasing in frequency, brightness and extent. It is theorized that this increase is connected to climate change."[170]

Parhelion: "(pl. parhelia). A relatively frequent halo phenomenon (commonly known as a mock sun or *sun dog*), consisting of a bright white or coloured spot of light at the same [observer's visual] altitude as the true Sun. The effect arises from the refraction of light through hexagonal ice crystals and is common in cirrostratus (where parhelia often occur in pairs, one on each side of the Sun) and in patches of cirrus… Depending on the Sun's altitude, a parhelion may lie at the same distance from the Sun as the 22° halo (which may not be visible), or as much as 14° farther away. When spectral colours are present, red is closest to the Sun, and a white tail frequently extends along the parhelic circle… On rare occasions, parhelia may also occur at other points on the parhelic circle, most commonly at 120° from the Sun (paranthelion) and 180° (anthelion); less frequently at 46°, 90°, and 140°." "Sundogs may appear as a colored patch of light to the left or right of the sun, 22° distant and at the same distance above the horizon as the sun, and in ice halos… Sundogs are best seen and are most conspicuous when the sun is low."[171]

Pileus: "(Latin for cap), also called scarf cloud or cap cloud, is a small, horizontal cloud that can appear above a cumulus or cumulonimbus cloud, giving the parent cloud a characteristic 'hoodlike' appearance. Pilei tend to change shape rapidly. They are formed by strong updrafts acting upon moist air at lower altitudes, causing the air to cool to its dew point. As such, they are usually indicators of severe weather, and a pileus found atop a cumulus cloud often foreshadows transformation into a cumulonimbus cloud, as it indicates a strong updraft within the cloud."[172]

Praecipitatio: "[Latin: 'fall'] A supplementary cloud feature: any form of precipitation from a cloud (drizzle, hail, ice pellets, rain, or snow) which is reaching the surface; this excludes virga."

Precipitation: "Water in either liquid or solid form that is derived from the atmosphere and falls to the surface. It thus includes drizzle, rain, freezing rain, hail, ice pellets, ice crystals, snow, and other forms. It specifically excludes clouds, dew, fog, frost, mist, and rime (which are either suspended in the atmosphere or deposited directly on to the surface), together with virga (which do not reach the ground)." To emphasize, VIRGA is not the same as PRECIPITATION.

Pyrocumulus: A cumulus cloud forming over a fire as a result of heating and resulting atmospheric convective instability along with the presence of smoke cloud condensation nuclei. (*MT8*-147)

Rotor clouds [aka *roll clouds*]: may form under an eddy peak or lenticular cloud of a lee cloud—these are extremely turbulent and present a hazard to aircraft. They are "a turbulent, altocumulus-type cloud formation found in the lee of some large mountain barriers, particularly in the Sierra Nevada near Bishop, California… The air in the cloud rotates around an axis parallel to the range. The term was first applied to clouds of this type in Europe, especially in the Riesengebirge and on Crossfell. The rotation may extend to the ground, cause hazards to aircraft, and carry large amounts of dust aloft. Rotor clouds are often associated with lee wave (lenticular) clouds that may be present above."[173] "At the surface the wind is in the opposite direction to the gradient wind."[174]

Spissatus = dense condensed or thickened, a species of cirrus cloud which has sufficient thickness to appear grey… [Partially analogous to the medical term, *inspissated*, as applied to dehydrated thick sputum]

Stratocumulus: "One of the main cloud genera. A distinct layer of low-level [C_L] cloud, in the form of regular clumps or rolls [or 'streets'], with dark shading… An extremely common cloud type, especially over the oceans. It may occur as the cloud species castellatus, lenticularis, and stratiformis, and in the cloud varieties duplicatus, opacus, perlucidus, translucidus, radiatus, and undulatus."

Stratus: "One of the main cloud genera. A predominantly grey, low-level layer [C_L] cloud that is relatively featureless and has a fairly uniform base. If visible, the Sun or Moon appear sharply defined and do not show any optical phenomena [e.g., no halo]. Stratus may produce small amounts of precipitation, in the form of drizzle, snow, or even grains of ice… Stratus is created by orographic or general uplift (as in a

[170] http://en.wikipedia.org/wiki/Noctilucent_cloud
[171] http://en.wikipedia.org/wiki/Sun_dog
[172] http://en.wikipedia.org/wiki/Pileus_cloud
[173] http://amsglossary.allenpress.com/glossary/search?id=rotor-cloud1
[174] http://www.weatheronline.co.uk/reports/wxfacts/Rotor-cloud.htm

depression), but not by convection. Fog may be regarded as stratus at ground level, and fog that has formed overnight will often lift with daytime heating to produce a layer of low stratus. Stratus may occur as the cloud species fractus or nebulosus, and the cloud variety opacus."

Tuba: "[Latin: 'trumpet'] A supplementary cloud feature consisting of a column or cone of cloud that descends from the base of a cumulonimbus or (occasionally) cumulus congestus cloud. It is the central core of a vortex in which the reduced pressure causes condensation to occur. Commonly known as a funnel cloud when not in contact with the surface, it may become a true landspout or waterspout if it does touch down."

Uncinus: "[Latin: 'hooked'] A cloud variety: cirrus with a distinct hook [superiorly] or comma shape. The generating head is not rounded (cumuliform), but is either simple or in the form of a small tuft."

Virga [Latin: 'rod'] "A supplementary cloud feature that consists of a trail of precipitation that does not reach the ground. Also known as a *fallstreak*. Virga are particularly associated with altocumulus, altostratus, cirrocumulus, cumulonimbus, cumulus, nimbostratus, and stratocumulus. Cirrus cloud, particularly cirrus uncinus, may also be regarded as virga, although not normally recorded as such."

Droplet and Ice Crystal Formation

This is a very complex subject which we reviewed only briefly. Chapter 6 of *ASI* is titled "Cloud Microphysics", but we did not read it. Some points of interest follow.

Overview: For cloud droplets to form and grow, the temperature must be sufficiently low, and the ratio of actual water vapor partial pressure to the saturation partial pressure e/e_s sufficiently high, and these variable factors also depend on the amount and type of solute present in the cloud condensation nucleus. Droplets are unlikely to condense and grow to a large size directly from pure water vapor unless temperature is extremely low. Droplet formation and growth is more probable if there are droplets or *aerosols* present—suspended particles of liquid, solid, or both. Such aerosols are termed *cloud condensation nuclei* (*CCN*). These provide a larger surface area particle with larger radius of curvature on which water vapor can condense to form a droplet *embryo* and exhibit growth. The aerosol may or may not dissolve in the wet droplet that is formed. Hygroscopic CCN aerosol particles suitable for droplet formation include dust, sea salt, clay, bacteria, and sulfate (including perhaps those derived from phytoplankton).

Kelvin Effect: Condensation of pure water vapor to pure water droplets (spontaneous nucleation) requires a very high supersaturation for initially small nuclei to form from random collisions (the "Kelvin effect", further discussed below). The Kelvin curve (RH vs. size, see graph below) shows at what combinations of RH and size pure water droplets can be in equilibrium with the air and neither grow nor shrink. For droplet embryos lying above the Kelvin curve (RH vs. size), droplets can grow, whereas those lying below the curve will evaporate.

Starting size therefore matters: For pure water to condense on a nucleus of radius 0.01 micrometers (i.e., for the nucleus to grow), the relative humidity (RH) must be 112.5%, whereas if the nucleus is 100 times as large, namely 1.0 micrometer in diameter, a RH of only 100.12% is required for nucleus growth.[175]

Solute Effect: A *haze* or mist of fine droplets can form over the sea even when humidity is less than 100% due to the presence in the air of sea salt particles, which serve as hygroscopic condensation nuclei. "Some hygroscopic aerosols (e.g., sea salt, sodium chloride, ammonium sulfate, etc.) are water soluble; aerosols dissolve when wet, lowering the equilibrium saturation vapor pressure (the Köhler solute effect)… Condensation begins at a RH of ≈75% for sulfuric and nitric acid particles."[176] In contrast, hydrophobic solutes resist condensation. Droplets small enough to be in stable equilibrium with the air are called haze droplets. All droplets in a state represented by points on a Köhler curve and to the left of the peak (the maximum) in the Köhler curves (see graph below) are *haze*.[177] [Wet] haze may be more prominent in the morning, when temperatures are cooler and RH higher, than in the afternoon, when temperatures are higher, the amount of solute CCNs has not changed, and the haze droplets have partly or completely evaporated (*MT8*-109).

Equilibrium droplets: When droplets that form are in stable equilibria with the air, if the drops grows a little, the vapor pressures adjacent to their surfaces would rise above that of the ambient air and they would evaporate back to their equilibrium sizes. Similarly, if the drops evaporates a bit, the vapor pressures would fall below that of the ambient air and they would grow back to their equilibrium sizes by condensation.

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[175] http://facstaff.unca.edu/cgodfrey/courses/atms455/ppt/nucleation.pdf
[176] ibid.
[177] ibid.

Köhler theory and Kohler curves: These combine the effects of surface tension and solute presence on droplet formation and growth. "Köhler theory describes the process in which water vapor condenses and forms liquid cloud drops, and is based on equilibrium thermodynamics... The Köhler curve is the visual representation of the Köhler equation. It shows the supersaturation [typically the positive or negative % increment over 100% saturation] at which the cloud drop is in equilibrium with the environment over a range of droplet diameters."[178] The Köhler equation (which I only partly understand) for a single component dilute fully soluble solute such as NaCl salt may be expressed as follows[179] (or it may be alternatively expressed in equivalent exponential form):

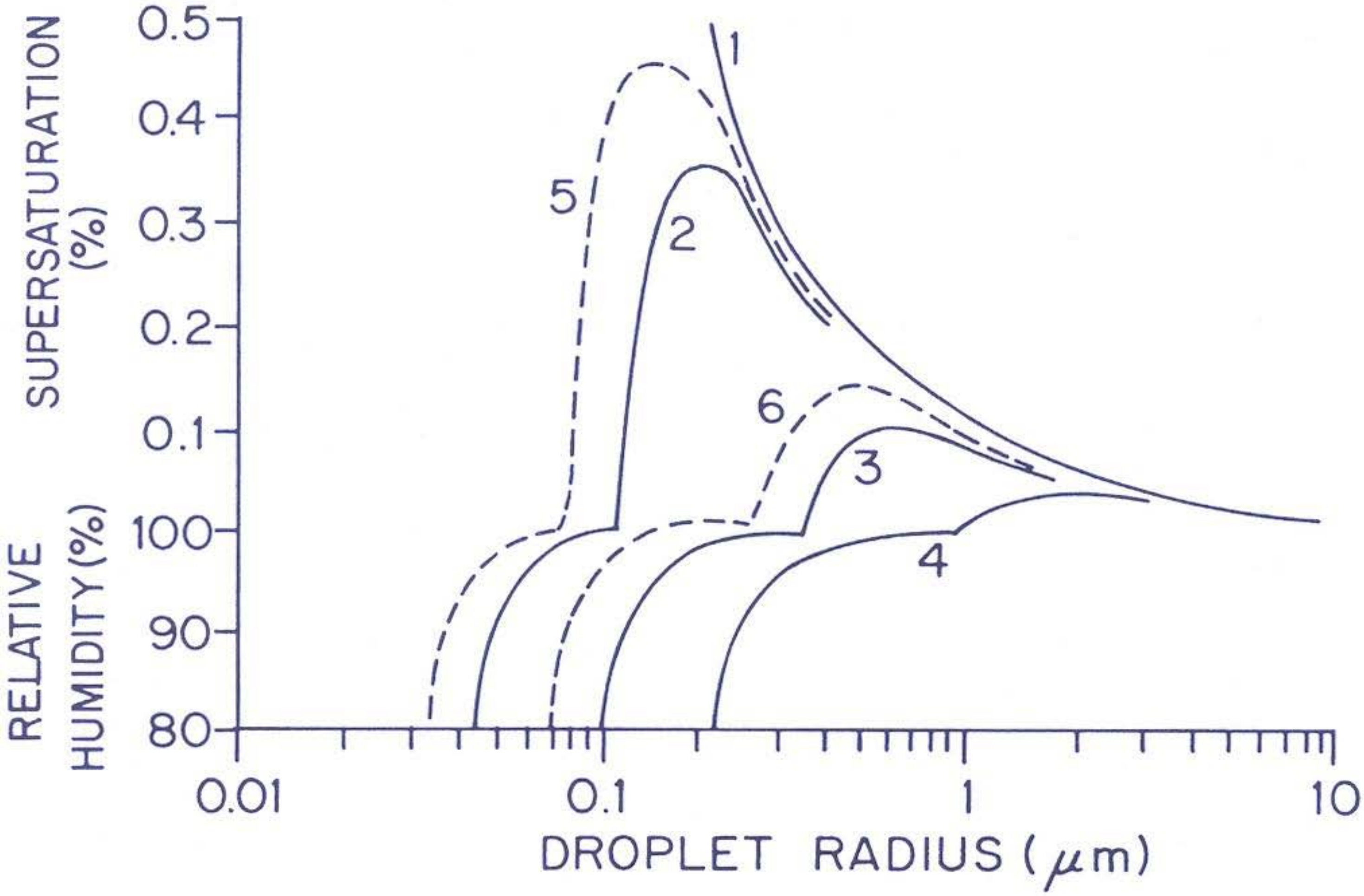
$$\ln\left(\frac{p_w(D_p)}{p^0}\right) = \frac{4M_w\sigma_w}{RT\rho_w D_p} - \frac{6n_s M_w}{\pi\rho_w D_p^3}$$

where $s = p_w/p^0$ is the actual saturation ratio of a wet particle at equilibrium,
$p_w(D_p)$ is the droplet water vapor pressure at temp T, and is dependent on diameter D_p
p^0 is the saturation vapor pressure over a flat surface for temp T
M_w is the molecular weight of water
σ_w is the droplet surface tension at the point of activation
R is the ideal gas constant
T is the temperature
ρ_w is the density of pure water
D_p is the wet cloud drop diameter
n_s is the moles of solute in the droplet

The first term on the right (the curvature or Kelvin term) depends on the droplet surface tension and tends to increase the required equilibrium saturation ratio, whereas the second term (the solute or Raoult's term) tends to decrease the equilibrium saturation ratio by the contribution of solute to the growing droplet.[180] The resulting Köhler curves ([2] through [6] in the graph) lie below the corresponding Kelvin curve ([1] in the graph) on the left, but the Köhler curves asymptotically approach the Kelvin curve on the right (where solute effect is minimal).

The following Köhler curves—taken from a NOAA publication[181]—show the pure water Kelvin curve [1] as well as curves for varying kg quantities of solutes dissolved in droplet nuclei. (For instance, [2] represents 10^{-19} kg NaCl, [3] represents 10^{-18} kg NaCl, [5] represents 10^{-19} kg $(NH_4)SO_4$, etc. (Note that the ordinate has a non-uniform scale, and that the horizontal scale is radius, not diameter.)

[178] http://en.wikipedia.org/wiki/K%C3%B6hler_theory
[179] ibid
[180] http://www.chbe.gatech.edu/fac_staff/faculty/nenes/kta/KTA%5B1%5D_files/page0002.htm
[181] http://ruc.noaa.gov/wrf/WG11/wrf_tutorial_2010/Fast.WRF-Chem.tutorial.pdf



Critical supersaturation and radius/diameter: The maximum saturation ratio S_c of Köhler curves is given by a formula (omitted here) expressing the peak values for each of Köhler curves. "S_c corresponds to the minimum level of water vapor saturation required for a CCN to develop into a cloud droplet. Since critical saturations are always higher than unity, the *critical supersaturation*, s_c (defined as S_c-1) is often used in its place. For each s_c, there is a characteristic dry diameter (d_{pc}), above which all particles with similar composition activate into cloud droplets."[182] The droplet diameter (or radius) at which the curve peaks is called the *critical diameter* (or *critical radius*), and such a droplet is said to have become *activated*.

Falling raindrops are spherical when very small, but larger drops become flattened at the surface facing downward and expanded laterally as a result of differences of air pressure. (*MT8*-175)

Droplet Growth Examples: It can be seen that a droplet positioned on the left hand side of one of the curves (such as [2] shown above) can grow along the left hand side of the curve, continue past the critical radius defined at the peak s_c (which serves as a relative barrier), and continue with further now accelerating growth on the right hand side of the curve, never reaching thermodynamic equilibrium—provided the actual atmospheric supersaturation s exceeds the critical supersaturation s_c defined for the curve (here, about 0.35% supersaturation).

However, if the atmospheric supersaturation s = 0.3%, a growing droplet ascending, say curve [2] or [5], is prevented from reaching the critical radius and critical supersaturation peak barrier s_c and therefore continued growth is prevented when the radius corresponds to s = 0.3%. For curve [5], the droplets will not exceed about 0.1 micrometers, whereas for curve [2] the droplets can be a little larger. These are the conditions in which the condition forms that is variously called *haze*, *mist,* or *wet haze*, and that does not evolve to rain.

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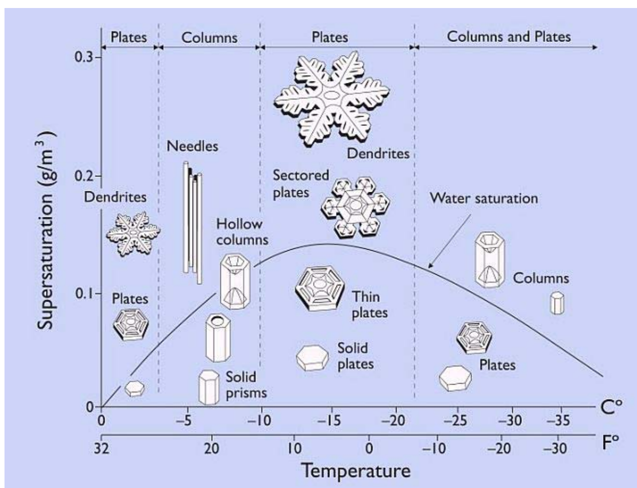
[182] L. T. Padró, A. Asa-Awuku, R. Morrison, and A. Nenes. "Inferring thermodynamic properties from CCN activation experiments: single-component and binary aerosols". *Atmos. Chem. Phys.*, 7, 5263–5274, 2007: available online at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.118.6602&rep=rep1&type=pdf

Droplet Collection and Coalescence: Once a large droplet forms, it can sweep up smaller cloud droplets in its path as it moves relative to them, usually as a result of gravity. The *Continuous Collection Equation* (rate of mass accumulation of the larger droplet) may be given by (RAH, see also *API*-225)

$$\frac{dM}{dt} = AVw_lE$$

where dM/dt = the time rate of mass accumulation of the large droplet
V = fall velocity of big drop relative to the cloud of smaller drops
A = the large droplet's cross-sectional area presented to the field of smaller droplets
w_l is mass of cloud water per unit volume of air
E = collection efficiency (needed because some droplets in the path of the collision are deflected and sweep past the collecting droplet, failing to coalesce with it)

Ice Formation: I have not reviewed this topic in detail. Ice has a hexagonal geometry and forms six-sided rectangular solid or hollow columns or prisms, hexagonal plates, capped columns, six-rayed sectored plates and dentrites, needles, tsuzumi crystals, etc. (Note: Through doubling there can be 12-sided snowflakes, but there are no eight-sided snowflakes in nature, despite Christmas ad copy, handwritten asterisks, and dingbats like ✱.) The best ice forming nuclei (those forming and/or growing ice at the temps closest to 0 °C) include especially ice crystals themselves, but also AgI (the traditional cloud-seeding chemical), PbI_2, CuO and CuS, vaterite and kaolinite, and enough certain organic crystals such as cholesterol and metaldehyde. The likelihood of ice crystal formation and the shape of crystals formed depend on the degree of supersaturation, temperature, presence of ice forming nuclei, etc.[183] All water is frozen below 40 °C. "…Thin plates and stars [*dendrites*] grow around -2 °C (28 °F), while columns and slender needles appear near -5 °C (23 °F). Plates and stars again form near -15 °C (5 °F), and a combination of plates and columns are made around -30 °C (-22 °F)."[184] The classic snow morphology diagram (relating temp, saturation, and morphology) and derived from Nakaya's 1954 classification with modifications by Furukawa, appears at several websites.[185]



Water vapor can directly freeze to form ice or snow crystals, a process requiring very low temperatures but aided by the presence of nuclei as with droplet condensation. Water vapor can also be directly deposited on ice surfaces. Snow crystals can grow by accretion (aggregation) to form coarse snow. Water droplets in supersaturated air (including *freezing rain* and supercooled fog) can rapidly condense out or be deposited as *hard* or *soft rime* on suitable nucleating surfaces (ice crystals, snow flakes, hail, the leading or windward surfaces of structures, aircraft wings, and ship masts, etc.), forming graupel, hail, rime ice, etc. *Graupel* is soft hail, sometimes conical in shape, "frozen precipitation in the form of opaque snow pellets produced when

[183] Kenneth G. Libbrecht: http://www.its.caltech.edu/~atomic/snowcrystals/class/class.htm
[184] http://www.its.caltech.edu/~atomic/snowcrystals/primer/primer.htm
[185] Snow morphology diagram:
- http://pandasthumb.org/archives/2007/01/mystery-in-the.html
- http://www.its.caltech.edu/~atomic/snowcrystals/primer/morphologydiagram.jpg etc.
- http://eands.caltech.edu/articles/Libbrecht%20Feature.pdf

supercooled water droplets collide and freeze [including with snow or ice crystals]. Typical graupel diameters are 2–5 mm."[186]

Dendrites form from hexagonal plates because, according to Kenneth G. Libbrecht, "The hexagonal growth is eventually unstable because the corners of the plate stick farther out into the supersaturated air and thus collect more water molecules. On the nanoscale..., what appears to be a straight facet actually contains many molecular steps. Diffusing molecules are more likely to hit the corners, but molecules are more likely to stick where the surface is rough, in between the corners."[187]

Thunderstorms (Unit 4)

This important and fascinating subject was only briefly surveyed in class, and I will defer summarization until I have had a chance to study some of it in much greater detail. Topics that we touched on or that are mentioned in the course PDF (plus a few hastily gathered links) include:

- Scales of convective clouds—from the humble cumulus humilis to *Mesoscale Convective Systems*[188] or *MCS's*
- Development and structure of cumulus congestus and cumulonimbus clouds, with cloud base at the LCL; anvil formation; life cycle of convective clouds and thunderstorms[189]
- Hail and Rain
- Ice crystals win out over droplets above the -40 °C level, where supercooled water cannot exist.
- *Cloud electrification*[190] involving collisions of ice crystal against. graupel; Atmospheric electricity
- *Lightning*: Formation of strikes, global distribution pattern of strikes[191]
- *Multicell thunderstorms* with multiple regions of updraft and downdraft and variable rain
- *Wet microbursts*[192] associated with negative buoyancy, *Gust fronts*, hazards to aviation from *Dry and Wet Microbursts*
- *Supercell thunderstorms*[193] with a *mesocyclone*[194] (a deep, continuously-rotating updraft), tornados,[195] hail
- *Wind shear*, splitting of thunderstorms into counterrotating vortices, leading to a left-moving storm and a right moving storm
- The *hodograph* diagram depicting varying wind vectors (speed and direction) at multiple vertical levels, thus wind shear. (*Hodos* derives from road or path.)[196]
- Tornadoes: Conditions favoring *tornado formation* in *Tornado Alley:*[197] wind shear created along a fast jet stream intersecting warm dry air from the Mexican Plateau to the SW and warm moist air from the Gulf of Mexico to the SE; Supercell tornadoes[198]

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[186] *A Dictionary of Weather*. Storm Dunlop. Oxford University Press, 2008. Oxford Reference Online, accessed 7 November 2010
[187] http://eands.caltech.edu/articles/Libbrecht%20Feature.pdf
[188] http://en.wikipedia.org/wiki/Mesoscale_convective_system
[189] http://atmo.tamu.edu/class/atmo352/ch3.pdf
[190] Atmospheric Electricity and Lightning:
I discuss many aspects of these topics in a separate summary in the section titled *Atmospheric Electricity* in http://www.mcgoodwin.net/pages/spacephysics_ess471.pdf
[191] Lightning Distribution:
Historical Pattern: http://geology.com/articles/lightning-map.shtml
Current: http://webflash.ess.washington.edu/
[192] http://en.wikipedia.org/wiki/Microburst
[193] http://en.wikipedia.org/wiki/Supercell_thunderstorm
[194] http://en.wikipedia.org/wiki/Mesocyclone
[195] http://en.wikipedia.org/wiki/Tornado
[196] Hodograph:
http://mysite.du.edu/~jcalvert/phys/hodo.htm
http://amsglossary.allenpress.com/glossary/search?id=hodograph1

- Tornado formation at the base of a *mesocyclone* below a visibly *overshooting top* of the cloud and often associated with a descending and rotating *wall cloud*[199] (visible condensation arising from lower pressure and higher dew point) and nearby hail, with rain further away
- Tornado severity: Enhanced Fujita scale (EF Scale)[200]
- *Multiple vortex tornadoes*[201]
- *Mesoscale Convective Systems* structure

Deep convection and associated thunderstorms and tornadoes are discussed extensively in *ASI* chapter section 8.3 (a section contributed to by RAH), and in *MT8* chapter 14. RAH's 1993 text *Cloud Dynamics* also deals with much of this material at an advanced level.

Atmospheric Kinematics and Dynamics (Unit 5)

This section, based on RAH lectures and PDF Unit 5 and *ASI* chapter 7 "Atmospheric Dynamics", continues mathematical topics begun in the section on Thermodynamics, etc. Regrettably, I can provide only a limited review of this important topic.

Kinematics of Fluid Flow

Kinematics (from Greek 'to move') is the branch of classical mechanics or mechanical engineering that describes the motion of bodies (objects) and systems (groups of objects) without consideration of the forces that cause the motion.[202]

In describing moving fluids, the following definitions apply to lines of flow:[203]
• *Streamlines* "are a family of curves that are instantaneously tangent to the velocity vector of the flow.
• *Streaklines* "are the locus of points of all the fluid particles that have passed continuously through a particular spatial point in the past. Dye steadily injected into the fluid at a fixed point extends along a streakline."
• *Pathlines* "are the trajectories that individual fluid particles follow. These can be thought of as a 'recording' of the path a fluid element in the flow takes over a certain period. The direction the path takes will be determined by the streamlines of the fluid at each moment in time."

In *AIS*-272, a number of kinematic terms for horizontal wind or fluid motions are described. These show the direction a fluid element will travel in at any point in time.". For a locally defined wind blowing along or parallel to wind contours (*streamlines*) that indicate wind direction:

V = instantaneous horizontal wind velocity magnitude,
s = natural coordinate expressing incremental displacement component along and parallel to the streamline
n = natural coordinate expressing displacement component perpendicular to s and the streamline
ψ = angle between the streamline or displacement s and an arbitrary fixed coordinate system

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[197] Tornado Alley:http://journals.ametsoc.org/doi/pdf/10.1175/1520-0434%282003%29018%3C0626%3ACEOLDT%3E2.0.CO%3B2
[198] Supercell Tornadoes: http://journals.ametsoc.org/doi/pdf/10.1175/MWR3349.1
[199] Wall Cloud:
• http://amsglossary.allenpress.com/glossary/search?id=wall-cloud1: These are "sometimes referred to as pedestal cloud. A local, often abrupt lowering from a cumulonimbus cloud base into a low-hanging accessory cloud, normally a kilometer or more in diameter.... A wall cloud marks the lower portion of a very strong updraft, usually associated with a supercell or severe multicell storm. It typically develops near the precipitation region of the cumulonimbus. Wall clouds that exhibit significant rotation and vertical motions often precede tornado formation by a few minutes to an hour." See also
• http://en.wikipedia.org/wiki/Wall_cloud
[200] http://www.spc.noaa.gov/efscale/
[201] http://en.wikipedia.org/wiki/Multiple_vortex_tornado
[202] http://en.wikipedia.org/wiki/Kinematics
[203] http://en.wikipedia.org/wiki/Streamlines,_streaklines,_and_pathlines

such as x-y.

Note that the instantaneous directions of the streamlines evolve and do not correspond exactly with the actual horizontal parcel trajectories (pathlines) taken.

The following kinematic quantities have units of s^{-1}.

Shear ≡ $-\partial V/\partial n$
Curvature ≡ $V(\partial\psi/\partial s)$
Vorticity[204] ≡ Shear + Curvature ≡ $-(\partial V/\partial n) + V(\partial\psi/\partial s) = \mathbf{k} \bullet \nabla \times \mathbf{V}$.
(where $\nabla \times \mathbf{V}$ is termed the curl of **V**, and
k • is the dot product giving the vertical vector component of the curl)
Diffluence/Confluence ≡ $V(\partial\psi/\partial n)$
Stretching / Contraction ≡ $(\partial V/\partial s)$
Divergence/Convergence ($Div_H V$) ≡ Diffluence + Stretching ≡ $V(\partial\psi/\partial n) + (\partial V/\partial s) = \nabla \bullet \mathbf{V}$
where $\nabla \bullet \mathbf{V}$ is divergence operator
Deformation ≡ $\partial u/\partial x - \partial v/\partial y$ and $\partial v/\partial x + \partial u/\partial y$

Dynamics

In contrast, *Dynamics* involves the study of the time evolution of physical processes under the influence of the laws affecting motion including a=F/m. *Atmospheric Dynamics* deals in part with the flow of fluids and gases in the atmosphere, as derived from the laws of motion such as F = ma, etc. Wikipedia states, "Atmospheric dynamics involves the study of observations and theory dealing with all motion systems of meteorological importance. The list includes diverse phenomena as thunderstorms, tornadoes, gravity waves, tropical cyclones, extratropical cyclones, jet streams, and global-scale circulations. The goal of dynamical studies is to explain the observed circulations on the basis of fundamental principles from physics. The objectives of such studies include improving weather forecasting, developing methods for predicting seasonal and interannual climate fluctuations, and understanding the implications of human-induced perturbations (e.g., increased carbon dioxide concentrations or depletion of the ozone layer) on the global climate."[205]

The coordinate system and method of designating velocities have been summarized above in *Mathematical Symbols*, etc. The horizontal wind velocity components are as previously noted **u** ≡ dx/dt (positive eastward) and **v** ≡ dy/dt (positive northward).

With the introduction of geopotential height Z and its close relationship with pressure, we can now choose between vertical wind components expressed by
w ≡ dZ/dt (time rate of change in geopotential height, aka traditional vertical wind speed, positive upward), or
ω ≡ dp/dt (Lagrangian time rate of change in pressure height value, a vertical velocity, negative upward)[206]

Equations of Horizontal Motion

Horizontal Force Components: We can usually ignore the vertical force and vertical wind component, as they tend to be small relative to horizontal force. The horizontal acceleration per unit mass due to forces on an element of air, ignoring vertical forced, is given as:

$$\frac{d\vec{V}}{dt} = (P_x + C_x + F_x)\vec{\imath} + \left(P_y + C_y + F_y\right)\vec{\jmath}$$

or equivalently,

$$\frac{d\vec{V}}{dt} = \vec{P} + \vec{C} + \vec{F}$$

[204] http://en.wikipedia.org/wiki/Vorticity
[205] http://en.wikipedia.org/wiki/Atmospheric_sciences#Atmospheric_dynamics
[206] Vertical velocity in pressure coordinates ω ≡ dp/dt:
• http://en.wikipedia.org/wiki/Omega_equation
• http://amsglossary.allenpress.com/glossary/search?id=omega-equation1

where P_x is the magnitude of the x-component of the pressure gradient force acceleration
P_y is the magnitude of the y-component
C_x is the magnitude of the x-component of the Coriolis force acceleration
C_y is the magnitude of the y-component
F_x is the magnitude of the x-component of the frictional force acceleration
F_y is the magnitude of the y-component

Pressure Gradient Force: The pressure acceleration is a vector oriented anti-parallel to the pressure gradient vector ∇p and proportional to its magnitude, and inversely proportional to the density ρ:

$$\vec{P} = -\frac{1}{\rho}\nabla p = -\frac{1}{\rho}\left(\frac{\partial p}{\partial x}\vec{i} + \frac{\partial p}{\partial y}\vec{j}\right)$$

As with any gradient, the magnitude of **∇p** ("*del p*") in "natural coordinates" is given by

$$\left|\overrightarrow{\nabla p}\right| = \left|\frac{\Delta p}{\Delta n}\right|$$

where Δp is the change in pressure between two isobar lines
Δn is the perpendicular distance between the 2 isobar lines

This PGF exists even if the air parcel is not initially moving.

The pressure gradient acceleration and therefore pressure gradient force PGF has magnitude inversely proportional to the spacing of the local isobars and has direction perpendicular to them toward lower pressure. This explains why the highest winds aloft typically occur in regions where isobars/isohypses are most crowded together (see further details with *geostrophic wind* below).

Coriolis Force (Coriolis Effect or Pseudoforce): For air movement in a horizontal plane, the horizontal components are given by

$$C_x = fv = (2\Omega\sin\varphi)\ v$$
$$C_y = -fu = -(2\Omega\sin\varphi)\ u$$

where f = Coriolis parameter = 2Ωsinφ
Ω = angular velocity of Earth (2π radians per sidereal day = 7.292 x 10^{-5} radians s^{-1})
φ = latitude

(A sidereal day is 23 hours, 56 minutes, 4.091 seconds = 23.93447 hours = 0.99726957 SI days.)[207]

Thus, the Coriolis force acceleration applies only to a frame rotating with Earth's rotation and occurs only when the air is moving relative to the Earth (as *wind*). Obviously, there is no vertical motion component for air motion confined to the horizontal plane. Regardless whether the initial wind direction is oriented N–S or E–W or in between, in the NH looking down from above, the Coriolis effect acts like a rightward perpendicular deflecting acceleration and force. (This is because the counterclockwise rotation of the Earth effectively moves a point that had been to the right into the inertial path of a thrown parcel during its time of flight).

In the NH (φ > 0), the Coriolis effect acts like a rightward perpendicular deflecting force and acceleration :
if v is positive (northward), C_x is positive (eastward)
if v is negative (southward), C_x is negative (westward)
if u is positive (eastward), C_y is negative (southward)
if u is negative (westward), C_y is positive (northward)

In the SH, the angle φ is negative, and the Coriolis effect acts like a leftward perpendicular deflecting force and acceleration :
if v is positive (northward), C_x is negative (westward)
if v is negative (southward), C_x is positive (eastward)
if u is positive (eastward), C_y is positive (northward)
if u is negative (westward), C_y is negative (southward)

The resultant Coriolis acceleration is given by

$$\vec{C} = fv\vec{i} - fu\vec{j} = -f\,\vec{k} \times \vec{V}$$

207 http://en.wikipedia.org/wiki/Sidereal_time

where $\vec{k}$ is the unit vector in the vertical direction, and

$\vec{k} \times \vec{V}$ = a cross product lying in the horizontal plane and orthogonal to both $\mathbf{k}$ and $\vec{\mathbf{V}}$.

Frictional Force: This is actually a complex subject but will be simplified for this course by assuming

$$\vec{\mathbf{F}} = -a\vec{\mathbf{V}}$$

where a is some constant > 0

Thus, the Frictional Force exists only for already moving air, and is simply a retarding force. It is significant only in the *planetary atmospheric boundary layer* (ABL) where surface friction plays a role. (The boundary layer is loosely and variably defined, and is said to have a thickness of a few hundred meters to a few kilometers.)[208] In the *free atmosphere* (above the boundary layer) it is negligible and can be ignored.

Vector Equation of Horizontal Motion: The resulting vector equation of horizontal motion, defined for constant geopotential height Z (such as at sea level), applying Newton's 2nd law and including all contributing forces is:

$$\frac{d\vec{V}}{dt} = -\left(\frac{1}{\rho}\nabla p\right)_Z - f\,\vec{k} \times \vec{V} - a\vec{V}$$

The textbook (*ASI*-280 and 295) gives an alternate form of this equation, defined on constant pressure surfaces (such as at 500 mb) so $\nabla p = 0$, as:

$$\frac{d\vec{V}}{dt} = (-\nabla\Phi)_p - f\,\vec{k} \times \vec{V} + \vec{F}$$

where the $\nabla\Phi$ term might be written instead as $g_0\nabla Z$ or $g\nabla z$.

Similarity of Patterns of Pressure Isobar Contours and Geopotential Height Isohypse Contours:

We can derive the following relation for the horizontal pressure gradient acceleration:

$$\vec{P} = \left(\frac{1}{\rho}\nabla p\right)_Z = -(g_0\nabla Z)_p$$

where the middle term expresses the pressure gradient acceleration in terms of pressure changes on a surface of constant geopotential height Z, and the right hand term expresses this in terms of geopotential height changes on a surface of constant pressure. Thus we see that for local conditions where the density varies little, these two form of expressing pressure gradient force differ only by a constant of proportionality (*ASI*-279). The textbook(*ASI*-279 to 280) states, "to a close approximation isobars on a constant geopotential surface (e.g., sea level) can be converted into geopotential height [isohypse] contours on a nearby pressure surface simply by relabeling them using a constant of proportionality based on the hypsometric equation… [These] yield virtually identical distributions of $\vec{P}$".

Geostrophic Balance and Geostrophic Winds

Although winds change continuously in speed and direction, the synoptic scale upper atmosphere winds including extratropical cyclones and baroclinic wave winds have long timescales for change, and can be said (at least for a while and to a useful approximation) to be "in balance" (*ASI*-281). Such theoretical or idealized winds are termed *geostrophic winds* and are said to have *geostrophic balance*,[209] where "stophic"=turning etymologically refers to the fact that these are winds created by the interaction of the PGF with the Earth's *turning* (the Coriolis effect). These are idealized non-surface (upper level) winds for which there is no frictional force and which have adjusted to the local pressure gradient. According to this idealized model definition of geostrophic flow, geostrophic winds blow cyclonically (thus gradually changing direction) around low pressure areas and parallel to the isobar or isohypse contours, with the Coriolis force exactly balancing the PGF. Recall that

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[208] Roland B. Stull. *An introduction to boundary layer meteorology.* 2003. Kluwer Academic Publishers.

[209] http://en.wikipedia.org/wiki/Geostrophic

$$\frac{d\vec{V}}{dt} = \vec{P} + \vec{C} + \vec{F}$$

For geostrophic balance conditions, in which (1) the frictional force is ignored and assumed to be zero, and (2) the pressure gradient force and Coriolis force balance each other,

$$0 = \frac{d\vec{V}}{dt} = \vec{P} + \vec{C}$$

or

$$\vec{P} = -\vec{C}$$

and there is no further net acceleration of the geostrophic wind $\mathbf{V_g}$ (at least for a while). In order for geostrophic balance to exist and acceleration to be zero, the idealized geostrophic wind must blow not down the pressure gradient but in fact perpendicular to it, thus parallel to the contour lines of pressure height (isohypse contours) or pressure (isobar contours). Its direction leaves lower pressure to its left, "justifying the identification of local pressure minima with cyclones and local pressure maxima with anticyclones" (*ASI*-281). When pressure contours change directions (which in reality is happening nearly continuously), the geostrophic wind quickly adjusts direction to restore geostrophic balance and maintain a direction parallel to the contours.

The magnitude of the geostrophic wind (speed) is given by

$$|\vec{V}| = \frac{g_0}{f}\frac{\Delta Z}{\Delta n}$$

where $\frac{\Delta Z}{\Delta n}$ = spatial rate of change of geopotential height perpendicular to the direction of flow, $f = 2\Omega\sin\varphi$, as before.

This formula confirms that geostrophic wind blows at a speed inversely proportional to the spacing of the pressure or pressure height contours on an upper level map, with tighter spacing being associated with greater wind speed.

The individual **geostrophic wind horizontal components** are given variously as (*ASI*-281 and *here*):[210]

$$u_g = -\frac{g_0}{f}\frac{\partial Z}{\partial y} = -\frac{1}{f}\frac{\partial \Phi}{\partial y} = -\frac{1}{\rho f}\frac{\partial p}{\partial y}$$

$$v_g = +\frac{g_0}{f}\frac{\partial Z}{\partial x} = +\frac{1}{f}\frac{\partial \Phi}{\partial x} = +\frac{1}{\rho f}\frac{\partial p}{\partial x}$$

Gradient Wind, Supergeostrophic and Subgeostrophic flow: *Supergeostrophic flow* describes wind speeds greater than the expected geostrophic wind speed, whereas *Subgeostrophic* flow describes wind speeds less than the expected geostrophic wind speed. According to the section on the *Gradient Wind* (*ASI*-283), which considers the effect of the centrifugal force, *subgeostrophic* flow arises when flow occurs cyclonically around a Low or around a sharp trough, in which case the centrifugal force reinforces the Coriolis force. As a result, geostrophic balance can be achieved with a smaller wind speed. In contrast, *supergeostrophic* flow arises when flow occurs anti-cyclonically around a High or sharp ridge, in which case the centrifugal force opposes the Coriolis force so that a geostrophic balance can be achieved only with a higher than normal wind speed. This is probably a complex topic and I have not taken the time to explore it in depth.

Thermal Wind: I mention this topic for completeness, though we did not study it. The textbook derives the *thermal wind equation*, which expresses the vertical shear of the geostrophic wind V_g in relation to ∇T (*ASI*-283). The vertical shear can be expressed by:

$$(\mathbf{V_g})_2 - (\mathbf{V_g})_1 = \frac{1}{f}\mathbf{k} \times \nabla(\mathbf{\Phi_2} - \mathbf{\Phi_1})$$

or

[210] http://www-paoc.mit.edu/12307/mass%20wind/geostrophic%20balance/geostrophic_balance.pdf

$$\left(\mathbf{V}_g\right)_2 - \left(\mathbf{V}_g\right)_1 = \frac{g_0}{f}\mathbf{k} \times \nabla(\mathbf{Z_2} - \mathbf{Z_1})$$

where the LHT represents geostrophic wind shear (difference in horizontal velocities) between two different pressure surfaces. and
the RHT incorporates the Coriolis effect and the gradient of the geopotential at the two levels…

The latter equation, including in expanded component form, states that "the vertically averaged vertical shear of the geostrophic wind within the layer between any two pressure surfaces is related to the horizontal gradient of thickness of the layer in the same manner in which geostrophic wind is related to geopotential height… In the northern hemisphere the thermal wind (namely the vertical shear of the geostrophic wind) 'blows' parallel to the thickness contours, leaving low thickness to the left…" (*ASI*-283-284) It is further shown that:

$$\left(\mathbf{V}_g\right)_2 - \left(\mathbf{V}_g\right)_1 = \left(\frac{R}{f}\ln\frac{p_1}{p_2}\right)\mathbf{k} \times \nabla(\overline{\mathbf{T}})$$

where $\overline{\mathbf{T}}$ is the vertically averaged temperature within the layer. Thus this equation expresses the linear relationship between the vertical shear of the geostrophic wind and the horizontal temperature gradient. I'll need to study this topic more to understand it fully.

Topics for Later Study: The Dynamics chapter 7 also discusses Vorticity and other advanced topics.

Effect of Friction Near the Surface on Wind in the Atmospheric Boundary Layer (ABL)

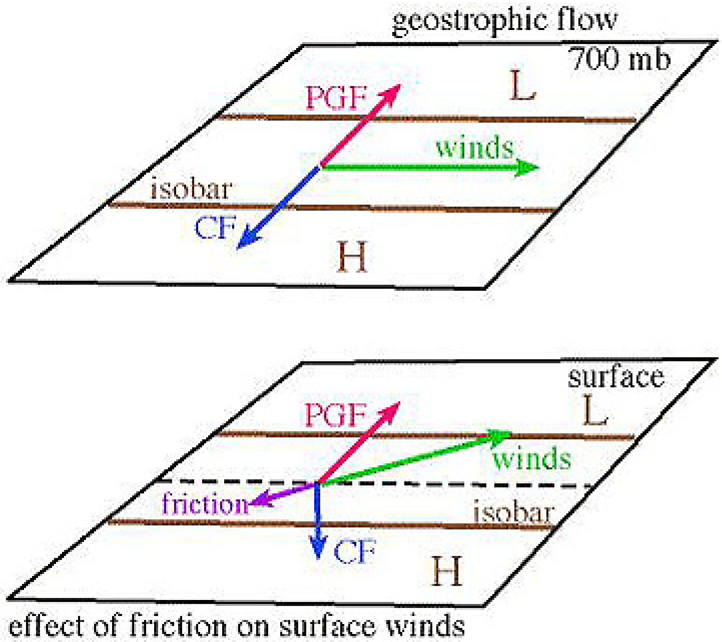
The Atmospheric Boundary Layer is the topic of *ASI* chapter 9 (which we did not read). The boundary layer is the lowest layer in the atmosphere, occupying the bottom 10–20% of the troposphere, and where friction with the ground and related turbulence is important. It is defined by the presence of significant frictional interaction with the wind. As a result, it is variable in thickness but typically is ~1 to 2 km thick, though it can range in thickness from only tens of meters to 4 km or more (*ASI*-375).

In this layer, the friction term $\vec{F}$ cannot be ignored. The frictional force is stronger over land than over ocean, due to greater aerodynamic roughness[211] of surface terrain and greater turbulence (factors which for instance can affect crop erodibility). Because it is a retarding force (as our simplified model here specifies), it is oriented directly antiparallel to the final wind vector. The resultant of $\vec{C} + \vec{F} \equiv \vec{R}$ again balances the pressure gradient force (PGF) $\vec{P}$, the latter being of course oriented along the pressure gradient, so that as before

$$0 = \frac{d\vec{V}}{dt} = \vec{P} + \vec{C} + \vec{F}$$

This frictional effect is depicted as follows. Note that when friction is included, the resultant vector sum of friction and Coriolis forces (CF) balance the PGF, with net force being zero and therefore final wind not accelerating:

[211] http://amsglossary.allenpress.com/glossary/search?id=aerodynamic-roughness-length1



Top diagram depicts geostrophic flow (green) at 700 mb level (about 3000 m), parallel to isobars and with no friction.
Bottom diagram depicts non-geostrophic surface flow resulting from adding friction, showing deviation of flow (green) toward the surface Low
(Image from NASA tutorial on remote sensing)[212]

When circulating about a Low pressure area (cyclone), the resulting ABL wind blows nearly parallel to the isobar or isohypse contour lines but is now deviated at an acute angle slightly across the contours toward the lower pressure. (Thus it is no longer geostrophic.) Similarly, when circulating about a relative High, the resulting ABL wind now is deviated at an acute angle slightly across the contour lines away from the higher pressure (thus again toward the lower pressure). This *cross-isobar flow toward lower pressure* is described and modeled as the *Ekman drift* or *Ekman spiral* (*ASI*-282 and *here*[213]). The term *spiral* reflects the fact that the intensity of this friction effect tapers off with height above the boundary surface causing the friction, and the flow direction with respect to the contour lines rotates in a spiral as one moves away from the surface boundary,[214] asymptotically approaching geostrophic flow direction at sufficient height.

The friction-affected surface wind vector $\mathbf{V_s}$ (*s* indicates 'surface') is deviated at an angle ψ toward the low with respect to the direction of the geostrophic (frictionless) flow vector $\mathbf{V_g}$. This angle is maximal at the surface though never more than 45°. The scalar wind speed is given by

$$V_s = \frac{1}{f}|P|\cos\psi$$

The formula for calculating horizontal wind components is complex,[215] but in general the scalar wind speed $V_s = |C|/f$ is smaller than $V_g = |P|/f$ (thus it is "*subgeostrophic*"), and the stronger the frictional drag, the greater the deviation angle ψ toward the Low.

Oceanic Current Ekman Drift: Interestingly, the same frictional boundary surface shear force acting on the wind also exerts a forward pull on the ocean surface water roughly in the direction of V_s, giving rise to wind-

[212] Vector diagrams of P, C, and F forces, and final wind:
•http://rst.gsfc.nasa.gov/Sect14/Sect14_1c.html
Also, for those with course password access, better images are available at:
•http://www.atmos.washington.edu/~ovens/loops/viewer.cgi?/home/disk/user_www/houze/301/protected/LectureGraphics/SurfaceWind+6 and
•http://www.atmos.washington.edu/~ovens/loops/viewer.cgi?/home/disk/user_www/houze/301/protected/LectureGraphics/SurfaceWind-SouthernHemisphere+6
[213] http://amsglossary.allenpress.com/glossary/search?id=ekman-spiral1
[214] http://en.wikipedia.org/wiki/Ekman_spiral
[215] http://amsglossary.allenpress.com/glossary/search?id=ekman-spiral1

driven currents. “Although the large scale surface [ocean water] currents…tend to be in geostrophic balance and oriented roughly parallel to the mean surface winds, the Ekman Drift [aka Ekman transport], which is directed normal [perpendicular] to the surface winds, has a pronounced effect on horizontal transport of near-surface water and sea-ice…” (*ASI*-282) Another source states, “a body of water can be thought as a set of layers. The top layer is driven forward by the wind [though apparently at an angle of 45 degrees], and each layer below is moved by friction. Each succeeding layer moves at a slower speed, and at an angle to the layer immediately above it ([more] to the right in the Northern Hemisphere, [more] to the left in the Southern Hemisphere) until friction becomes negligible. Though the direction of movement is different for each layer in the stack, the theoretical average direction of flow of water in the Northern Hemisphere is 90° to the right of the prevailing surface wind.”[216] Another source states, “the classical Ekman theory is not able to describe properly the observed deflection of the currents to the right [in the NH] of the wind direction and their decay with depth. This deflection is 10° near the sea surface and increases to approximately 50° in 25-m depth.”[217] Thus, there appear to be contradictory statements among these sources—this is a very confusing topic that requires much more study by me.

Convergence and Divergence: Differential heating and other factors lead to surface lows and highs. Surface lows (cyclones) are associated with converging wind at the surface, rising initially warmer air (often causing precipitation), and divergence aloft. Similarly, surface highs (anticyclones) tend to be associated with converging cold air aloft, which descends in spiraling motions to reach the surface as a pressure high, and surface air divergence. The diverging air aloft over a surface Low migrates to the upper region over a nearby surface high, where the flow is converging.[218]

Relationship Between Horizontal Wind and Temperature Changes

Using the FLT formula $dQ = C_p dT - \alpha dp$, and defining $\dot{H} \equiv \frac{dq}{dt}$, the FLT can be expressed in a form used to predict the time rate of change of T of a parcel of air. The total derivative (Lagrangian) of T with respect to t for a moving parcel is:

$$\frac{dT}{dt} = \frac{\dot{H}}{c_p} + \frac{\alpha}{c_p}\omega$$

where $\omega \equiv \frac{dp}{dt}$ (Vertical velocity in pressure coordinates)

The local derivative (Eulerian) at a fixed point is:

$$\left(\frac{\partial T}{\partial t}\right)_{x,y,p} = \frac{dT}{dt} - u\frac{\partial T}{\partial x} - v\frac{\partial T}{\partial y} - \omega\frac{\partial T}{\partial p}$$

The local temperature at a fixed point (x,y,p) can be further expressed using the FLT in a form useful for forecasting:

$$\left(\frac{\partial T}{\partial t}\right)_{x,y,p} = \left(-u\frac{\partial T}{\partial x} - v\frac{\partial T}{\partial y}\right) + \omega\left(\frac{\alpha}{c_p} - \frac{\partial T}{\partial p}\right) + \frac{\dot{H}}{c_p}$$

The 3 terms on the RHS of this equation are here summarized:

(1st term) *Horizontal Advection:* the effect of horizontal wind bringing in air of different temperatures.

(2nd term) The effect of vertical air motion, negative for upward motion indicating cooling, where
Dry static Stability is the quantity in parentheses,
α ≡ Specific Volume ≡ volume per unit mass at a specified pressure P and temp T
$\omega \equiv \frac{dp}{dt}$

(3rd term) *Direct heating* rate (by radiation from the Sun, radiative cooling, etc.)

These are further discussed as follows:

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216 http://www.eeb.ucla.edu/test/faculty/nezlin/PhysicalOceanography.htm
217 http://www.agu.org/pubs/crossref/1993/93JC01898.shtml
218 http://rst.gsfc.nasa.gov/Sect14/Sect14_1c.html

Horizontal Advection:

To express the bulk movement of air in the horizontal plane, we have this term

$$\left(-u\frac{\partial T}{\partial x} - v\frac{\partial T}{\partial y}\right) = -\left|\vec{V}\right|\frac{\partial T}{\partial s} \simeq -\left|\vec{V}\right|\frac{\Delta T}{\Delta s}$$

where Δs and ∂s are increments along the natural distance coordinate s (parallel to the streamlines).

A *cold front* (a front in which cold air behind the front is advancing toward receding warm air) exhibits "cold advection, for which

$$-\left|\vec{V}\right|\frac{\Delta T}{\Delta s} < 0$$

It is thus blowing from lower to higher temperatures, cooling off the region into which it moves.

A *warm front* (which retreats from warm air toward colder air)) exhibits "warm advection", for which

$$-\left|\vec{V}\right|\frac{\Delta T}{\Delta s} > 0$$

The wind blowing in is moving from higher to lower temperature, thus it is warming up the region into which it blows.

Static Stability: The atmosphere is usually either stable S or conditionally unstable CU. The atmospheric sounding lies between the dry adiabat Γ_d, and the moist adiabat Γ_s (CU) or it lies above the moist adiabat Γ_s (S). In either case, the difference of the dry adiabatic lapse rate in p-coordinates $\left(\frac{\alpha}{c_p}\right)$ and the environmental lapse rate (i.e., the sounding's lapse rate) in p-coordinates $\left(\frac{\partial T}{\partial p}\right)$, satisfies

$$\left(\frac{\alpha}{c_p} - \frac{\partial T}{\partial p}\right) > 0$$

The term $\omega \equiv \frac{dp}{dt}$ can be negative or positive, and therefore determines the overall effect of the vertical air motion:

ω < 0 for upward motion	implies local cooling
ω > 0 for downward motion	implies local warming.

Relationship Between Horizontal Wind and Vertical Air Motion: Continuity Equations

This derives from the conservation of mass $\frac{d(Mass)}{dt}$=0. The derivation considers a 3-D element with horizontal x-y plane area A, extending vertically from Z to Z+ΔZ (or alternatively from pressure surfaces p to p+Δp). Recall that $\omega \equiv \frac{dp}{dt}$. As Δp→0, we have the *Continuity Equation*:

$$\frac{\partial \omega}{\partial p} = -\frac{1}{A}\frac{dA}{dt}$$

This may be interpreted as follows:

If the horizontal area of a volume of air at the surface is shrinking (as with convergence), then $\left(-\frac{1}{A}\frac{dA}{dt}\right) > 0$, and the top must be rising, so $\frac{\partial \omega}{\partial p} > 0$. This explains why we have upward motion over a surface low. (This is not entirely clear to me.) If the horizontal area of a volume of air at the surface is expanding (as with divergence), then $\left(-\frac{1}{A}\frac{dA}{dt}\right) < 0$, and the top must be falling, so $\frac{\partial \omega}{\partial p} < 0$

A more useful form for calculations of the continuity equation is:

$$\frac{\partial \omega}{\partial p} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

or in greatest generality

$$\frac{\partial\omega}{\partial p} + \nabla \cdot \vec{V} = 0$$

where $\nabla \cdot \vec{V}$ is the divergence of $\vec{V}$ (*ASI*-295).

Weather Prediction (Unit 6)

Weather Prediction from Local Signs: This has been the subject of human experience and popular wisdom for millennia, at least back to Theophrastus. A valid example is: A halo around the sun or moon (ice crystals aloft in cirrostratus) means that rain is on the way. *MT8*-349 lists a table of observations that can be used to predict near-term weather.

Another familiar example: "Red Sky In Morning, Sailors Warning; Red Sky At Night, Sailors Delight". "This saying only applies to mid-latitude locations (winds are easterly in the tropics / in the high latitudes the sun rises and sets at a large deviation from the east-west trajectory). Storm systems in the middle latitudes generally move west to east. A red sky in the morning implies the rising sun in the east is shining on clouds to the west and conditions are clear to the east. Clouds moving from the west (especially upper level cirrus) indicate an approaching storm system. A red sky at night implies the sun (setting in the west) is shining on clouds to the east and conditions are clear to the west (because the sun can be seen setting). If you can see the sunset, the sky will be redder. Clouds to the east indicate an exiting storm system in the middle latitudes. Upper level clouds (especially cirrus) are noted for giving the sky a reddish hue during dawn or dusk. As a mid-latitude cyclone approaches, it is the upper level cirrus that are seen first, followed by lower clouds. The approach of upper level cirrus from the west often indicates an approaching storm system. The sky will not be as red at night if a storm system is approaching because the sun is setting behind the clouds approaching from the west. A red sky at night implies 'the storm system moving through has ended!'; The clouds have broken and the sun is shining on and reddening the exiting clouds. The sun will continue to shine on clouds for a period of time after the sun has dipped below the horizon (especially cirrus). Keep in mind this saying was developed before satellite, radar and modern meteorological knowledge. Much of the knowledge of an approaching storm system back then was cloud and wind patterns. Of course, this saying (weather folklore) has some profound problems... (omitted).
SUMMARY: If you can see the sunrise but the west part of the sky is dark: look out for approaching bad weather. If you can see the sunset: the weather conditions will be nice."[219]

Cloud Watching: One can infer warm advection aloft (increasing air stability) and cold advection aloft (increasing air instability, towering cumulus, and showers) by watching the clouds. In the NH, winds that *veer* (change direction clockwise) with height indicate warm advection, whereas winds that *back* (change direction counterclockwise) with height indicate cold advection. (*MT8*-351)

Surface Charts: These are useful for short-range weather prediction, especially if we have maps from several days previously as well. We would use the following rules of thumb:
(1) "Mid-latitude cyclonic storms and fronts tend to move in the same direction and at approximately the same speed as they did during the previous 6 hours."
(2) "Low pressure areas tend to move in a direction that parallels the isobars in the warm air ahead of the cold front."
(3) "Lows tend to move toward the region of greatest pressure drop, while highs tend to move toward the region of greatest rise."
(4) Surface pressure systems tend to move in the same direction as the wind at 5500 m..., the 500 mb level. The speed at which surface systems move is about half the speed of the winds at this level." (Quoted from *MT8*-352, see full discussion there.) Use of *isoallobars* (contours depicting equal amounts of 3-hour pressure rise or fall, thus showing pressure tendencies) help to visualize where pressures are changing. The region of 3greatest fall in pressure helps to infer the direction in which the current low center will move. (*MT8*-353, with many more examples to follow)

Numerical Prediction: Modern weather prediction begins with *Numerical Weather prediction*. "Numerical weather prediction uses current weather conditions as input into mathematical models of the atmosphere to predict the weather. Although the first efforts to accomplish this were done in the 1920s, it wasn't until the

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[219] http://www.theweatherprediction.com/habyhints/139/

advent of the computer and computer simulation that it was feasible to do in real-time. Manipulating the huge datasets and performing the complex calculations necessary to do this on a resolution fine enough to make the results useful requires the use of some of the most powerful supercomputers in the world. A number of forecast models, both global and regional in scale, are run to help create forecasts for nations worldwide. Use of model ensemble forecasts helps to define the forecast uncertainty and extend weather forecasting farther into the future than would otherwise be possible."[220]

Numerical Weather prediction typically assumes independent variables or coordinates (x,y.p,t), where t is time. Note that pressure here is used as the vertical coordinate, one of the 4 independent variables (whereas geopotential height Z is considered a dependent variable).

Within this coordinate system, the goal of weather prediction is to predict the course of 6 dependent variables (T, ρ, Z, u, v, ω), starting with an initial state of these dependent variables and determining how they evolve. This is typically done iteratively with starting conditions at times t, then using the predicated state at t+Δt as the starting condition for the next iteration, which predicts the state at t+2Δt, etc. These are done in a grid which defines a model domain. The 4-D data points (x,y.p,t) at which (T,ρ,Z,u,v,ω) are evaluated are at 3-D spatial grid points (x,y.p), which have volume Δx•Δy•Δp.

To predict the future evolution of the dependent variables, we need 6 equations in these 6 unknowns. Three of these equations are the "*prognostic equations*"—i.e., they contain time derivatives and are used to predict directly the future state of dependent variables T, u, and v at a fixed point (x,y.p,t). They are given by the *Prognostic Equation for Temperature* (as before):

$$\left(\frac{\partial T}{\partial t}\right)_{x,y,p,t} = \frac{\dot{H}}{c_p} + \frac{\omega}{\rho c_p} - u\frac{\partial T}{\partial x} - v\frac{\partial T}{\partial y} - \omega\frac{\partial T}{\partial p}$$

and the *Prognostic Equations for u and v* (given previously and on *ASI*-295):

$$\left(\frac{d\vec{V}}{dt}\right)_{x,y,p,t} = -g_0 \nabla p_Z - f\,\vec{k} \times \vec{V} - a\vec{V}$$

or, broken into u and v components:

$$\left(\frac{\partial u}{\partial t}\right)_{x,y,p,t} = -g_0\frac{\partial Z}{\partial x} + fv - au - u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - \omega\frac{\partial u}{\partial p}$$

and

$$\left(\frac{\partial v}{\partial t}\right)_{x,y,p,t} = -g_0\frac{\partial Z}{\partial y} - fu - av - u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - \omega\frac{\partial v}{\partial p}$$

To calculate the other 3 variables, we use the "diagnostic equations". These do not contain time derivatives and are used in each iteration after the prognostic equations have predicted the state of T, u, and v. They consist of the *Equation of State*, the *Hydrostatic Equation*, and the *Continuity Equation*, respectively, and these predict the state of the dependent variables ρ, Z, and ω, again at a particular 4-D point (x, y. p, t)

$$p = \rho R_d T_v$$

$$\frac{\partial Z}{\partial p} = -\frac{1}{\rho g_0}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0$$

The grid volume element dimensions determine the resolution of the model. A finer grid is potentially more accurate in its predictions, but takes more time to compute. Moreover, the precision of the input data may or may not justify the use of a particularly fine resolution grid. According to RAH, it is standard practice to use a grid dimension of 50 km for global scale predictions, and somewhat finer resolution for regional models.

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[220] http://en.wikipedia.org/wiki/Numerical_weather_prediction

For example, this WRF-GFS model[221] uses 36-km resolution, the Canadian Global GEM model[222] has 0.6x0.6 degree or 30 km resolution, and the Canadian regional[223] GEM has 15 km resolution. At the UW, regional models with resolutions as fine as 4 km are presented[224], and an experimental Pacific Northwest high-resolution terrain resolution of 1 1/3 km may be seen *here*.[225]

RAH presents examples of simple numerical weather prediction (not included here).

Despite the availability of substantial detailed atmospheric data (albeit never enough), good formulas for predicting its future evolution, and massive supercomputer capability, the success of weather forecasting is limited past a few days and very limited or essentially non-existent past 1 and certainly past 2 weeks.[226] Long-range forecasts (monthly and seasonal forecasts for one to up to 13 months, including "90-day outlooks") can only predict broad climate trends.[227] To some extent this is due to:

(1) coarseness of the input data grid or incompleteness of or error in input data,
(2) a lack of understanding, observation, or modeling of finer small scale processes, and
(3) the imperfectly understood effects of friction and heating.

However, a major contributor to the uncertainty in forecasting beyond the short range is the presence of chaotic behavior (as defined mathematically). This type of behavior was first accurately described by Edward Lorenz,[228] who reported such behavior in his classic 1963 paper "Deterministic nonperiodic flow",[229] including the depiction of the *Lorenz strange attractor*,[230] which is defined in a 3 dimensional space. The field of chaos theory and its impact on weather prediction and other complex systems is well presented in the 1987 James Gleick text *Chaos* previously mentioned. A key feature of chaotic regimes is their *extreme sensitivity to initial conditions*. Minimal observational errors in determining initial conditions, or slight perturbations, lead to dramatically different outcomes after a few days. I won't further discuss mathematical chaos theory now, though I have summarized the Gleick book *here*[231] and I especially recommend the more substantial book on chaos theory by Peitgen, et al.[232] The *variability* and assessment of potential *reliability* of various weather model *medium range forecasts* (having a forecast period variably defined as from 3 to 7 or up to 15 days) is assessed using *Ensemble forecasting*,[233] summarized *here*.[234]

The public's perception and disparagement of the accuracy of weather forecasting is somewhat disappointing to RAH. The public's skepticism, it seems to me, relates in part to a lack of understanding of forecasts presented as probabilities. This seems similar to the public's sometimes disproportionate fear regarding the risks of low-level medical ionizing radiation, risks which are also presented in terms of probabilities. Many people understandably want black-and-white categorical Yes or No answers, and are not satisfied with probabilities.

Reporting of Precipitation Probability: The NWS[235] uses the following percentage probabilities and what they consider to be appropriate equivalent verbal translations to express likelihood of measurable precipitation (≥0.01 inch liquid water) under conditions of *steady precipitation* or *showery precipitation* (*MT8*-345). They begin with the term *Probability of Precipitation (PoP)*, a quantitative term from weather modeling define as, "The probability that precipitation will be reported at a certain location during a specified period of

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[221] http://www.atmos.washington.edu/~ovens/loops/wxloop.cgi?mm5d1_500t+//72/3
[222] http://www.weatheroffice.gc.ca/grib/High-resolution_GRIB_e.html
[223] http://www.weatheroffice.gc.ca/model_forecast/index_e.html
[224] http://www.atmos.washington.edu/mm5rt/rt/gfsinit.frame1.html#4km
[225] http://www.atmos.washington.edu/mm5rt/highresinit.html
[226] http://www.esrl.noaa.gov/psd/map/lim/week5.html (only partially functional when accessed 12/4/2010)
[227] Long-range predictions including 90-day outlooks:
• http://www.cpc.noaa.gov/products/forecasts/
• http://www.cpc.noaa.gov/products/predictions/90day/
[228] http://en.wikipedia.org/wiki/Edward_Norton_Lorenz
[229] Edward Norton Lorenz, Deterministic nonperiodic flow. J. Atmos. Sci., 20, 130-141, 1963
[230] http://en.wikipedia.org/wiki/Lorenz_attractor
[231] http://www.mcgoodwin.net/pages/otherbooks/jg_chaos.html
[232] Peitgen H, Jurgens H, and Saupe D. *Chaos and Fractals: New Frontiers of Science*. Springer-Verlag, 1992.
[233] http://www.esrl.noaa.gov/psd/map/images/ens/ens.html
[234] http://www.esrl.noaa.gov/psd/spotlight/12012001/
[235] http://pajk.arh.noaa.gov/info/articles/survey/poptext.htm

time.”:[236]

NWS PoP = Probability of Precipitation	Forecast English wording for “***steady precipitation***” [This is the probability of measurable precipitation at any single specified point in the forecast area during the time of the forecast, usually 12 hours. This conforms to the definition of PoP.][237]	Forecast English wording for “***showery precipitation***” [This is the probability of measurable precipitation occurring somewhere in broader but apparently unspecified parts of the forecast area during the time of the forecast]
20%	*Slight chance* of precipitation	*Widely scattered showers* [This unfortunate usage is quite counterintuitive—it does not mean a greater likelihood compared to “Scattered showers”, but rather that the distance between convective cells and showers is wider, thus greater]
30 to 50%	*Chance* of precipitation	*Scattered showers*
60 to 70%	Precipitation *likely*	*Numerous showers*
≥ 80%	Precipitation (rain or snow) *will* occur (This is sometimes narrowed down further as to time of day or to specific locale, such as the PSCZ, see below)	*Showers*

NOAA further explains, “*Probability of Precipitation* (PoP) describes the chance of precipitation occurring at any point you select in the area Mathematically, PoP is defined as follows:

PoP = C x A

where C = the confidence that precipitation will occur somewhere in the forecast area, and

A = the percent of the area that will receive measureable precipitation, if it occurs at all.

So… in the case of the forecast … [‘A 40 PERCENT CHANCE OF SHOWERS AND THUNDERSTORMS… CHANCE OF RAIN 40 PERCENT’], if the forecaster knows precipitation is sure to occur (confidence is 100%), he/she is expressing how much of the area will receive measurable rain. (PoP = "C" x "A" or "1" times ".4" which equals .4 or 40%.) But, most of the time, the forecaster is expressing a combination of degree of confidence and areal coverage. If the forecaster is only 50% sure that precipitation will occur, and expects that, if it does occur, it will produce measurable rain over about 80 percent of the area, the PoP (chance of rain) is 40%. (PoP = .5 x .8 which equals .4 or 40%.)”[238]

Radiation and Climate Change (Unit 7)

This section is based on RAH course PDF for Unit 7 and *ASI* chapter 4 entitled “Radiative Transfer” plus some enrichment from *MT8* and the IPCC reports.

The following radiation topics in *ASI* were not discussed in this course:

Scattering of Light (*ASI*-123)
Chemistry and Spectrometry of Absorption and Emission (*ASI*-127)
Radiative Transfer in Planetary Atmospheres (*ASI*-130)
Details of Atmospheric Layer Reflection and Absorption (*ASI*-133)
Vertical Profiles of Radiative Heating Rate (*ASI*-138)
Remote Temperature Sensing by Satellite, including Brightness Temperatures (*ASI*-140)
Radiation Balance at the Top of the Atmosphere (*ASI*-144)

[236] http://www.weather.gov/glossary/index.php?letter=p
[237] http://boards.straightdope.com/sdmb/showthread.php?t=299
[238] http://www.srh.noaa.gov/ffc/?n=pop

Interesting Atmospheric Light Phenomena

Light and optical atmospheric phenomena—blue skies; red/orange sunsets; white clouds; brown smog; twinkling stars; the green flash at the upper rim of the setting sun; mirages including fata morgana; halos, sundogs and sun pillars from ice crystals; rainbows; coronas and glories (from droplets); cloud iridescence (from droplets or crystals); and Heiligenschein (from dew)—are discussed in *MT8* chapter 19. (Some of these, including sun dogs and halos, are presented elsewhere in this summary.)

Rainbows

As a starting point in the discussion of light, consider this inconsequential natural phenomenon which has inspired artists and intrigued physical scientists through the ages. The observer sees the returning light of a *primary rainbow* (formed by two surface refractions and a single internal reflections in falling spherical rain drops) differently for each wavelength. The returning light returns from opposite the sun with respect to the observer at a wide range of angles but strongest at about 41–42º. The violet band is seen maximally at a lower position (about 40º above the path of the sun's rays through the observer's head and with his/her eyes at the vertex) than the red band (which is maximally seen at about 42º).

For the weaker *secondary rainbow*, (formed by two surface refractions and two internal reflections in the falling spherical rain drops), the strongest returning light is seen at about 50º. The violet band is seen at a higher position (about 54º above the path of the sun's rays through the observer and with the eyes at the vertex) than the red band (which is seen at about 50.5–52º).[239] It is possible on rare occasions to see tertiary and possibly even quaternary rainbows.

Inside bright primary rainbows may be seen "one or more predominantly green, pink and purple fringes. Their numbers and spacing can change from minute to minute. They are seen most often near the top of the bow..."[240] "In some rainbows, faint arcs just inside and near the top of the primary bow can be seen. These are called *supernumerary arcs* and were explained by Thomas Young in 1804 as arising from the interference of light along certain rays within the drop. Young's work had a profound influence on theories of the physical nature of light and his studies of the rainbow were a fundamental element of this... The interference can be constructive, in which case the rays produce a brightening, or destructive, in which case there is a reduction in brightness. This phenomenon is clearly described in Nussenzveig's article *The Theory of the Rainbow* in which he writes: 'At angles very close to the rainbow angle the two paths through the droplet differ only slightly, and so the two rays interfere constructively. As the angle increases, the two rays follow paths of substantially different lengths. When the difference equals half of the wavelength, the interference is completely destructive; at still greater angles the beams reinforce again. The result is a periodic variation in the intensity of the scattered light, a series of alternately bright and dark bands.' "[241]

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[239] Rainbow:
• http://www.phy.ntnu.edu.tw/ntnujava/index.php?topic=44 (nice interactive Java demo and source of angle estimates for secondary rainbow)
• http://en.wikipedia.org/wiki/Rainbow
• http://www.straightdope.com/columns/read/2279/what-causes-double-rainbows

[240] http://www.atoptics.co.uk/bows.htm (supernumerary rainbows)

[241] http://eo.ucar.edu/rainbows/ (theory of supernumerary rainbows)

Double rainbow
Red above blue in primary bow,
red below blue in secondary bow.
(from http://cmhas.wikispaces.com/Atmospheric_Phenomena)

Supernumerary rainbows inside primary rainbow
(from http://en.wikipedia.org/wiki/Rainbow)

Basic Properties of Light

Light is a wave-like electromagnetic radiation (*EM radiation*), having mutually perpendicular magnetic and electric fields, both of which oscillate perpendicular to the direction of propagation), and is also particle-like.

The relationship of light *wavelength* to *frequency* in vacuum is given in *ASI*-113 by

$$c^* = \lambda\tilde{\nu}$$

where c^* = speed of light in vacuum = 3 x 10^8 m s^{-1}
λ = wavelength (m are SI units, but usually expressed in μm or nm)
$\tilde{\nu}$ = frequency (Hz or s^{-1})

Note the non-standard representation of frequency chosen by *ASI*, namely $\tilde{\nu}$. The quantity ν is used in *ASI*-113 to express the *wave number*, or number of waves per unit length in the direction of propagation = 1/λ.

However, frequency is more commonly represented as ν in traditional physics sources, and wavenumber can be represented by $\tilde{\nu}$.[242] Hereafter, I will use the more conventional symbols (also used by RAH in his PDFs):

$$c^* = \lambda\nu$$

where c^* = speed of light in vacuum = 3 x 10^8 m s^{-1}
λ = wavelength (m are SI units, but usually expressed in μm or nm)
ν = frequency (Hz or s^{-1})

$$\tilde{\nu} = 1/\lambda$$

Photons are the particles or wave packets that make up bulk light. The energy of one photon depends solely on the frequency:

$$E = h\,\nu$$

where E = energy (Joules)
ν = frequency (Hz or s^{-1})
h = Planck constant (or Planck's constant) = 6.626 x 10^{-34} J s

Photons carry *momentum* with magnitude $|\vec{p}| = h/\lambda$ and hence exert pressure (expressed in N m^{-2} or Pa).

242 http://en.wikipedia.org/wiki/Wavenumber

Division of the EM Spectrum

With respect to atmospheric science, it is useful to divide the electromagnetic spectrum arising as solar and terrestrial radiation into:
(1) *longwave*: λ > 4 µm (mostly of terrestrial origin, includes infrared IR and microwave), and
(2) *shortwave*: λ < 4 µm (mostly of solar origin, includes near IR, visible light, UV, and x-rays. This is not the same as traditional radio shortwave (about 10 - 120 m.)

Miscellaneous Qualitative Aspects of Irradiance on Earth

Some rather obvious points of interest: On the day of the summer solstice in the NH, the relative rate of radiant heating at the Earth's surface is greater at the Tropic of Cancer than at the Equator or at any other latitude. (*MT8*-58). Hills that face south in the NH get more sunshine in winter than north facing surfaces and are warmer. (*MT8*-62). Black asphalt surfaces absorb more sunlight and heat up more than lighter colored surfaces. At night, clear air and calm windless conditions lead to greater radiational cooling of a surface exposed to the sky, and the air cooled over this surface descends to the lowest regional point (a valley floor, etc.), creating a local inversion with warmer uncooled air higher up (*MT8*-67). The radiational cooling occurring on clear nights can also lead to radiation fog developing over the cooled ground surface (MT8-*111*). Thermometers should be shielded from sunlight in order to measure the actual air temperature.

Division of EM Spectrum: With respect to atmospheric science, it is useful to divide the electromagnetic spectrum arising as solar and terrestrial radiation into:
(1) *longwave*: λ > 4 µm (mostly of terrestrial origin, includes infrared IR and microwave), and
(2) *shortwave*: λ < 4 µm (mostly of solar origin, includes near IR, visible light, UV, and x-rays. This is not the same as traditional radio shortwave (about 10 - 120 m.)

Radiation Quantitation (Radiometry)

There is considerable confusion in this subject's terminology, with some variations found when moving among various disciplines. In order to keep them straight, it is helpful to examine the specified units for each of these definitions. For most of these quantities, there is an equivalent definition utilizing wavenumber rather than wavelength, and for these definitions, the simpler *ASI* symbol used for wavenumber, namely ν, might be preferred rather than the more conventional $\tilde{\nu}$. There are also analogous definitions based on frequency. For brevity, I will only list the wavelength equations, but the alternatives with wavenumber or frequency can be readily derived or are available at the sources cited. For purity of SI units, one would represent wavelengths in meters, but I have followed the more commonly employed convention of showing their units as micrometers (µm, aka microns). Wavenumbers may be expressed in μm^{-1}, and frequency in Hertz (Hz). Some of chapter 4 of *ASI* is summarized in this webpage,[243] and an excellent and highly detailed summary of radiometry from an astronomer's point of view is given by Zombeck.[244]

When the phrase *per unit solid angle*, or *per unit area*, etc. is used, the intention of *per unit* terminology is always to express a limit of a ratio as increments of solid angle or area, etc., go to zero, thus to express a derivative. For example,[245] "[Radiant] Intensity is flux 'per unit solid angle', expressed in watts per steradian. Again a steradian is a very large angle. What is actually meant is the following. If δΦ is the [radiant] flux radiated into an elemental solid angle δω (which, in spherical coordinates, is sin θ δθ δφ) then the average [radiant] intensity over the solid angle δω is δΦ/δω. The [radiant] intensity in a particular direction (θ ,φ) is"

$$I(\omega) = I(\theta, \varphi) = \lim_{\delta\omega \to 0} \frac{\delta\Phi}{\delta\omega} = \frac{d\Phi}{d\omega}$$

Solid Angle and Steradians

A solid angle Ω is measured in steradians (sr), a dimensionless SI derived unit (m^2/m^2). A solid angle Ω is, "the two-dimensional angle in three-dimensional space that an object subtends at a point. It is a measure of how large that object appears to an observer looking from that point… An object's solid angle is equal to the

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[243] http://www.geog.ucsb.edu/~joel/g266_s10/lecture_notes/chapt04/oh10_4_1/oh10_4_1.html
[244] Zombeck PDF: http://www.astrohandbook.com/ch14/radiation_defs.pdf
(an online supplement to Martin V. Zombeck, *Handbook of Space Astronomy and Astrophysics, 3rd Edition*, 2007)
[245] ibid., p. 3

[curving] area of the segment of [a] unit sphere (centered at the vertex of the angle) restricted by the object… A solid angle equals the area of a segment of unit sphere in the same way a planar angle equals the length of an arc of unit circle."[246] A steradian is defined[247] as the solid angle subtended at the center of a sphere of radius r by a portion of the [curving] surface of the sphere whose area, A, equals r^2. The unit sphere has area $4\pi r^2 = 4\pi$, and (like all spheres) subtends a solid angle of 4π sr. A true hemisphere subtends a solid angle on a unit sphere (or any other sphere) of 2π sr. (The latter fact is derived by integration of spherical coordinates at *ASI*-115.)

Lambertian Radiating Surface

A lambertian radiating surface is one whose intensity of emitted radiation varies with angle according to *Lambert's Law*:

$I(\theta)=I(0)\cos\theta$

where $I(0)$ is the intensity found at the zenith angle $\theta = 0$, thus directly overhead.

(This definition also may be extended to a plane surface with incident radiation following this relationship.) An emitting Lambertian surface has the same radiance (power per unit solid angle per unit projected source area) and appears uniformly bright over its surface and for all viewing angles—that is, they radiate isotropically. The radiance of a black body is lambertian. In contrast, the Sun is not a perfect Lambertian surface, as it has maximal brightness at the center and exhibits visible peripheral limb darkening.[248]

Radiant Energy

Symbol: Q

Definition: A total amount of radiant energy given off by a body (in all directions and at all wavelengths and over a particular amount of time).[249]

Units: J

Radiant Flux

Symbol: E; E_S for the Sun in *ASI-116*, but the symbols Φ and P are found in other sources[250]

Synonyms: Radiant Power, Total Radiant Flux

Definition: The total amount of radiant energy given off per unit time and in all directions by a body, such as the Sun. thus dQ/dt. When computed as the amount of energy passing through a spherical surface surrounding a uniformly radiating source such as the Sun, the value is independent of radius, and is the same for the sphere defining the Sun's surface and the sphere about the Sun at the distance to Earth. Another definition: "The total power emitted, received, or passing in the form of electromagnetic radiation."[251]

Units: $W = J\ s^{-1}$

Comments: Examples include the radiant flux emitted by a point or stellar source. This usually refers to total EM radiation including non-visible EM. For the Sun, this is essentially equivalent to *bolometric Luminosity* (total EM radiation power at all wavelengths, but excluding neutrino radiation), a variable quantity but currently[252] given as 3.839×10^{26} W. See also *Flux Density* below regarding a plane surface.

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[246] http://en.wikipedia.org/wiki/Solid_angle
[247] http://en.wikipedia.org/wiki/Steradian
[248] Lambertian Surface:
• http://www.astrohandbook.com/ch14/radiation_defs.pdf , p. 12
• http://en.wikipedia.org/wiki/Lambert%27s_cosine_law
[249] http://en.wikipedia.org/wiki/Radiant_energy
[250] Symbols for Radiant Flux:
• http://en.wikipedia.org/wiki/Radiant_flux
• http://hyperphysics.phy-astr.gsu.edu/hbase/vision/radiant.html
• http://science.jrank.org/pages/60249/phi.html
• http://www.astrohandbook.com/ch14/radiation_defs.pdf
[251] A Dictionary of Physics. Ed. John Daintith. Oxford University Press, 2009. Oxford Reference Online. Oxford University Press
[252] Sun Luminosity:
• http://en.wikipedia.org/wiki/Luminosity

Radiant Intensity

Symbol: I_e or I

Definition: The radiant flux per unit solid angle emitted by a point source[253] or other source, thus $\frac{d\Phi}{d\omega}$.

Units: W sr^{-1}

Comments: This usually refers to total EM radiation including non-visible EM. For the Sun, this is essentially equivalent to *bolometric Luminosity* (i.e., total EM radiation at all wavelengths, but excluding neutrino radiation), a quantity which varies but currently[254] is given as 3.839×10^{26} W. See also below usage regarding a plane emitting surface.

Monochromatic Intensity

Symbol: I_λ (also, I_ν or $I_{\tilde{\nu}}$ for frequency and wavenumber respectively.)

Synonyms: *Spectral intensity; monochromatic radiance, spectral radiance*

Definition: The energy (radiant flux or radiant power in W) from EM radiation in a specific direction transferred (or passing through or emitted from), per projected unit area normal to that direction, and per unit wavelength interval, and per unit solid angle. The solid angle ω is the projected solid angle in which the radiation falls, centered about the specified direction.

NIST (see Refs) defines it as "the radiant flux at a given point, direction , and wavelength per unit of projected area, solid angle, and wavelength interval", and provides the following formula of differentials (where θ is the angle made between the radiation's direction and the direction normal to dA):

$$I_\lambda = L_\lambda = \frac{d^3\Phi}{dA\cos\theta \ d\omega \ d\lambda}$$

Units: $W \cdot m^{-2}\ sr^{-1} \cdot \mu m^{-1}$

Comment: The SI definition has units of $W \cdot m^{-3}\ sr^{-1}$.

Refs: *ASO*-114, NIST[255], and *here*[256,257]

Intensity (Radiance)

Symbol: I

Definition: The integral of the Monochromatic Intensity over a finite range of wavelengths λ in the EM spectrum, defined under the same conditions as above.

$$I = \int_{\lambda_1}^{\lambda_2} I_\lambda d\lambda$$

Units: $W \cdot m^{-2}\ sr^{-1}$

Comment: This characterizes total amount of light (watts) that passes through or is emitted per unit area over a range of wavelengths, and per unit solid angle in a specified direction. Separate integrations are often carried out for longwave and shortwave EM radiation. This quantity, which may vary with solid angle, accommodates non-isotropic radiation sources.

Refs: same as I_λ

Monochromatic Flux Density

Symbol: F_λ

• http://en.wikipedia.org/wiki/Solar_luminosity
• http://www.nature.com/nature/journal/v443/n7108/abs/nature05072.html

[253] A Dictionary of Physics. Ed. John Daintith. Oxford University Press, 2009. Oxford Reference Online. Oxford University Press.

[254] Sun Luminosity:
• http://en.wikipedia.org/wiki/Luminosity
• http://en.wikipedia.org/wiki/Solar_luminosity
• http://www.nature.com/nature/journal/v443/n7108/abs/nature05072.html

[255] http://www.nist.gov/calibrations/upload/sp250-1.pdf p. 1

[256] http://en.wikipedia.org/wiki/Radiance

[257] http://www.physics.thetangentbundle.net/wiki/Optics/spectral_radiance

Synonyms: *Monochromatic irradiance, Spectral irradiance*[258]
Definition: (ASI-115) "The rate of energy transfer per unit area by radiation with a given wavelength through a plane surface with a specified orientation in three dimensional space. If the radiation impinges on a plane surface from one direction (e.g., upon the horizontal surface from above) the flux density is said to be *incident* upon that surface…" To clarify a potentially confusing point, the "direction" referred to here may be an integrated effect from incoming radiation over the entire sky. The formula for radiation incident on a horizontal surface from above is given by integration over the overlying hemispheric 2π solid angle:

$$F_\lambda = \int_{2\pi} I_\lambda \cos\theta \, d\omega$$

Note that the *zenith angle* θ in this integration varies with the direction of the solid angle differential element dω and may be regarded as centered in dω.
Units: $W \cdot m^{-2}\ \mu m^{-1}$
Comments: The SI definition has units of $W \cdot m^{-3}$. The *zenith angle* term cos θ term is needed to adjust for the fact that rays arriving from directly overhead (θ = 0) have a maximal energy transfer rate, whereas rays arriving at the same unit area at greater zenith angles are slanted and more spread out and thus "diluted" on that unit area. This variation with angle of course typifies winter sunlight conditions.

Flux Density or Irradiance

Symbol: F (F_S applies specifically for solar irradiance on a horizontal surface, see below)
Synonyms: *Irradiance* is the term preferred by RAH and MCM. This should not be called *Intensity.* (Note also the terms *Radiant exitance* or *radiant emittance*, defined below.)
Definition: (ASI-115) "The rate at which radiant energy [for a range of wavelengths] passes through a unit area on a plane surface." It is given by

$$F = \int_{\lambda_1}^{\lambda_2} \int_{2\pi} I_\lambda \cos\theta \, d\omega \, d\lambda$$

As before, the *zenith angle* θ applies to the direction of the solid angle differential element dω with respect to the normal to the specific plane surface.
Units: $W \cdot m^{-2}$
Comments: This term applies to radiation impinging on a surface, regardless how much of that radiation is reflected, absorbed, or transmitted. It is most readily computed for incident radiation when the source of the radiation is assumed to emit isotropically, equally in all directions across its face. The term might also be applied to radiation emanating from a surface, although other terms are sometimes preferred:
The term *Radiant exitance* (preferred term over the older term *radiant emittance*) may be used when the radiation is emerging from the surface.[259]

The term *Normal Flux Density* is used to refer to flux density for a plane perpendicular to the direction of the radiation.

According to *ASI*-116 and partially clarified *here*[260] (but still confusing to me): Consider radiation emitted from a flat plane surface (size of the emitting surface is not specified in the problem and is apparently irrelevant). Furthermore, it must be a Lambertian surface and the radiation is emitted isotropically, and thus with uniform intensity I in all directions. Then the flux density of that radiation is given by πI. This might for instance apply at the surface of a star. The calculation over the hemisphere (solid angle 2π) is as follows:

$$F\ (\text{flux density}) = \int_{2\pi} I \cos\theta \, d\omega = \int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi/2} I \cos\theta \sin\theta \, d\theta \, d\varphi = \pi I \ \ (W\ m^{-2})$$

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[258] http://en.wikipedia.org/wiki/Spectral_irradiance
[259] Exitance and Emittance:
• http://en.wikipedia.org/wiki/Radiant_exitance , also
• A Dictionary of Physics. Ed. John Daintith. Oxford University Press, 2009. Oxford Reference Online. Oxford University Press.
[260] Zombeck, op. cit., p. 15

Total Radiant Flux

Symbol: E or E(δA)

Definition: According to *ASI*-117, the flux of radiant energy emitted by, incident upon, or passing through a planar surface area δA per unit time, is given by:

$$E = \int_{\delta A} \int_{2\pi} \int_{\lambda_1}^{\lambda_2} I_\lambda(\phi, \theta) d\lambda \cos\theta \, d\omega \, dA$$

Units: W

Comments: This repeats the definition of radiant flux E given above, but in a form suitable for use with planar areas.

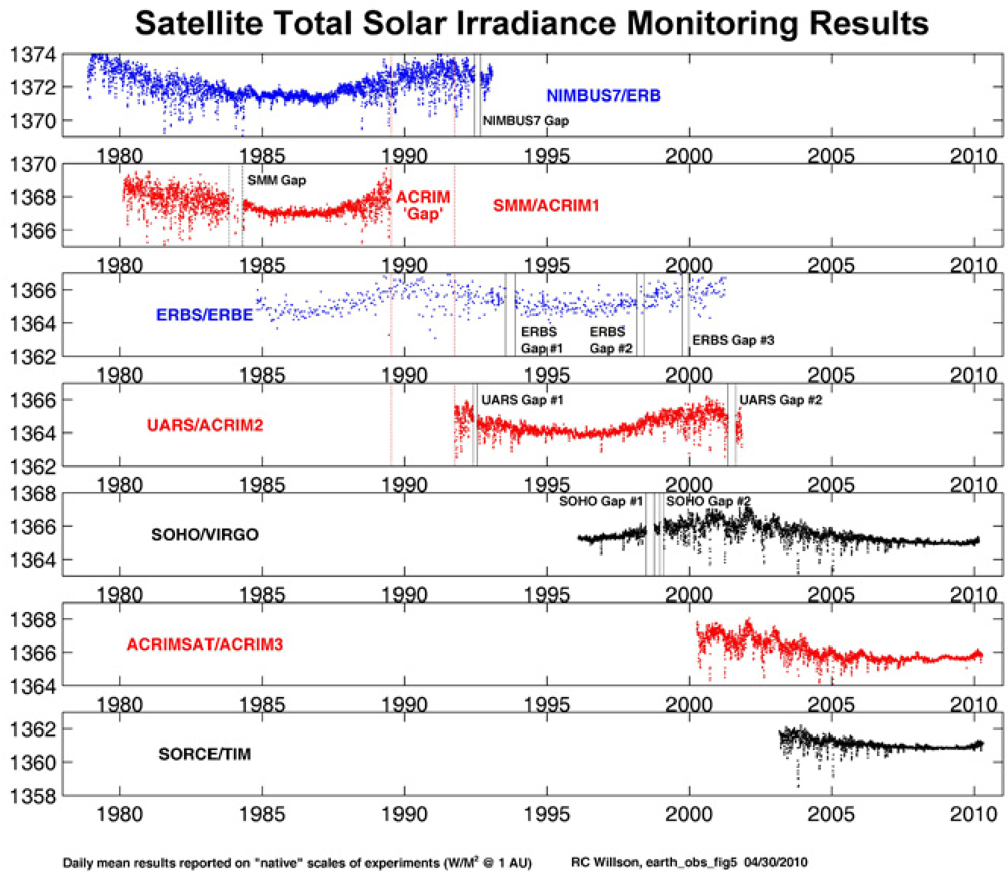
Total Solar Irradiance (TSI) of Earth; Relation to Sunspots; Local Irradiance Pattern

The *Total Solar Irradiance TSI* or F_S is defined as the solar EM at all wavelengths incident at the top of the Earth's atmosphere, before any absorption or reflectance has occurred[261] (see also above). This quantity, Total Solar Irradiance, is also but rarely termed the *Total Solar Flux Density*. The actual *Total Solar Irradiance* is a quantity that varies somewhat due to orbital variation in Earth-Sun distance and to intrinsic solar output variation during sunspot cycles, etc. The values reported for TSI are typically adjusted by the inverse square law so they are expressed at the mean Earth Sun distance (1 astronomical unit or AMU). These adjusted numbers are the TSI @ 1 AMU, also called *The Solar Constant*. Currently TSI @ 1 AMU measures about 1366 W m^{-2} (listed as 1368 W m^{-2} in *ASI*-115—a sample calculation by RAH yielded 1379 W m^{-2}). It is measured by satellite at, or adjusted to, the average distance between the Sun and Earth (1 AMU) and on a virtual plane perpendicular to the line between the center of the Sun and the measuring device.

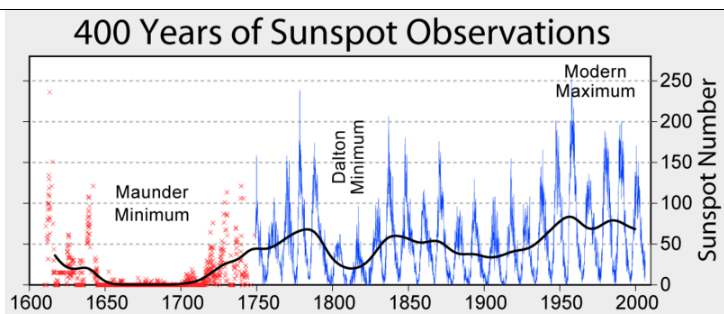
The actual direct solar irradiance at the top of the Earth's atmosphere, unadjusted for Sun-Earth orbital distance, fluctuates by about 6.9% during a year (from 1.412 kW/m^2 in early January to 1.321 kW/m^2 in early July), due to the Earth's varying distance from the Sun. Note that the Earth is actually closer to the Sun during the NH winter. Typically there is much less than one part per thousand variation from day to adjacent day.[262,263,264]

Total Solar Irradiance TSI plays an important role in the discussion of Global Warming. The following graphs depict Total Solar Irradiance TSI in W m^{-2} at 1 AMU as determined by many satellite systems—thus the values have been adjusted for orbital distance (and represent the Solar Constant):

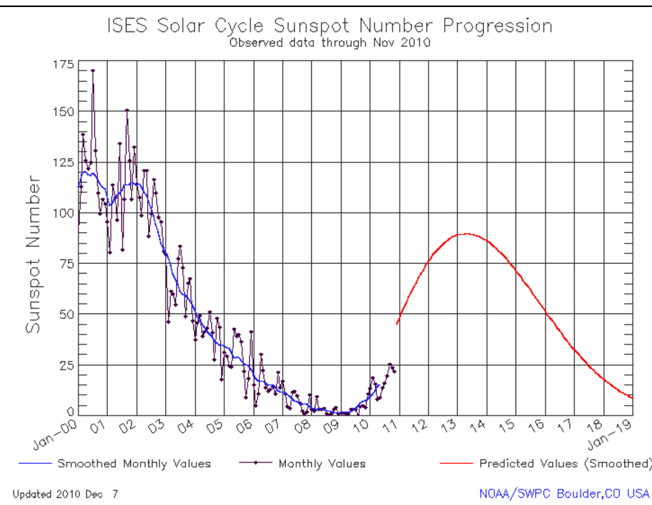
[261] http://en.wikipedia.org/wiki/Solar_constant
[262] http://en.wikipedia.org/wiki/Solar_constant
[263] http://lasp.colorado.edu/sorce/data/tsi_data.htm
[264] http://en.wikipedia.org/wiki/Sunlight



Variation in measured total solar irradiance TSI at 1 AMU, ~1978 to April 2010.[265]
This resized diagram reflects some of the uncertainties in values
for various satellites making these measurements over the years.
These values as noted have been adjusted to a mean solar distance of 1 astronomical unit.[266]



Historical variation in number of sunspots from c. 1600 – c. 2007.[267]



Sunspot numbers in 2000 – 2019 , observed 2000 – 2010, and projected by NOAA 2010 - 2019.[268]

Variation in Sunspot Numbers (which correlate with Total Solar Irradiance TSI: ↑sunspots→↑TSI)

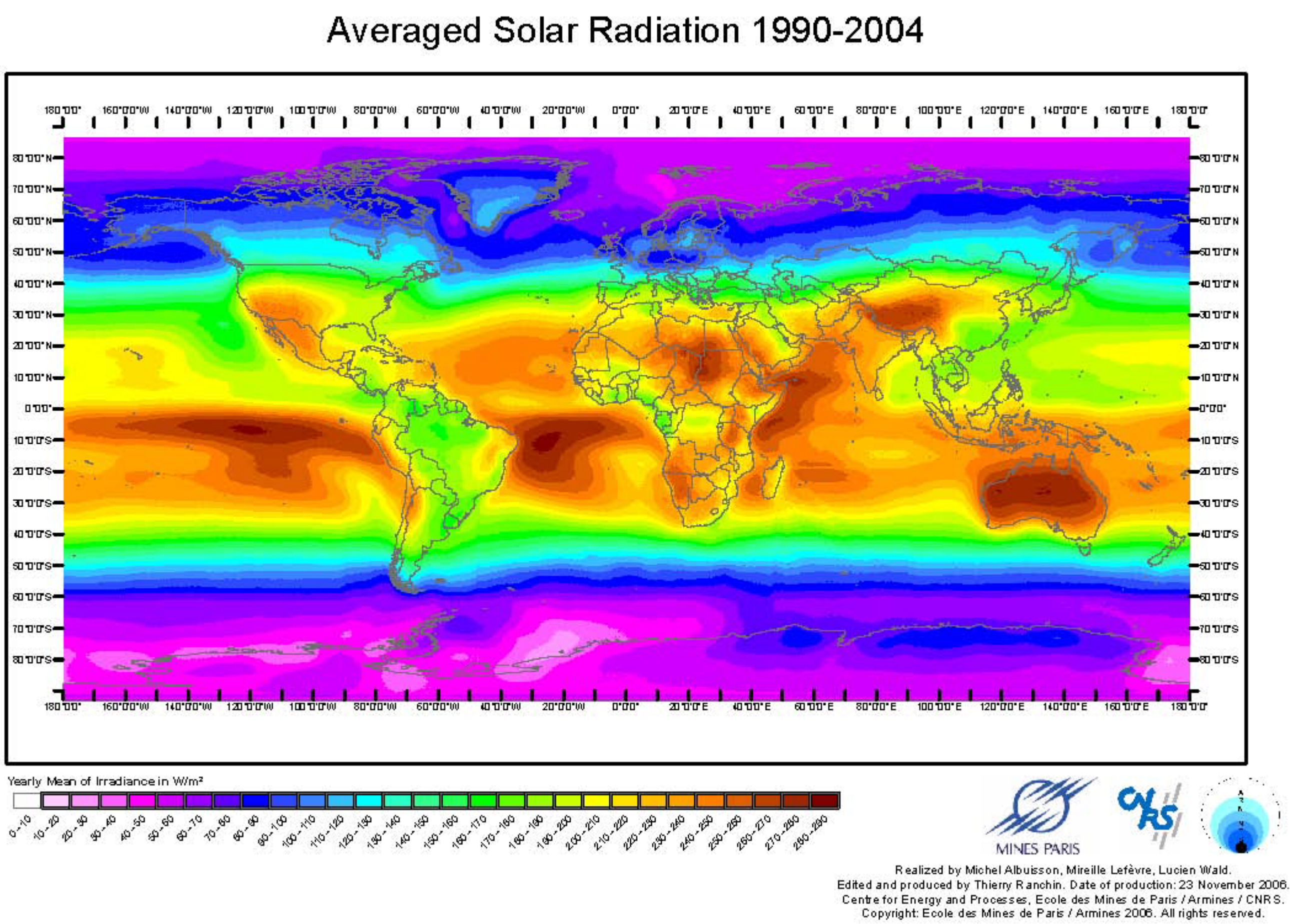
[265] http://www.global-greenhouse-warming.com/solar-irradiance-measurements.html
[266] http://acrim.com/TSI%20Monitoring.htm
[267] http://en.wikipedia.org/wiki/Sunspot
[268] http://www.swpc.noaa.gov/SolarCycle/

ASI-115 includes a derivation of approximate *solar radiation intensity (radiance)* I_S as defined above (this is not the same as TSI): Assuming the Sun's face emits EM radiation isotropically (not actually true), and using simplified measurements of the solar radius ($7x10^8$ m) and distance to the Sun ($1.5x10^{11}$ m), this simplified calculation yields a solid angle occupied by the Sun of $6.8x10^{-5}$ sr and a calculated $I_S \approx 2.0x10^7$ W m^{-2} sr^{-1}. This *solar radiation intensity (radiance)* I_S is independent of distance from the Sun (assuming no intervening absorption by dust, etc.)

The total solar energy flux (Radiant Flux) $E_S = F_S \times 4\pi r^2$ is relatively constant (i.e., ~3.839×10^{26} W), but the flux density (total solar irradiance TSI) is proportional to the arc solid angle subtended by the Sun, which varies with the inverse square of the distance.

Variation in Earth Surface Irradiance by Latitude and Longitude

The average empiric annual surface irradiance in W m^{-2} is shown in this proprietary but readable map of the world (their data source is not specified):



© Mines ParisTech/Armines 2006, from http://www.soda-is.com/eng/map/ (see also ref.[269])

Blackbody Radiation

The mathematics of this topic is abstruse, and I present the following without having fully mastered the relationships. The idealized *black body* or *blackbody* absorbs all EM radiation falling on it without reflection or transmission through it (thus it is *black*). It can be accurately approximated by a small opening on a

[269] Similar data but from the ECMWF may be found at http://www.ecmwf.int/research/era/ERA-40_Atlas/docs/section_B/charts/B05_LL_YEA.html

closed cavity. where radiation is emitted. A blackbody emits EM radiation in a characteristic *black body spectral radiance density distribution* that is dependent only on its temperature.

Planck's Distribution Formula or Law

Black body radiation satisfies the *Planck Function*,[270] which is commonly expressed as

$$I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{(e^{h\nu/kT} - 1)}$$

where $I(\nu, T)$ = emitted power per unit area of emitting surface in the normal direction, per unit solid angle, per unit frequency ν

ν = frequency
T = Temperature (K)
h = Planck constant = 6.626069×10^{-34} J s
k = Boltzmann constant = 1.38065×10^{-23} J K^{-1}
c = speed of light = 299,792,458 m s^{-1}

The function $I(\nu, T)$ peaks at for hν=2.82 kT.

Trying to explain this initially empirical law caused a crisis for classical physics, and became one of the foundational issues for the new quantum theory.

The radiance is proportional to the cosine of the viewing angle. Therefore, the spectral radiance of a black body surface viewed from an arbitrary angle θ is $I(\nu, T) = I(\nu, T) \cos\theta$.

Alternates forms of this function are also used. It is given in the following form given in *ASI*-117,

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{(e^{hc/\lambda kT} - 1)} = \frac{c_1 \lambda^{-5}}{\pi(e^{c_2/\lambda T} - 1)}$$

where $B_\lambda(T)$ = monochromatic intensity emitted by a blackbody

λ = wavelength
$c_1 = 2hc^2\pi = 3.74 \times 10^{-16}$ W m^2
(this constant includes a π to cancel out the π shown in the denominator of the RHS above)
$c_2 = hc/k = 1.45 \times 10^{-2}$ m K

$B_\lambda(T)$ has units of W m^{-2} μm^{-1} sr^{-1}

The wavelength version of Planck's Law "peaks for hc = 4.97 λkT, a factor of 1.76 shorter in wavelength (higher in frequency) than the frequency peak. As for $I(\nu, T)$, ... its peak is the more commonly used one in Wien's displacement law.[271]

Wien's Displacement Law

Wilhelm Wien was German—thus his last name should be pronounced "Veen". There is an inverse relationship between the wavelength of the peak of the emission of a blackbody and its temperature when expressed as a function of wavelength, and this is often called *Wien's displacement law.* The peak λ for a given temperature T is obtained[272] by setting to zero the first derivative of $B_\lambda(T)$ with respect to T:

$$\lambda_{max} = \frac{b}{T}$$

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270 http://en.wikipedia.org/wiki/Planck%27s_law
See also http://scienceworld.wolfram.com/physics/PlanckLaw.html
271 http://en.wikipedia.org/wiki/Planck%27s_law
272 http://physics.info/planck/

where λ_{max} = peak wavelength
T = absolute temperature K of the blackbody
b = 2.89777×10^{-3} m·K = 2898 µm·K (Wien's displacement constant)[273]

This is the relationship given in *ASI*. For example, for the Sun's photosphere where T ≈ 5780 K, this formula yields a λ_{max} of 0.501 µm (in the green part of the visible light spectrum), consistent with the predominance of solar EM radiation in the visible range and shortwave IR range). Similarly, for a *color temperature* (given by λ_{max} = 0.475), the corresponding T = 6100 K.

Considering the spectrum of monochromatic absorptivity (*ASI*-118), the Earth's atmosphere is nearly transparent to and selectively passes visible light (the Sun's predominant radiation) plus a few windows in the IR, whereas it blocks UV and most IR wavelengths (the latter including most of the Earth's intrinsic emission.

In contrast to the Sun, the Earth behaves as a black body with T = 255 K (see below), so this yields λ_{max} = 11.4 µm (longwave infrared emission).

Expressed using frequency ν, Wien's displacement law becomes

$\nu_{max} \approx 5.879 \text{ x } 10^{10}$ Hz K^{-1}) T

"Because the spectrum from Planck's law of black body radiation takes a different shape in the frequency domain from that of the wavelength domain, the frequency location of the peak emission does not correspond to the peak wavelength using the simple relationship between frequency, wavelength, and the speed of light."[274]

Stefan-Boltzmann Law

This gives the blackbody flux density (the irradiance, or more precisely the exitance integrated over all wavelengths) obtained by integrating the Planck function over all wavelengths:

$$F = \sigma T^4$$

where F = total blackbody flux density (irradiance, W·m^{-2})
σ = Stefan-Boltzmann constant = 5.6704x10^{-8} W m^{-2} K^{-4} (Ref.[275])

One may use the Solar Constant F_S (above) as an alternate means of estimating the blackbody temperature of the Sun's photosphere. This yields an *effective emission temperature* T_F = 5770 K. Like other real objects, the Sun does not exactly conform in emission spectrum to the emission of a black body, accounting for the discrepancy between the predicted T by Wien Displacement law color temperature versus the Stefan-Boltzmann predicted temperature.

To calculate the outgoing radiant flux emitted from the Earth surface as blackbody longwave radiation F_E (RAH used E_o) as a result of the radiation F_S at 1 AMU incident on the Earth's upper atmosphere, we assume the flux emitted F_E is equal to the incident flux absorbed at the surface F_i:

$$E_{out} \equiv F_E = \sigma T_E{}^4 = F_i = \frac{(1-A)F_S}{4} = 239 \text{ W m}^{-2}$$

where F_S = Solar Constant at 1 AMU (RAH used S)
A = Earth albedo = 0.3

The divisor 4 arises because the cross sectional area presented for intercepting incoming solar energy is πR_E^2, whereas the area for emission entire surface area of the Earth, namely $4\pi R_E^2$.

(Note that RAH used F_E differently, as radiant flux intercepted by earth before reflectance from albedo.)

Using the Stefan-Boltzmann equation and solving for T_E:

$$T_E = \sqrt[4]{\frac{F_E}{\sigma}} = \sqrt[4]{\frac{239}{\sigma}} = 255 \text{ K}$$

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[273] http://physics.nist.gov/cuu/Constants/codata.pdf
[274] http://en.wikipedia.org/wiki/Planck%27s_law
[275] http://physics.nist.gov/cuu/Constants/codata.pdf

This is the effective blackbody temperature of the Earth, allowing for albedo.

In general, a planet with solar constant F_S and albedo A has effective black body emission temperature T_E given by

$$T_E = \sqrt[4]{\frac{(1-A)F_S}{4\sigma}}$$

Radiation for Non-Black Bodies

Unlike idealized blackbodies, gaseous media can transmit and reflect incident radiation as well as absorb it and emit it. The ratio of the monochromatic intensity (RAH uses monochromatic irradiances) of a non-black body I_λ to that of the idealized blackbody intensity is defined as *monochromatic emissivity*:

$$\textit{monochromatic emissivity } \varepsilon_\lambda \equiv \frac{I_\lambda(\text{emitted})}{B_\lambda(T)}$$

where $B_\lambda(T)$ is the exitance for a black body for wavelength λ and temp T.

This quantity is 1.0 for a blackbody but may be < 1.0 for other bodies. (Note: The term *exitance* is currently favored over the older term *emissivity*.)

The ratio for *monochromatic absorptivity* is

$$\textit{monochromatic absorptivity } \alpha_\lambda \equiv \frac{I_\lambda(\text{absorbed})}{I_\lambda(\text{incident})}$$

This quantity is 1.0 for a blackbody and may otherwise vary with λ. This quantity can be < 1.0. The emissivity for such bodies is often assumed to be a constant (a so-called "gray body").[276]

The ratio for *monochromatic reflectance* is

$$\textit{monochromatic reflectivity } R_\lambda \equiv \frac{I_\lambda(\text{reflected})}{I_\lambda(\text{incident})}$$

The ratio for monochromatic transmittance is

$$\textit{monochromatic transmissivity } T_\lambda \equiv \frac{I_\lambda(\text{transmitted})}{I_\lambda(\text{incident})}$$

Kirchoff's Law states that for a system in radiative equilibrium,

$$\text{emissivity } \varepsilon_\lambda = \text{absorptivity } \alpha_\lambda.$$

This relationship also applies even when there is no isotropy or overall equilibrium in the atmosphere, provided there is *local thermodynamic equilibrium*, which is the case below ~60 km. Substances only emit in wavelengths at which they also absorb.

Climate Change; The Greenhouse Effect and Factors Which Can Modify It

The Intergovernmental Panel on Climate Change (IPCC) Reports

Recent data and conclusions including anthropogenic factors contributing to climate change (global warming) are discussed in *Climate Change 2007: The Physical Science Basis*, published in 2007 by the Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).[277] The *Summary for Policymakers* contained in this report is a useful condensed version.

The effects of anthropogenic greenhouse gases, including carbon dioxide, and other factors affecting long-term global temperatures are expressed in terms of *Radiative forcing* : "Radiative forcing is a measure of the influence that a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. Positive forcing tends to warm the surface while negative forcing tends to cool it. In this report, radiative forcing

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276 http://en.wikipedia.org/wiki/Emissivity

277 http://www.ipcc.ch/ipccreports/ar4-wg1.htm

values are for 2005 relative to pre-industrial conditions defined at 1750 and are expressed in watts per square metre (W m^{-2})…"[278]

This IPCC report summarizes current evidence for and impacts of actual global warming, including:
- warmer average global temperatures of the atmosphere and oceans (especially in the Arctic regions);
- increasing atmospheric water vapor;
- shrinking glaciers, ice sheets including Greenland, and snow cover including the NH;
- rising sea level;
- decreasing permafrost;
- changing precipitation and evaporation patterns;
- worsening droughts and heat waves; and
- a likely increase in "activity" of tropical cyclones at least in some area.

So far, the data has not demonstrated or is insufficient to demonstrate trends in the following:
- increase in the annual numbers of tropical cyclones overall;
- shrinkage of Antarctic sea ice; or
- changes in "the meridional overturning circulation (MOC) of the global ocean or in small-scale phenomena such as tornadoes, hail, lightning and dust-storms".[279]

Their report of course includes the projections of future global surface warming by 2100 compared to 2000, ranging from the low scenario value ("B1",[280] using clean and resource-efficient technologies) of 1.8 °C (likely range 1.1 – 2.9 °C) to the high scenario value ("A1FI"[281], using fossil-fuel intensively) of 4.0 °C (likely range 2.4 °C– 6.4 °C).

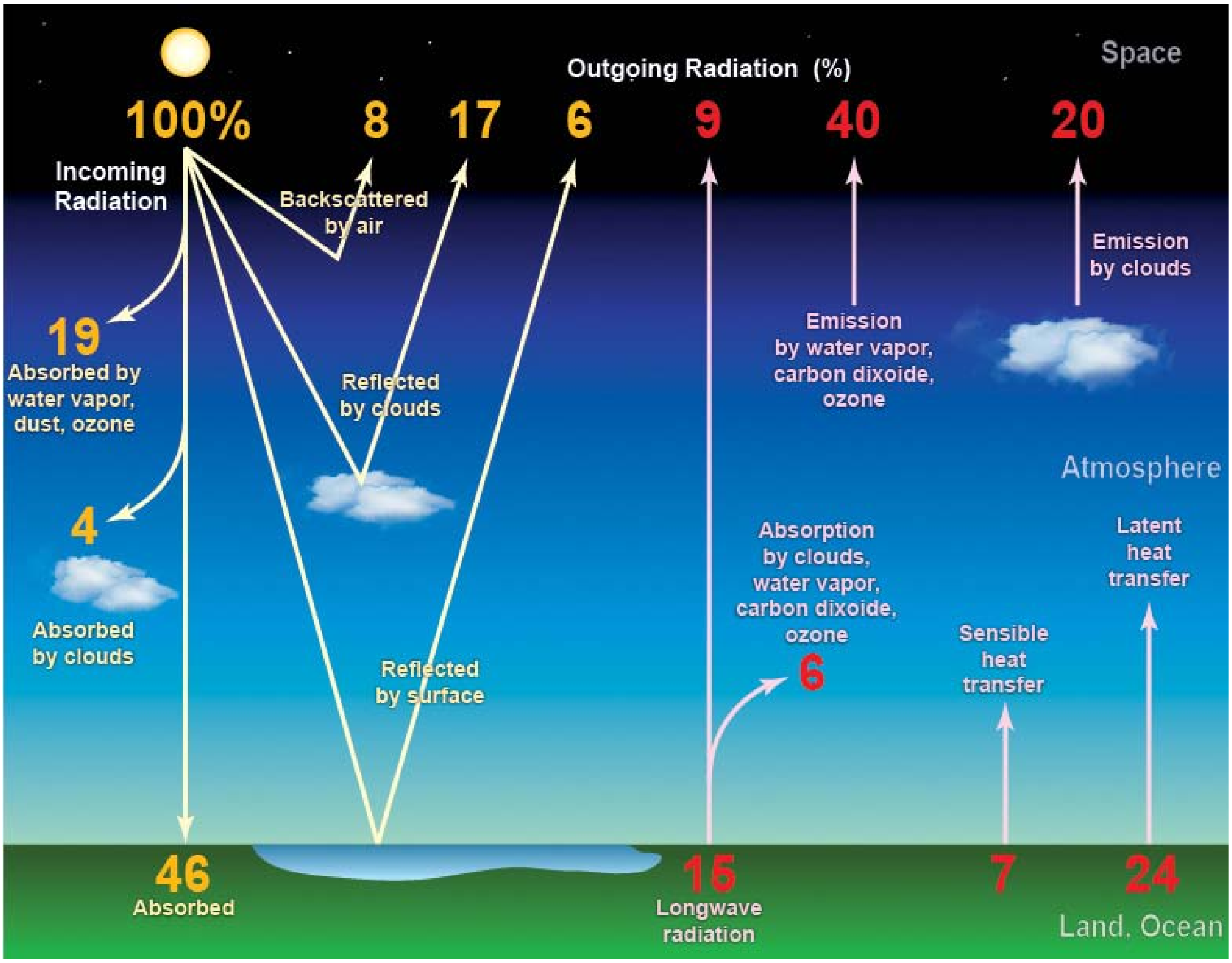
Every citizen should read this document (and I need to read it more carefully). A lot of folks, a lot of animals, and a lot of plants are being hurt, and are going to be hurt worse if we don't change our ways.

Implications of a Three-way Radiative Equilibrium Model of the Sun–Earth–Atmosphere

Our review of this topic was less thorough than in *ASI*. Unlike the Sun and Earth's surface, which radiate in a pattern similar to blackbodies, the atmosphere has absorption bands and does not resemble a blackbody. Atmospheric gases absorb terrestrial longwave IR radiation preferentially but are nearly transparent to solar shortwaves (especially visible light).

A good diagram of the actual Earth-Atmosphere Energy Balance, and how it divides up between solar and longwave terrestrial radiation, is presented as follows by the NWS:[282]

[278] ibid., p. 2
[279] ibid. p. 9
[280] B1 scenario: "The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives." ibid. p. 18
[281] A1FI Scenario: "The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil-intensive (A1FI) …"
ibid. p. 13-14
[282] http://www.srh.noaa.gov/jetstream/atmos/energy_balance.htm



NOAA/NWS Earth-Atmosphere Energy Balance Diagram
Gold color is solar radiation (mostly visible light); Red is longwave infrared radiation.
(from http://www.srh.noaa.gov/jetstream/atmos/energy_balance.htm)

In a somewhat more simplified model presented by RAH of the Sun–Earth system, we may consider the atmosphere to be a single layer acting as a graybody with:

• absorptivity α_λ that is very low (nearly transparent) for shortwave radiation (primarily of solar origin) (<2 µm, initial model sample $\alpha_{sol} = 0.1$, allowing for some absorption of UV by stratospheric ozone); and
• absorptivity α_λ that is nearly opaque to longwave IR (primarily of terrestrial origin) (>2 µm, initial model sample $\alpha_{IR} = 0.8$).

In this model, the initial Earth albedo is assumed to be 0.3, which causes reflectance of 30% of incident radiation—the reflection is apparently assumed to occur at the space-atmosphere interface (such as might occur at high white cloud tops) rather than at the Earth surface (where low albedo surfaces such as land and ocean predominate over ice, etc.)

It is also assumed that EM that is neither reflected at the space atmosphere boundary nor absorbed in the atmosphere reaches the Earth's surface where it is absorbed perfectly by the Earth acting as a blackbody. For a Total Solar Irradiance at 1 AMU = Solar Constant = Flux density at 1 AMU = 1368 W m^{-2} and albedo of 0.3, the irradiance (flux density) reaching the Earth's surface is 239 W m^{-2}. (Note: minor discrepancies have arisen in my Excel calculations compared to RAH's reported values due to differences in values of constants and F_S, etc.) At equilibrium, this incoming radiation must be reemitted by the Earth as blackbody radiation.

Most of the EM emitted as IR by the Earth is absorbed in the atmosphere by CO_2 and H_20 (thus an initial model sample value of $\alpha_{IR} = 0.8$). The atmosphere acts as a graybody, emitting predominantly IR radiation, some of which passes through an IR window and escapes to space, and some of which returns to Earth and is absorbed, adding heat to the surface.

To summarize, an irradiance (radiant flux) of TSI x 0.3 reaches the Earth The irradiance emitted by the ground surface at Earth's blackbody surface temperature T_E is given by

$$x = \sigma T_E^4$$

Ground emitted IR passes back to space in the amount of $(1-\alpha_{IR})x$.

Finally, the atmosphere gives off graybody radiation y in all directions at its equivalent blackbody temperature T_A, which radiation reaches the ground and space in equal amounts, and y can be shown to be:

$$y = \alpha_{IR}\sigma T_A^4$$

Greenhouse Effect: The Earth's surface temperature is higher when an absorbing atmosphere is present:

Example 1: For $\alpha_{sol} = 0.1$, $\alpha_{IR} = 0.8$, the calculated T_E (Earth blackbody temperature) = 286 K and T_A (Atmosphere equivalent blackbody temperature) = 245.

Example 2: For $\alpha_{sol} = 0.0$, $\alpha_{IR} = 0.0$, the calculated T_E = 255 K and T_A = 0.

The second example applies when the atmosphere is absent or has no effect.

The higher Earth surface temperature T_E when the atmosphere absorbs some of the radiation (as in Example 1) is the so-called *Greenhouse Effect*.

Impact of Increasing Greenhouse Gases: Consider what happens when we further increase α_{IR} by adding more atmospheric CO_2 or other gases that contribute to the greenhouse effect[283] and therefore to global warming (H_20, methane, nitrous oxide, etc.):

Example 3: For $\alpha_{sol} = 0.1$, $\alpha_{IR} = 0.85$, the calculated T_E = 289 K and T_A = 251.

Thus, adding more IR absorption from rising CO_2, etc. causes a rise of Earth temperature by several degrees K.

Impact of Raising Albedo: If IR absorption remains increased but albedo is also significantly increased (so that less incoming solar radiation reaches the ground), these two factors partially offset each other. For instance,

Example 4: For albedo of 0.35, $\alpha_{sol} = 0.1$, $\alpha_{IR} = 0.85$, the calculated T_E = 284 K and T_A = 246.

Thus despite the greater IR absorption by CO_2 etc., the increased atmospheric albedo has led to a lowering of Earth temperature.

The potential beneficial effect of raising albedo is the basis for several practical or far-fetched geoengineering suggestions to accomplish this. The following is quoted from *here*:[284]

• "Build white or otherwise lightly-colored roofs and roads, as advocated by Stephen Chu, the United States Secretary of Energy
• Increase the albedo of clouds through the mechanical generation of sea-salt spray into the atmosphere, which would potentially increase the concentration of clouds' condensation nuclei. This is commonly referred to as 'cloud seeding'.
• Cover expanses of desert with a highly reflective material, the top of which would be made of a white polyethylene.
• Emit increased amounts of [reflective] sulfate aerosols [as well as reflective dusts or other reflective pollutants into Earth's atmosphere]...
• Place so-called 'sunshades' in space as satellites that would reflect portions of incoming solar radiation before the energy in entered into the atmosphere."

Needless to say, I would personally prefer to see humanity fix the problem at the source, reducing CO_2 emissions and at the same time reducing other atmospheric pollutants, thereby lowering ocean acidification, and reducing other deleterious anthropogenic effects.

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[283] http://en.wikipedia.org/wiki/Greenhouse_gas

[284] Albedo:

• http://climate.org/climatelab/Albedo
• See also http://en.wikipedia.org/wiki/Solar_Radiation_Management

Nuclear Winter: Using the same model, consider what happens from a hypothetical widespread nuclear war. Aside from extensive lethal radiation and fallout, it would presumably raise atmospheric smoke and soot, extending into the stratosphere. If we drastically raise solar absorption accordingly and leave IR absorption unchanged, we get:

Example 5: For albedo of 0.3, $\alpha_{sol} = 0.9$, $\alpha_{IR} = 0.8$, the calculated T_E = 249 K and T_A = 256.

This represents a catastrophic cooling of the Earth's surface—in fact, it has become frozen (T_E is below 273 K)—thus the so-called *Nuclear Winter*.[285] Moreover, because the atmosphere is now warmer than the Earth's surface (rather than the usual lapse rate conditions found in the troposphere), the atmosphere has become very stable, convection and vertical mixing are severely reduced, and settling out of the atmospheric contaminants is retarded. This severe cooling could last for years.

Stratospheric Ozone Depletion and the "Ozone Hole" Centered Over Antarctica

Atmospheric ozone (O_3) is essential for absorption of ultraviolet light at wavelengths of 0.2 to 0.3 µm in the stratosphere. This reduces ultraviolet reaching the surface and heats the stratosphere.

O_3 is produced by the photochemical reaction:[286]

$O_2 + h\nu$ (photons < 0.24 µm) $\rightarrow O + O$
$O + O_2 + M \rightarrow O_3 + M$
(where M is a catalyst such as N_2). The more photons that are available, the more ozone is produced.

Most ozone is produces in the tropics, but the stratosphere is stable to convection, inhibiting vertical mixing, and normally allows horizontal transport (migration) between the equator to the poles.

The absorption of UV photons by ozone splits the ozone into diatomic oxygen (O_2) and monoatomic oxygen (O) and eventually produces all O_2.

$O_3 + h\nu$ (between 0.2 - 0.3 µm)$\rightarrow O_2 + O$
$O_3 + O \rightarrow O_2 + O_2$

The Earth's ozone layer blocks 97-99% of solar UV (solar UVA = 400 nm – 320 nm, UVB = 320 nm – 290 nm, and UVC = 290 nm – 100 nm),[287] preventing penetration through the atmosphere. "98.7% of the ultraviolet radiation that reaches the Earth's surface is UVA. (UVC and more energetic radiation is responsible for the generation of the ozone layer…)"[288]

The increasing use of huge quantities of *chlorofluorocarbons* (CFCs) and *hydrochlorofluorocarbons* (HCFCs) including Dupont's dichlorodifluoromethane (R-12® or Freon-12®) in the 1960s and 1970s (compounds which were widely used as refrigerants, propellants in aerosol applications, and solvents) led to accumulation of these highly stable products in the upper atmosphere.[289] Chlorofluoromethanes (Freon 31®, R-31®, HCFC-31®), and related compounds such as Halon®, 1,1,1-trifluoroethane (halothane®), carbon tetrachloride CCl_4, and trichloroethane were also involved.[290]

Exposed to UV radiation, these compounds undergo photochemical scission reactions, releasing reactive chlorine species such as ClO and the chlorine free radical Cl•, the latter of which is long lived in the upper atmosphere and can catalyze the conversion of ozone to other oxygen species:[291]

$CCl_3F \rightarrow CCl_2F\bullet + Cl\bullet$
$Cl\bullet + O_3 \rightarrow ClO + O_2$
$ClO + O_3 \rightarrow Cl\bullet + 2\ O_2$
$O_3 + h\nu \rightarrow O_2 + O$
$O + O_3 \rightarrow 2O_2$

In the Antarctic winter and spring, the persistent polar vortex acts as a barrier, preventing normal meridional stratospheric mixing, blocking the infusion of new ozone from the equator and allowing a buildup of Cl•.

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285 http://en.wikipedia.org/wiki/Nuclear_winter
286 http://en.wikipedia.org/wiki/Ozone
287 http://www.physlink.com/education/askexperts/ae300.cfm
288 http://en.wikipedia.org/wiki/Ultraviolet
289 http://en.wikipedia.org/wiki/Chlorofluorocarbon
290 http://en.wikipedia.org/wiki/Ozone_depletion
291 ibid.

Moreover, very cold *Polar Stratospheric Clouds* (PSCs, aka nacreous clouds) form which have ice particles that serve as catalytic sites for release of Cl_2 and which tie up NO_2. The rising Cl_2 leads to photodissociation in the spring to Cl•, and the diminished NO_2 prevents Cl• depletion. These chlorine radicals react as above, causing increasing consumption of ozone, leading to an Antarctic ozone hole in the spring and early summer.

"Reductions of up to 70% in the ozone column observed in the austral (southern hemispheric) spring over Antarctica and first reported in 1985 ... are continuing. Through the 1990s, total column ozone in September and October [over Antarctica] have continued to be 40–50% lower than pre-ozone-hole values. In the Arctic the amount lost is more variable year-to-year than in the Antarctic. The greatest [Arctic] declines, up to 30%, are in the winter and spring, when the stratosphere is colder.... In middle latitudes it is preferable to speak of *ozone depletion* rather than holes. Declines are about 3% below pre-1980 values for 35–60°N and about 6% for 35–60°S. In the tropics, there are no significant [depletion] trends."[292]

"The large ozone losses in the Southern Hemisphere polar region during spring continued unabated [as of 1998] with approximately the same magnitude and areal extent as in the early 1990s. In Antarctica, the monthly total ozone in September and October has continued to be 40 to 55% below the pre-ozone-hole values of approximately 320 m-atm cm ('Dobson units'), with up to a 70% decrease for periods of a week or so. This depletion occurs primarily over the 12- to 20-km altitude range [the lower stratosphere], with most of the ozone in this layer disappearing during early October..."[293]

RAH presented graphs showing the progression of the "ozone hole" over Antarctica during 2001-2002. (According to the caption of this data, it was acquired by the NASA Total Ozone Mapping Spectrometer (TOMS) when this instrument was flying aboard the Earth Probe (EP) satellite platform.)[294] The normal baseline atmospheric ozone in the total atmosphere column is expressed in *Dobson units* (*DU*), defined as a total columnar density of 2.69 x 10^{20} O_3 molecules m^{-2} of ground level surface area. "Over the Earth's surface, the ozone layer's average thickness is about 300 Dobson Units or a layer [of ozone] that is 3 millimeters thick [if compressed to sea level pressure]... What scientists call the Antarctic Ozone 'Hole' is an area where the ozone concentration drops to an average of about 100 Dobson Units. One hundred Dobson Units of ozone would form a layer only 1 millimeter thick if it were compressed into a single layer [at sea level pressure]."[295] The EP/TOMS images indeed show DUs falling to as low as 100 DU over Antarctica on Oct 1, 2001 (in the austral spring), rising to 150 in November, 175 in Dec 1, and back to 300 by Jan 1, 2002, falling somewhat lower to 225 in March.

NASA provides the following historical information about the atmospheric "ozone hole", presumably over Antarctica. The DU data begins in 1979, a year for which the DU were above 220, the cutoff level for which the ozone hole is currently defined. (Dobson first measured ozone over Halley Bay in Antarctica in 1956, at which time "he was surprised to find that it was ~320 DU, about 150 DU below spring levels, ~450 DU, in the Arctic. What Dobson describes is essentially the [Antarctic spring] baseline from which the ozone hole is measured..."[296] Measurements after about 1978 begin to show a significant falloff.)[297] The maximal size of the spring ozone hole (in km^2) attained, and the lowest DU attained are shown. The worst ozone hole, based on lowest DU, occurred in 1994, when a DU of 73 was measured (the graph indicates a DU=92 in 1994). The largest ozone hole by area was found in 2006, namely $29.3x10^6$ m^2. (For unknown reasons, the data in the accompanying table show somewhat different values than what the red markers indicate in these graphs.) This webpage also includes several useful animations. To my eyes, a recent minimal trend toward improvement may be present in the hole areas—if so, this might be attributable to adoption of the Montreal protocol and other efforts to reduce CFCs, etc.

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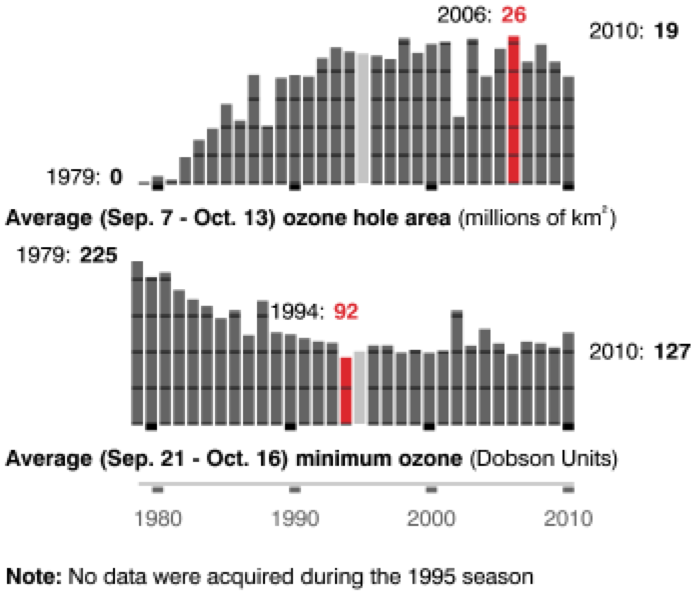
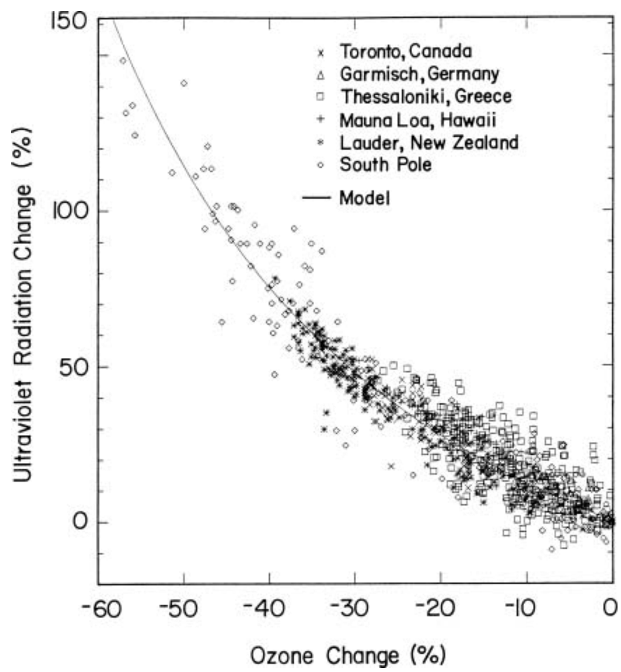
[292] ibid.
[293] http://www.esrl.noaa.gov/csd/assessments/ozone/1998/executive_summary.html
[294] http://www.agu.org/pubs/crossref/2010/2010JD014178.shtml
[295] http://ozonewatch.gsfc.nasa.gov/facts/dobson.html
[296] http://en.wikipedia.org/wiki/Ozone_depletion
[297] http://www.atm.ch.cam.ac.uk/tour/part2.html



http://ozonewatch.gsfc.nasa.gov/ and
http://ozonewatch.gsfc.nasa.gov/meteorology/annual_data.html

"The ozone hole over Antarctica has in some instances grown so large as to reach southern parts of Australia, New Zealand, Chile, Argentina, and South Africa…",[298] thus putting human populations at increased risk from UV exposure. The decline of UV absorption arising from a decline in total ozone, with a resultant rise in potentially injurious UV reaching the surface, is expressed by this graph:



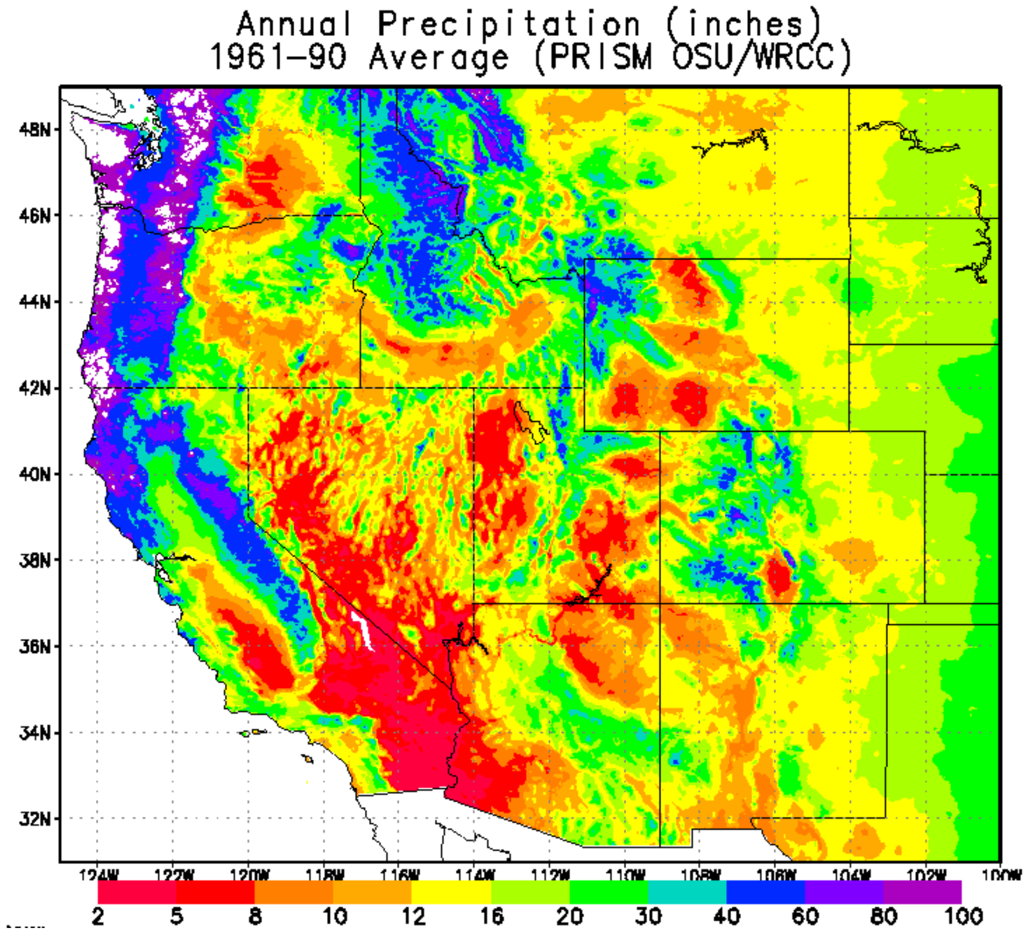
Increases in Erythemal (Sunburning) Ultraviolet Radiation Due to Ozone Decreases
from http://www.esrl.noaa.gov/csd/assessments/ozone/1998/faq8.html

[298] ibid.

Pacific NW Weather (Unit 8)

Washington state and the Pacific NW have some distinctive weather features. Climate data for WA and the Pacific NW may be found *here*.[299] The UW's Professor Cliff Mass has written a very readable 2008 book on Pacific NW weather which I enjoyed.[300] To some extent, this section emphasizes Washington weather.

Precipitation, Rain Shadow, and Chinook Föhn Wind



Average annual Western US precipitation 1961 - 1990, from http://www.wrcc.dri.edu/images/west.gif
Color scale is in inches/year of liquid water. White color means precipitation exceeding 100 inches per year.

Precipitation is maximal in Washington over the Olympics Mountains and the Cascades, especially the highest volcanic peaks. As the map shows, there is a marked difference between the wet West and the dry East in WA, OR, and Northern CA. Prevailing westerlies bring moist relatively warm air into the West of the state from the Pacific Ocean. The moisture is dumped in the Olympics and Cascades due to orographic lifting, adiabatic cooling, and condensation, leaving dry *föhn* (foehn) conditions—locally known as the Chinook wind[301]—east of the Cascades. Chinook winds undergo adiabatic heating as they flow downslope on the leeward side and are therefore relatively warm winds. In fact they are warmer than they were on the windward side at the same elevation, due to warming from the release of latent heat of condensation and the larger adiabatic lapse rate for dry compared to moist air.[302] The mountains therefore create a *rain shadow*,[303] such as the rain shadow cast by the Olympic Mountains on the dry Dungeness Valley centered on Sequim on the northern Olympic Peninsula.

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[299] http://www.wrcc.dri.edu/CLIMATEDATA.html
[300] Cliff Mass, *Weather of the Pacific Northwest*. 2008, University of Washington Press. Website here.
[301] http://en.wikipedia.org/wiki/Chinook_wind
[302] http://en.wikipedia.org/wiki/Foehn_wind
[303] http://en.wikipedia.org/wiki/Rain_shadow

"The Northwestern United States and Canada (Oregon, Washington, British Columbia, and Southern Alaska) see prevailing westerly flow off the northern Pacific Ocean. Places on the sea-facing side of coastal mountains see in excess of 140 inches (over 3.5 m) of precipitation per year. These locales are on the side of the mountains which are in the path of storm systems, and therefore receive the moisture which is effectively squeezed from the clouds."[304]

Washington Storms

A mild cold snap and a mild snowfall comes to normally temperate Seattle

The following actual observations show temperatures and snowfall in Seattle on Nov. 23, 2010[305] (see METAR abbreviations listed above). Note that snow precipitation is expressed in inches of liquid water (quantitative amounts omitted here though in the original report). Recall the following symbols: BL = Blowing, BR = Mist; FG = Fog; FZ = Freezing; HZ = Haze; RA = Rain; SN = Snow; –SN = mild snow.
Data is listed in reverse chronological order over 2 columns.

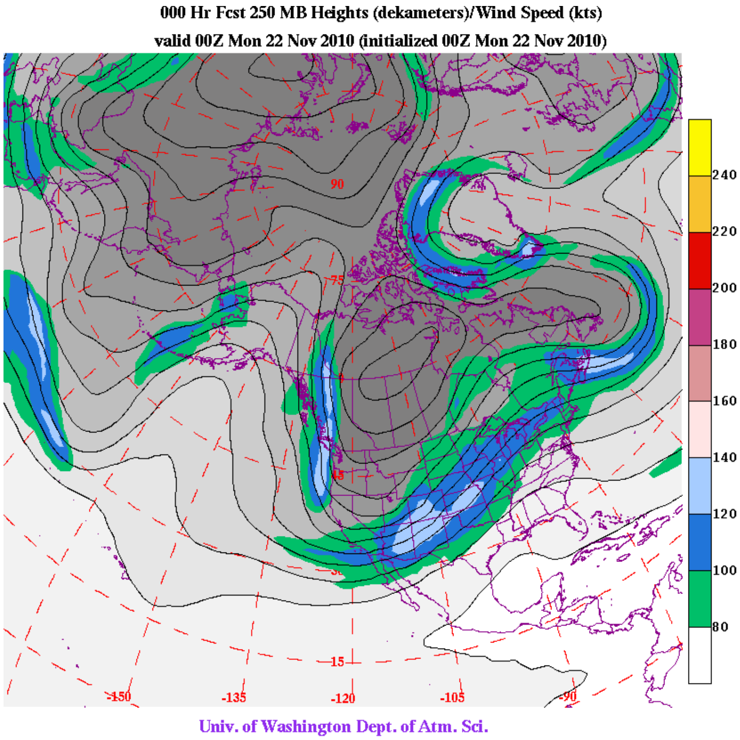
Date/Time	T °C	T_d °C	Weather WX
23 Nov 12:34 am	27	16	
23 Nov 12:12 am	27	18	-FZRA BLSN
22 Nov 11:53 pm	25	19	-SN BLSN
22 Nov 11:45 pm	25	19	-SN BLSN
22 Nov 11:21 pm	25	21	-SN BLSN
22 Nov 11:13 pm	25	21	-SN BLSN
22 Nov 11:00 pm	25	21	-SN BLSN
22 Nov 10:53 pm	26	21	-SN BLSN
22 Nov 9:53 pm	25	22	SN BLSN
22 Nov 9:48 pm	27	21	SN BLSN
22 Nov 9:15 pm	25	21	-SN BLSN
22 Nov 8:53 pm	25	21	-SN BLSN
22 Nov 8:00 pm	25	21	-SN BR
22 Nov 7:53 pm	25	20	BLSN
22 Nov 7:09 pm	25	19	BLSN
22 Nov 7:02 pm	25	19	BLSN
22 Nov 6:55 pm	25	19	BLSN
22 Nov 6:53 pm	26	19	BLSN
22 Nov 6:22 pm	27	19	BLSN
22 Nov 6:15 pm	27	21	BLSN
22 Nov 5:53 pm	27	21	HZ
22 Nov 5:42 pm	27	21	HZ
22 Nov 5:12 pm	28	21	-SN BR
22 Nov 5:05 pm	28	21	-SN BR
22 Nov 4:53 pm	29	25	-SN BR
22 Nov 4:15 pm	30	25	-SN

Date/Time	T °C	T_d °C	Weather WX
22 Nov 3:53 pm	30	27	SN FZFG
22 Nov 2:53 pm	31	28	-SN BR
22 Nov 2:42 pm	30	28	-SN BR
22 Nov 2:27 pm	30	28	-SN BR
22 Nov 1:53 pm	31	29	BR
22 Nov 12:53 pm	31	27	BR
22 Nov 12:10 pm	30	27	
22 Nov 11:57 am	30	27	-SN
22 Nov 11:55 am	30	27	-SN BR
22 Nov 11:53 am	30	27	-SN BR
22 Nov 11:00 am	30	25	-SN
22 Nov 10:53 am	30	25	-SN
22 Nov 10:07 am	28	25	-SN BR
22 Nov 9:53 am	30	26	SN
22 Nov 9:51 am	28	27	SN
22 Nov 9:43 am	28	27	-SN
22 Nov 9:09 am	30	25	-SN
22 Nov 8:53 am	30	24	-SN
22 Nov 8:20 am	30	25	-SN
22 Nov 7:53 am	30	25	-SN
22 Nov 7:51 am	30	25	-SN
22 Nov 7:50 am	30	25	-SN
22 Nov 7:44 am	30	25	-SN
22 Nov 6:53 am	30	25	-SN
22 Nov 5:53 am	31	23	-SN
22 Nov 4:53 am	32	19	-SN
22 Nov 3:53 am	33	16	

[304] http://en.wikipedia.org/wiki/Orographic_lift
[305] Nonpersistent weather data past 7 days for Seattle Boeing field (station KBFI): http://www.wrh.noaa.gov/mesowest/getobext.php?wfo=sew&sid=KBFI&num=168&raw=0&dbn=m&banner=header

Why did this snowfall occur? The answer lies in the baroclinic waves, showing troughs and ridges aloft.

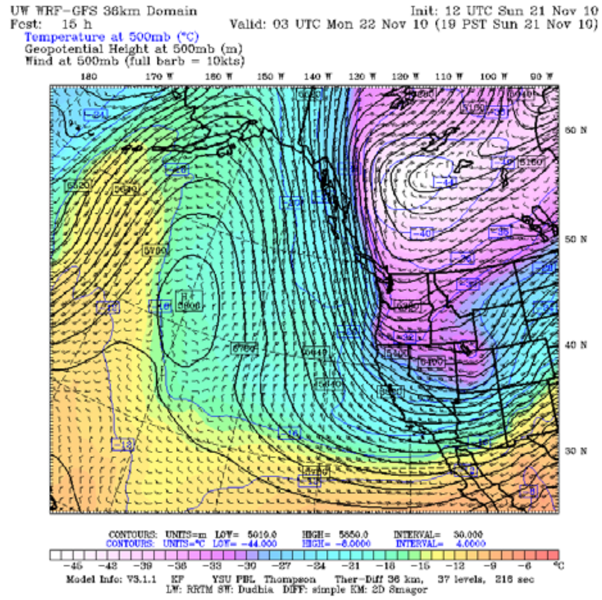
Strong winds are blowing down from the Arctic...



Pressure height contours (isohypses) at 250 mb (~10400 m height) combined with wind speeds at that height (in knots, color) for Sunday 11/21/2010 at 1600 PST. Shown in the synoptic scale long wavelength baroclinic waves (with "90" = North Pole) is a prominent high pressure ridge peaking to the west of Seattle over Alaska, and a deep trough immediately to its east extending to the Baja Peninsula. The leading (east) ridge edge (trailing west edge of the trough) has narrow contour intervals and predicted high speed and nearly N–to–S winds (blue & green), up to 120 knots, aimed at W Washington.

(nonpersistent image from http://www.atmos.washington.edu/~ovens/loops/wxloop.cgi?h250_wind+/-168//)

... and cold air is intruding into the Pacific NW

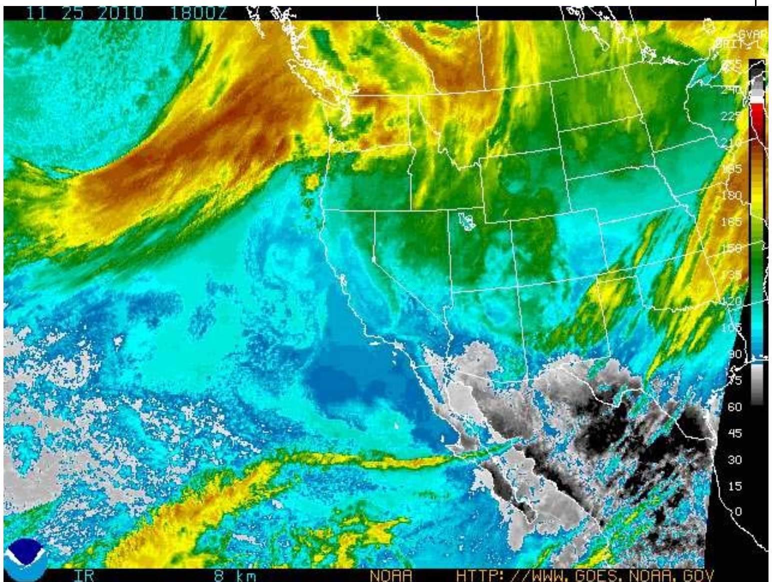


Pressure height contours (isohypses) and temperature (color) at 500 mb (~5575 m) forecast for Sunday Nov. 21, 2010 at 1900 PST. Prominent cold air (purple and white) intrudes into WA, OR, ID, MT, and northern NV and CA from Canada and the Arctic. Pressure height contours along the interface with warmer air to the W are tightly spaced, correlating with strong winds forecast up to 50 knots at 500 mb (shown as wind barbs, though hard to make these out in detail). At the surface, a cold front (not shown) is advancing into the warmer air displacing it upward, eventually causing condensation and precipitation.

This cold "Arctic air mass" brought snow to Seattle the following day Nov. 22, as documented in the preceding table.

(nonpersistent image from http://www.atmos.washington.edu/~ovens/loops/wxloop.cgi?mm5d1_500t+//72/3)

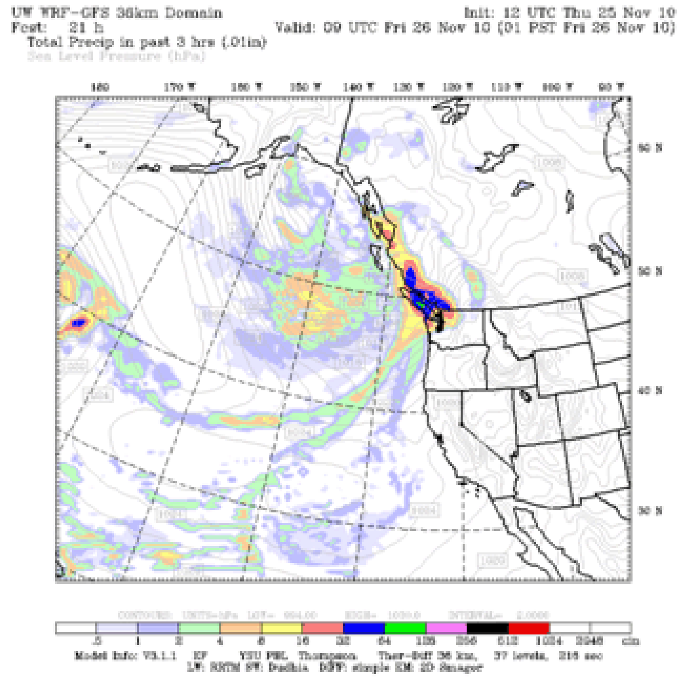
A few days later, heavy clouds are coming our way...



GOES Western US Infrared Image (IR Ch 4)
Only light snow had fallen in Seattle on the day the image was taken (Thursday 11/25/2010 1800 UTC (1000 PST).
Color scale (right) is keyed to GVAR pixel brightness B, & translates to T follows:
For B > 176,T (K) = 418 - B; for B <=176, T (K) = 330 - (B/2).
Thus medium brown has B = 202 → 418-202=216 K = -57 °C, indicating the coldest and therefore highest cloud tops.

(Non-persistent continually updated image from http://www.goes.noaa.gov/WCIR3.html)

... and more precipitation is forecast in 21 hours. (But will it be rain or snow?)



Up to 64/100 inch Precipitation was forecasted to occur in 21 hours for NW WA and SW BC, namely on Friday 11/26/2010 at 0100 am PST

This precipitation did arrive, from 1 to 6 AM, but in the form of rain, not snow. This was because surface temperatures (data not shown) had returned to the more typical mid-30s range as warmer air moved in from the W.

(Non-persistent continually updated image from http://www.atmos.washington.edu/~ovens/loops/wxloop.cgi?mm5d1_pcp3+//72/3)

Storms with high winds

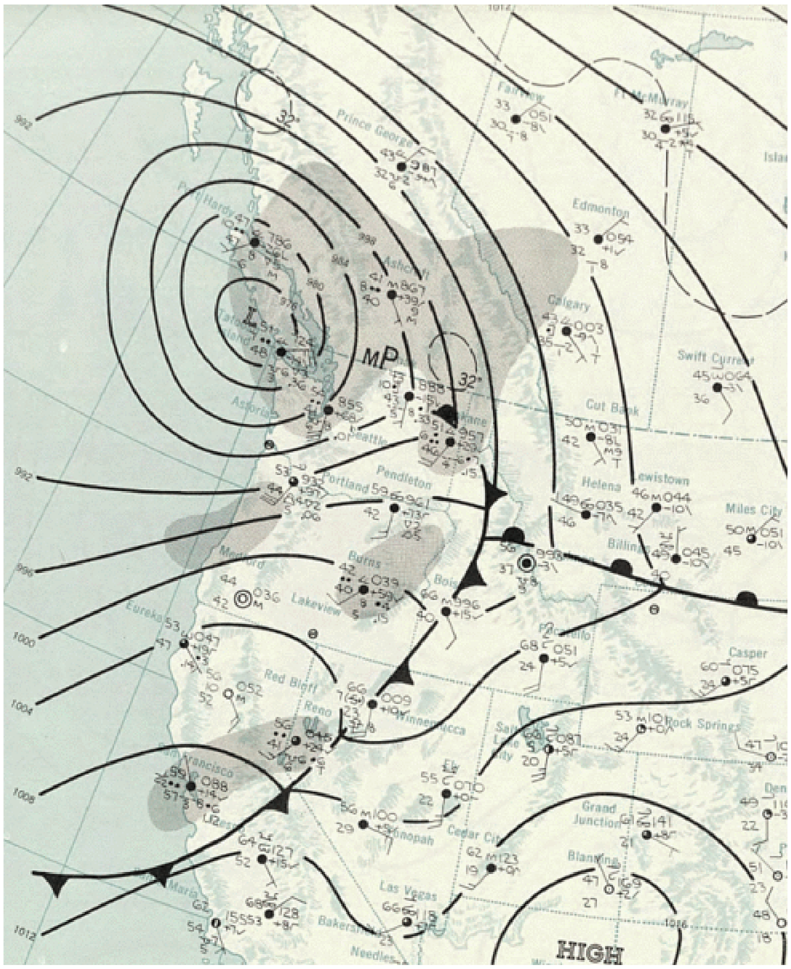
Washington is not immune to severe storms, heavy winds and rains, flooding, ice storms, etc.[306] Many strong midlatitude cyclones "have struck the West Coast within the relatively short period of meteorological record. These systems can match a Category 3 hurricane in both minimum central pressures and sustained wind speeds. Such storms have a reach far beyond that of a typical hurricane: they can throw a cold rain into the Alaska Panhandle while at the same time pummel the San Francisco Bay Area with a warm, saturated gale. These tempests are killers, and can cause damage into the hundreds of millions, even billions... *Extratropical cyclones* (*Mid-latitude cyclones, middle latitudes cyclones*) are extensively discussed in *MT8*-309.

Columbus Day Storm of 1962: There seems to be an idea that severe weather somehow doesn't strike the Pacific Northwest. This seems to be largely an eastern misconception. A strong argument could be made that the great Columbus Day Storm of 1962 [the most powerful windstorm to strike the Pacific Northwest in the 20th century] holds the 'Storm of the Century' title, and for good reason... The Columbus Day Storm was a relatively warm early-Autumn system and snow just did not happen, save perhaps at the highest elevations. However, wind speeds are a different matter. Wind generally causes more damage than snow... Of the storms on record, only eastern hurricanes, possibly some wake low events, and some thundergusts match the

[306] http://www.wrh.noaa.gov/pqr/paststorms/washington10.php

strength of winds reported during the Columbus Day Storm. For the Columbus Day Storm, official wind gusts reached 127 mph in the Willamette Valley. Many stations had gusts between 75 and 100 mph, and this includes quite a few locations that were inland (including Corvallis)...

...In 1962 dollars, the Columbus Day Storm caused an estimated $230-280 million in damage to property in California, Oregon, Washington and British Columbia combined, with $170-200 million happening in Oregon alone. This damage figure is comparable to eastern hurricanes that made landfall in the 1957-1961 time period: Audrey, 1957, $150M, Donna, 1960, $387M, and Carla, 1961, $408M. (Portions of this section paraphrased from *here*[307])



For Columbus Day 1962 Pacific NW Wind Storm, Surface Pressures and Fronts Analysis.
This map shows the extratropical cyclone (a Low as low as 960 mb) centered near Victoria BC, and the nearby occluded front created by the rapid cyclonic circulation.[308]

"The extratropical wave cyclone deepened to a minimum central [surface] pressure of at least 960 hPa... and perhaps as low as 958 hPa..., a pressure which would be equivalent to a Category 3 hurricane on the Saffir-Simpson hurricane scale. Since it was an extratropical cyclone, its wind field was neither as compact nor as strong as a tropical cyclone. All-time record-low land-based pressures (up to 1962) included 969.2 hPa... at Astoria, 970.5 hPa... at Hoquiam, Washington, and 971.9 hPa... at North Bend, Oregon... At Oregon's Cape Blanco, an anemometer that lost one of its cups registered wind gusts in excess of 145 mph (233 km/h); some reports put the peak velocity at 179 mph (288 km/h)."[309]

Other wind storms: Another major storm on December 12, 1995 had an even lower pressure minimum of 966.1 hPa at Astoria.[310] "In the early morning of February 13, 1979, as average winds exceeded 80 mph (and

[307] http://www.climate.washington.edu/stormking/October1962.html
[308] http://en.wikipedia.org/wiki/Columbus_Day_Storm_of_1962
[309] ibid.
[310] http://www.climate.washington.edu/stormking/December1995.html

perhaps even reached 105 mph), the Hood Canal Floating Bridge finally succumbed to one of the greatest storms to strike the upper Kitsap region."[311] The Inauguration Day [for Pres. Clinton] storm of January 20, 1993 had a low pressure of 976 mb—it had the strongest winds (98 mph near Tillamook) and created the most destruction in Washington State since the 1962 storm.[312] Another major regional windstorm was the Hanukkah Eve wind storm of 2006, beginning December 14, with pressure as low as 979 mb, wind gusts as high as 70 to 100 mph on the coasts of WA and OR, and record rains in Seattle.[313]

Strong windstorms can arise from strong oceanic low pressure centers. The winds on the SE side of a cyclone blow toward the NE. The low pressure center tends to migrate toward the NE (RAH slide).

Windstorms can also blow westward (from E to W) in WA when a High is positioned E of the Cascades (per RAH slide), for instance as anti-cyclonic circulation on the south side of a High pressure anti-cyclone.

Storms with Flooding and the Pineapple Express

The Pineapple Express is a popular non-technical term for a strong and persistent flow, driven by the subtropical jet stream, of atmospheric moisture and associated heavy rainfall from the waters adjacent to the Hawaiian Islands and extending to any location along the Pacific coast of North America.[314] "This flow pattern often forms when a dip in the jet stream coincides with atmospheric moisture associated with the Madden-Julian Oscillation [MDO]."[315] This MDO is "an irregular tropical disturbance that travels eastward around the globe and has a cycle of roughly 30 to 60 days. It is associated with regional [tropical] westerly winds that replace the easterly trades, along with enhanced showers and thunderstorms, particularly over regions of high sea-surface temperatures in the Indian and western tropical Pacific oceans. The MJO propagates eastward most vigorously during northern winter/spring and can influence weather beyond the tropics. In the late summer and autumn, the MJO can enhance hurricane activity in the Gulf of Mexico. The MJO is an important source of intraseasonal variability in the tropics."[316] According to a diagram of RAH, the dip in the jet stream to Hawaii is often in the form of a longwave trough, and the leading edge of this trough is associated with a cold front over the Pacific, and a warm front with warm wet weather is encountered in WA.

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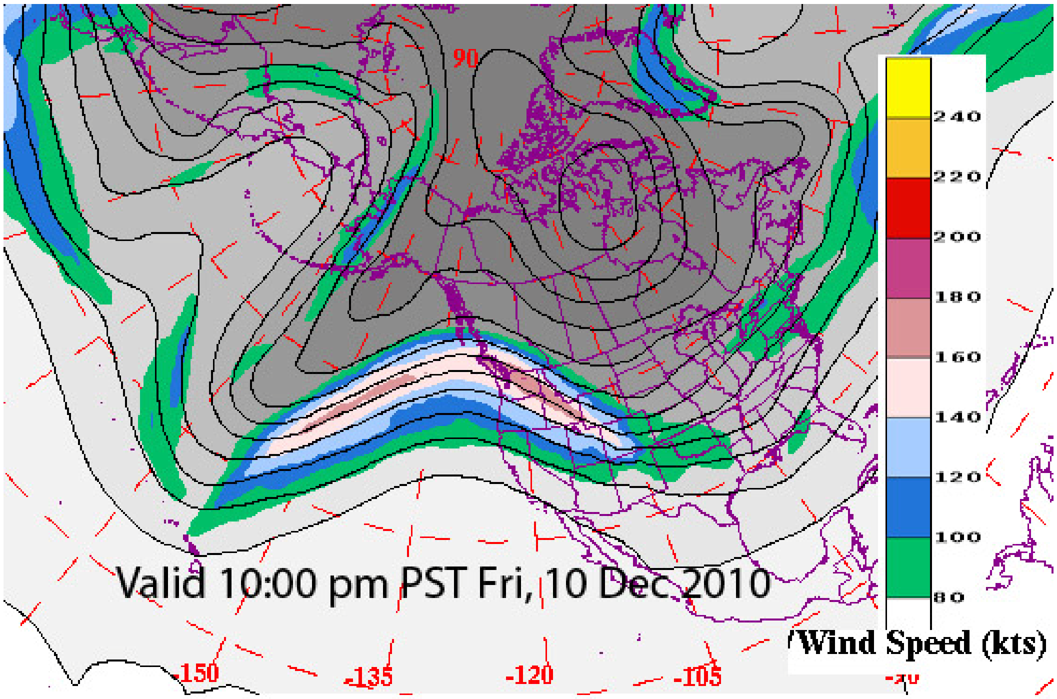
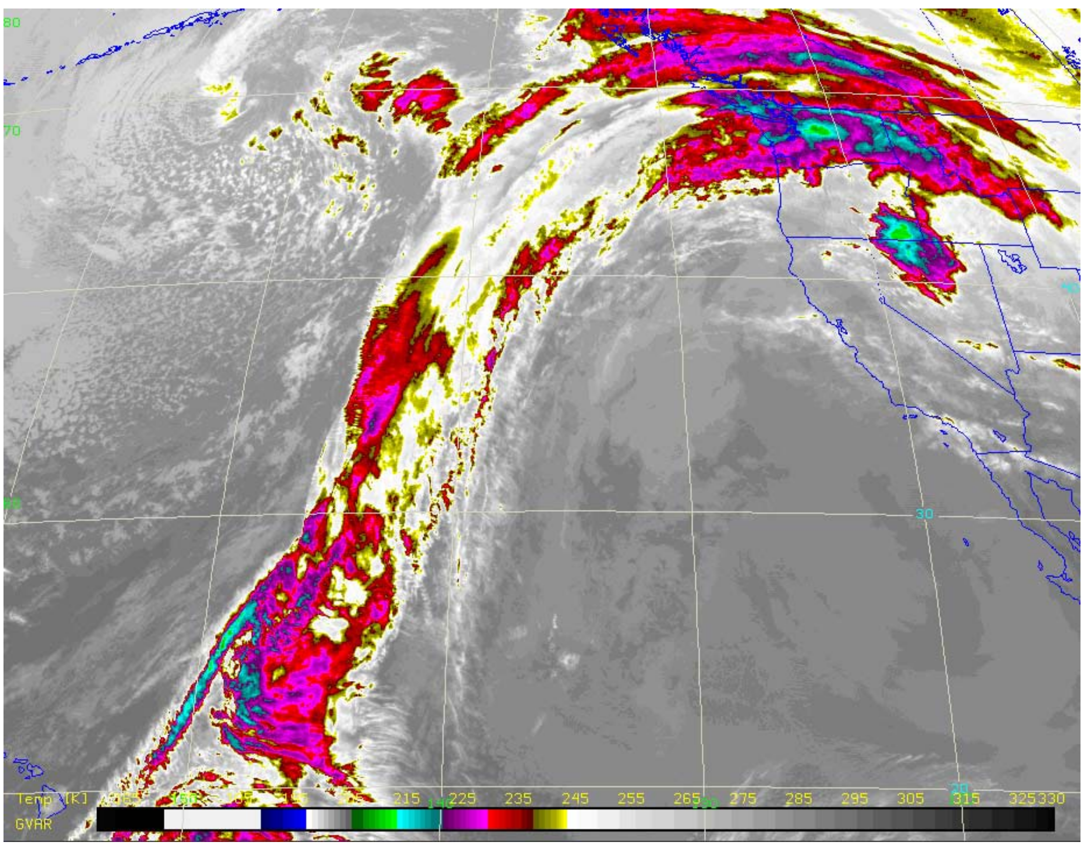
311 http://www.climate.washington.edu/stormking/February1979.html
312 http://www.climate.washington.edu/stormking/January1993.html
313 http://en.wikipedia.org/wiki/Hanukkah_Eve_Wind_Storm_of_2006
314 http://en.wikipedia.org/wiki/Pineapple_Express
315 http://www2.ucar.edu/news/backgrounders/arctic-oscillation-pineapple-express-weather-maker-glossary
316 ibid., "m"

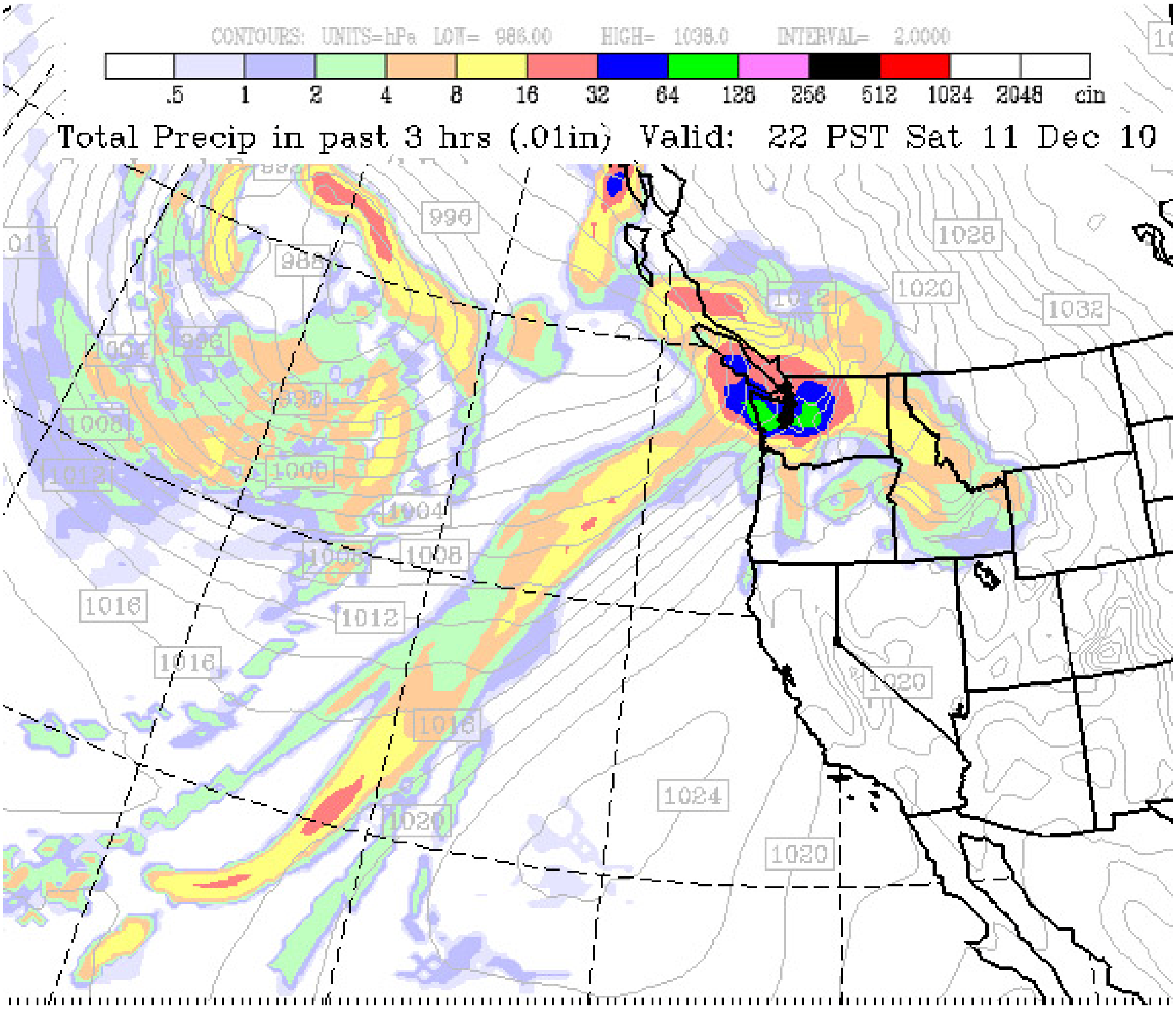


Univ. of Washington Dept. of Atm. Sci.

A strong jet stream is seen aloft (at 250 mb) blowing toward and across WA state late Friday 12/10/2010
(Image truncated and modified from non-persistent image from UW Atm S,
http://www.atmos.washington.edu/~ovens/loops/wxloop.cgi?npole_h250_wind+/-168//)

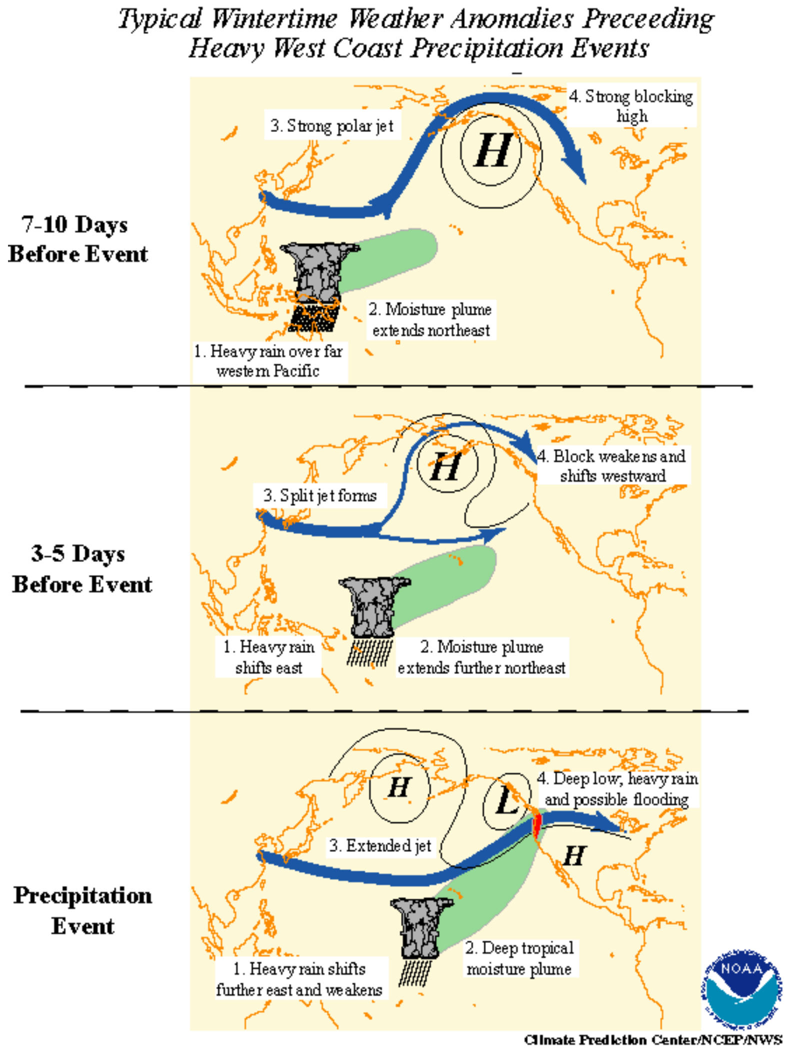


Pineapple Express 04:30 pm PST Sat 11 Dec 2010
Moisture laden tall convective clouds are blowing toward the NW from a deep trough extending to near Hawaii [lower left] along a fast jet stream (previous image) all the way to WA state, bringing high rains and flooding.
(non-persistent satellite IR image from UW Atm S, http://www.atmos.washington.edu/~ovens/loops/wxloop.cgi?ir_enhanced+/12h/)



Heavy rain is forecasted for western WA as of later Saturday night 12/11/2010.
(Image truncated and modified from non-persistent image from UW Atm S,
http://www.atmos.washington.edu/~ovens/loops/wxloop.cgi?mm5d1_pcp3+//72/3)

The following shows a proposed sequence leading to formation of the Pineapple Express and to the flooding which results:



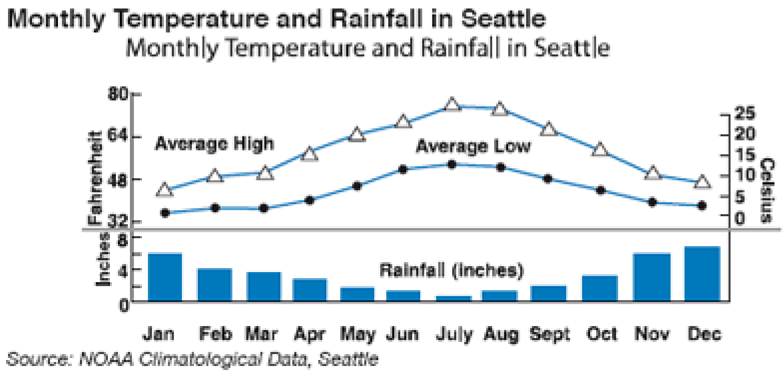
NOAA image showing postulated sequence leading to Pineapple Express:
(image from http://www.cpc.ncep.noaa.gov/products/winter_outlook/pineapple.gif)

In this sequence, a polar jet passing N along a strong longwave ridge or High is partially blocked by the High. It splits off a more southerly branch as a shortwave trough and Low forms, and the southern branch of the jet becomes gradually more intense and finally dominates. This extended southern jet flows NE cyclonically along the leading edge of the new trough and Low, bringing deep tropical moisture, heavy rains, and flooding. (The heavy rainclouds normally found originally in the W Pacific are displaced further NE.) According to RAH, a surface cold and adjacent warm front forms beneath the leading edge of a shortwave (or here, a long-wave) trough or Low aloft, in the manner previously discussed with Fronts, and this region of the fronts is the zone where heavy clouds and rains occur.

Pacific NW snowstorms

Snow forms when the dew point is close to the temperature of convecting air parcels—condensation commences above the LCL, and is snow and ice crystals at temperatures below freezing. According to an RAH slide, a 500 mb longwave ridge (LWR) and trough (LWT) comes into the Pacific NW, not as usual from the Pacific but from a much deviated wave excursion into W Canada. The leading edge of this ridge (trailing edge of the trough) is associated with southward flow of cold (below 0 °C) “Arctic” air, flowing toward the SE, S, or SW depending on the actual orientation of the axes of the LW ridge and LW trough. This cold air has often been termed a “Polar air mass”. A shortwave trough (SWT) often moves through the longer wavelength wave, associated with an enhancement of the precipitation. A surface Low and front are frequently associated with and move along with the leading edge of the SWT aloft, and these sweep the cold continental air from Canada deeper into WA, forming a cold front which lifts the warm air it invades, causing snow to form.

Seattle Area Rainfall and Temperatures

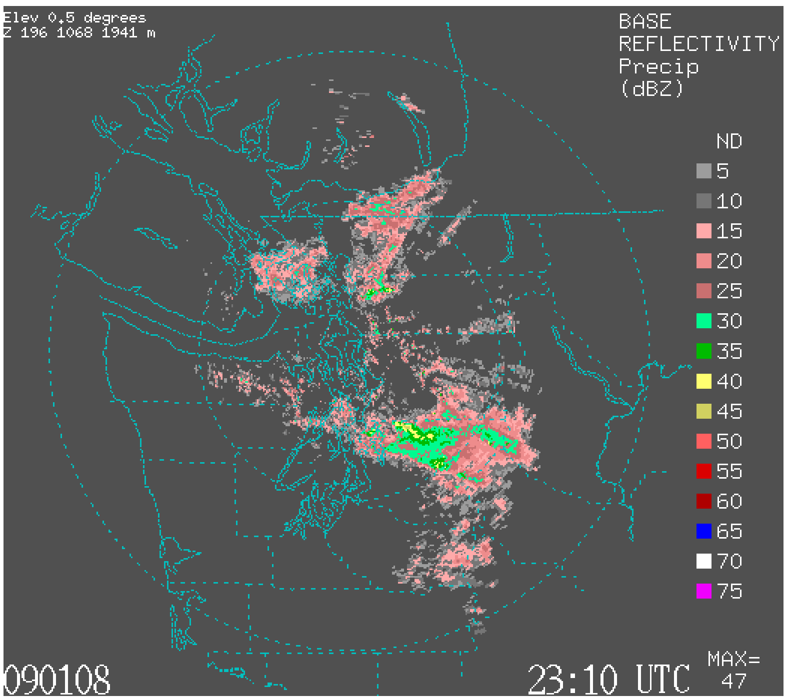


Seattle weather (from http://www.seattle.gov/oir/datasheet/quality.htm)

"It is a pertinent point that the 36 inches of annual rainfall received by Seattle... is less than the annual rainfall of places like New York. It is just that the rain comes down over a longer period—often precipitating as a slow drizzle, begrudgingly deposited by low lying clouds that seem to hang around far longer than necessary to get the job done."[317] "Average yearly rainfall in Seattle is 36.2 inches (92 cm), compared to 19.5 inches (50 cm) in San Francisco, 34.5 (88 cm) in Chicago, 39 inches (99 cm) in Washington, DC and 40.3 inches (102 cm) in New York City."[318]

Puget Sound Convergence Zone (PSCZ)

Unlike the Chinook wind, which is related to orographic lifting, this is a phenomenon of deviated horizontal flow.



Example of PSCZ maximal over N Seattle
(from http://archive.atmos.washington.edu/cgi-bin/get_old_obs.cgi)
See *here*[319] for an extended loop of this PSCZ example.

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[317] http://www.gonorthwest.com/Washington/seattle/weather.htm
[318] http://www.seattle.gov/oir/datasheet/quality.htm
[319] PSCZ loop:
http://www.atmos.washington.edu/~ovens/loops/wxloop.cgi?atx_bref1_archive+start+2009010816:00+end+2009010902:00+interval+

"The Puget Sound Convergence Zone (PSCZ) is a meteorological phenomenon that occurs over Puget Sound in Washington. It is formed when the large-scale [westerly] air flow splits around the Olympic Mountains and then converges over Puget Sound. This convergence zone generally occurs between north Seattle and Everett and can cause updrafts and convection, which leads to a narrow band of precipitation. This is evidenced by the 140-180+ inches (356 cm-457+ cm) of precipitation annually over Glacier Peak to the east of Puget Sound [which of course is aided by orographic lifting]...

The Puget Sound Convergence Zones, variable in both location and strength, tend to form in the general vicinity of central and southern Snohomish and northern King counties, from Everett, Washington, to the Northgate neighborhood of Seattle. The strongest part of the Convergence Zone (where the heaviest precipitation falls) tends to lie along and adjacent to the King-Snohomish County line so that neither county is left dry. The proximity of the PSCZ to the King-Snohomish County line is the reason that cities located just north or south of the line, which are located within the rain shadow of the Olympic Mountains, approach Seattle in annual precipitation [i.e., are higher than would otherwise result from the rain shadow]. The effect of the PSCZ nearly offsets that of the rain shadow. Without the PSCZ, cities such as Edmonds, Mountlake Terrace, and Lynnwood in Snohomish County and Shoreline, Lake Forest Park, and Bothell in King County would be noticeably dryer than Seattle...

The PSCZ's prime location in the southern third of Snohomish County and the northern third of King County, including North Seattle, make the Zone's presence on the University of Washington and surrounding U-District often minimal, despite the fact that the general area comprising the UW community is located only 1-2 miles from what can be reasonably deemed as the "northern third" of Seattle or "North Seattle"... It is entirely possible for areas from Shoreline to the Roosevelt neighborhood of Seattle (which encompasses NE 75th and NE 65th Streets) to be berated with heavy rainfall and strong winds, while areas not even a mile to the south are subjected to nothing more than overcast skies, due to the "calm zone" often present immediately outside the PSCZ."[320]

"The Puget Sound Convergence Zone (PSCZ) works best when there is a northwest flow [i.e., flowing toward the SE] in the upper atmosphere, and unstable air. They tend to be most frequent following a storm system, as usually winds blow from the northwest following a cold front passage... Those northwest winds will collide with the Olympic Mountains. Part of the air flow [the northern branch] will be deflected east down the Strait of Juan de Fuca, while the other part [the southern branch] will be deflected down the western side of the Olympics... When the northern branch reaches the I-5 Corridor and the Cascade Mountains, it will then be forced to the south... Meanwhile, when the southern branch [passes through the Chehalis gap and] reaches the I-5 corridor and Cascade Mountains past the southern side of the Olympics, it will then turn to the north... Eventually, the south-flowing branch and the north-flowing branch will converge. When that happens, the air has nowhere to go but up. Rising air will lead to convection. That will lead to cloud and storm development... If the atmosphere is unstable, you can get strong thunderstorms, hail, or on cold days, heavy snow... The [PSCZ] can go as far north as Northern Skagit County, and as far south as northern Pierce County... There tends to be a calm zone on either side [of the PSCZ] because once those winds shoot up inside the Zone, they tend to subside on either side... As air sinks, it tends to dry out, thus usually breaking up the cloud cover around the Zone."[321]

Tropical Meteorology (Unit 9)

Limited summaries of selected topics follow:

Intertropical Convergence Zone (ITCZ)

"The Intertropical Convergence Zone (ITCZ) is the area encircling the earth near the equator where winds originating in the northern and southern hemispheres come together... The ITCZ appears as a band of clouds, usually thunderstorms, that circle the globe near the equator. In the Northern Hemisphere, the *trade winds* move in a southwestern direction from the northeast, while in the Southern Hemisphere, they move northwestward from the southeast. When the ITCZ is positioned north or south of the equator, these directions change according to the Coriolis effect imparted by the rotation of the earth. For instance, when the ITCZ is situated north of the equator, the southeast trade wind changes to a southwest wind as it crosses the equator... The ITCZ is formed by vertical motion largely appearing as convective activity of thunderstorms

[320] http://en.wikipedia.org/wiki/Puget_Sound_Convergence_Zone
[321] http://www.komonews.com/weather/faq/4306427.html

driven by solar heating, which effectively draw air in—these are the trade winds . The ITCZ is effectively a tracer of the ascending [i.e., convecting] branch of the Hadley cell, and is wet. The dry descending branch [at about 30°] is the *horse latitudes*."[322]

Note that the global atmospheric circulation exhibits, in addition to the tropical Hadley cells, the *Ferrel cells* (which exhibit subsidence at the horse latitudes 30°, and ascent convection at about 60°, as well as the polar cells (all discussed above).

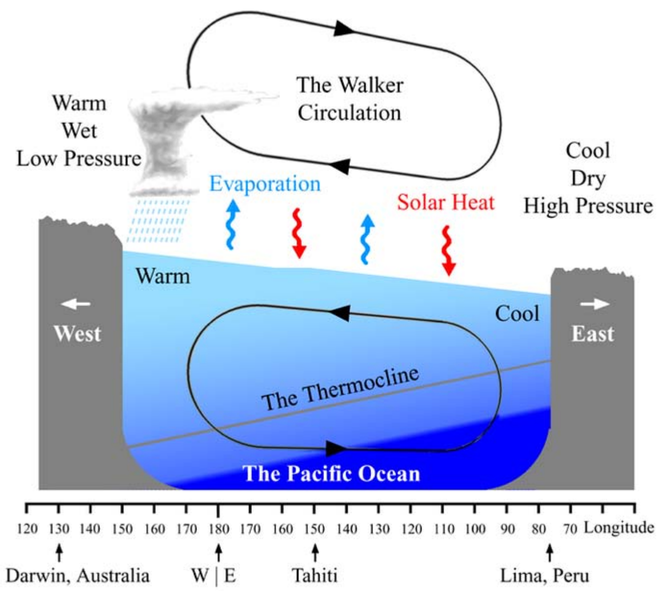
Thermocline, Walker Circulation, ENSO

Thermocline

For our purposes, this is a thin but distinct layer or boundary in the ocean in which temperature changes more rapidly with depth than it does in the layers above or below. Below the thermocline, the ocean water is not affected much by seasonal heating and cooling, whereas above the thermocline temperature is affected significantly by seasonal heating and cooling. The ENSO (see diagram below) alters the thermocline of the Pacific Ocean: whereas it normally slants upward toward the east, it flattens out more during El Niño.

Walker Circulation

Discovered by Sir Gilbert Thomas Walker,[323] it is "a model of the air flow in the tropics in the lower atmosphere (troposphere). According to this model parcels of air follow a closed circulation in the zonal [x] and vertical [z] directions. This circulation, which is roughly consistent with observations, is caused by differences in heat distribution between ocean and land."[324] The following diagram is from that article and shows rising warm air in a prevailing low pressure region in the W Pacific, the eastward flow aloft, the subsidence in the cooler high pressure area of the E Pacific, and the return as easterly trade winds to complete the loop, all resulting from differences in heating in E versus W. The ocean correspondingly exhibits warmer ocean water in the west with higher mean surface elevation and cooler water from upwelling in the E.



The Walker Circulation in a non-El Niño year. Horizontal scale is longitude,
which changes from W to E as marked. Surface trade winds and ocean current are shown.
The air over the eastern Pacific has a high pressure and is relatively cool, like the water underneath it.
The W Pacific is 20 to 60 cm higher than the E Pacific (scale of sea level rise is exaggerated here).

[322] ITCZ:
• http://en.wikipedia.org/wiki/Intertropical_Convergence_Zone
• http://www.srh.noaa.gov/jetstream//tropics/itcz.htm
[323] http://www.walker-institute.ac.uk/about/sir_gilbert.htm
[324] http://en.wikipedia.org/wiki/Walker_circulation

El Niño/Southern Oscillation (ENSO), El Niño, and La Niña

Average ENSO conditions in the Pacific: "Normally, sea surface temperature is about 14°F higher in the Western Pacific than the waters off South America. This is due to the trade winds blowing from east to west along the equator allowing the upwelling of cold, nutrient rich water from deeper levels off the northwest coast of South America. Also, these same trade winds push water west which piles higher in the Western Pacific. The average sea-level height is about 1½ feet higher at Indonesia than at Peru. The trade winds, in piling up water in the Western Pacific, make a deep 450 feet (150 meter) warm layer in the west that pushes the thermocline down there, while it rises in the east. The shallow 90 feet (30 meter) eastern thermocline allows the winds to pull up water from below, water that is generally much richer in nutrients than the surface layer." The nutrients promote growth of photosynthetic phytoplankton,[325] which are a principle food source for krill and other invertebrates in the food chain leading to fish and beyond.

ENSO: The ENSO is a fluctuation in the global weather pattern in response to changes in the Pacific Ocean and atmosphere overlying it. At the extremes of this fluctuation are El Niño and La Niña events. In describing these events, ENSO *episodes* last 5 to 7 months, more pronounced ENSO *conditions* last about 9 to 12 months. ENSO effects extend into mid-latitudes and beyond, and for instance affect N America, Alaska, and Canada weather conditions (see below). ENSO tropical Pacific patterns are studied using statistical index regions termed *Niño 1+2*, *Niño 3*, *Niño 4*, *Niño 3.4*, etc.[326]

ENSO is "is a quasi-periodic climate pattern that occurs across the tropical Pacific Ocean on average every five years, but over a period which varies from three to seven years."[327] It is characterized by variation in the temperature of the surface water of the tropical eastern Pacific Ocean (especially that off the coast of S America)—a warming known as El Niño or cooling known as La Niña, respectively—and variation in the air surface pressure in the tropical western Pacific—known as the *Southern Oscillation*. The two variations are coupled: the warm oceanic phase, El Niño, accompanies high air surface pressure in the west Pacific, while the cold phase, La Niña, accompanies low air surface pressure in the west Pacific."[328] "What is surprising is these changes in sea surface temperatures are not large, plus or minus 6°F (3°C) and generally much less. However these minor changes can have large effects our global weather patterns."[329] The Southern Oscillation in air pressure is monitored with the Southern Oscillation Index (SOI),[330] which is based on pressure differences between Tahiti and Darwin in NW Australia (see below).

El Niño: In an *El Niño* peak year, the equatorial warm pool in the western Pacific expands to the east. NOAA defines El Niño as: "A phenomenon in the equatorial Pacific Ocean characterized by a positive sea surface temperature departure from normal (for the 1971-2000 base period) in the Niño 3.4 region greater than or equal in magnitude to 0.5C, averaged over three consecutive months."[331] "The term El Niño (the Christ child) comes from the name Paita sailors called a periodic ocean current because it was observed to appear usually immediately after Christmas. It marked a time with poor fishing conditions as the nutrient rich water off the northwest coast of South America remained very deep."[332] The loss of nutrients reduces the phytoplankton bloom that feeds the food chain.

"When the air pressure patterns in the South Pacific reverse direction (the air pressure at Darwin, Australia is higher than at Tahiti), the trade winds decrease in strength (and can reverse direction). The result is the normal flow of water away from South America decreases and ocean water piles up off South America. This pushes the thermocline deeper [in the E Pacific] and [causes] a decrease in the upwelling. With a deeper thermocline and decreased westward transport of water, the sea surface temperature increases to greater than normal in the Eastern Pacific. This is the warm phase of ENSO, called El Niño. The net result is a shift of the prevailing rain pattern from the normal Western Pacific to the Central Pacific. The effect is the rainfall is more common in the Central Pacific while the Western Pacific becomes relatively dry."[333]

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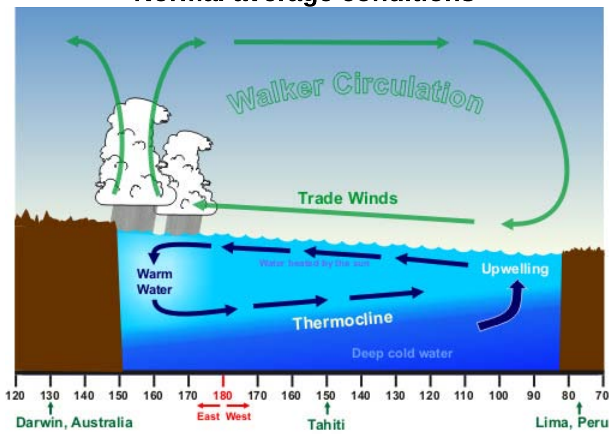
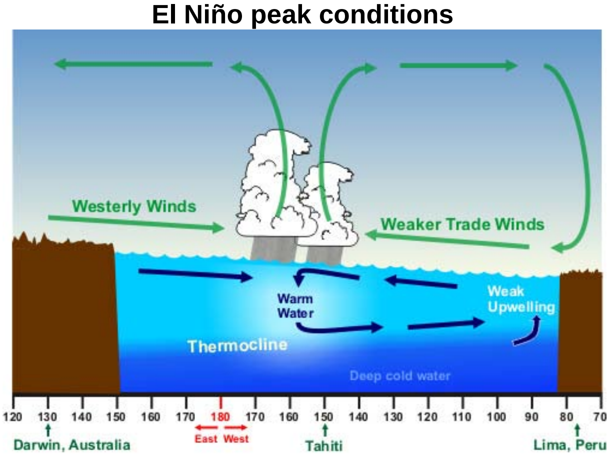
[325] http://en.wikipedia.org/wiki/Phytoplankton
[326] http://www.srh.noaa.gov/jetstream//tropics/enso.htm
[327] http://en.wikipedia.org/wiki/El_Ni%C3%B1o-Southern_Oscillation
[328] http://en.wikipedia.org/wiki/El_Ni%C3%B1o-Southern_Oscillation
[329] http://www.srh.noaa.gov/jetstream//tropics/enso.htm
[330] http://www.cgd.ucar.edu/cas/catalog/climind/soi.html
[331] http://usgovinfo.about.com/cs/spacescience/a/elnino.htm
[332] http://www.srh.noaa.gov/jetstream//tropics/enso.htm
[333] http://www.srh.noaa.gov/jetstream//tropics/enso_patterns.htm

Normal average conditions



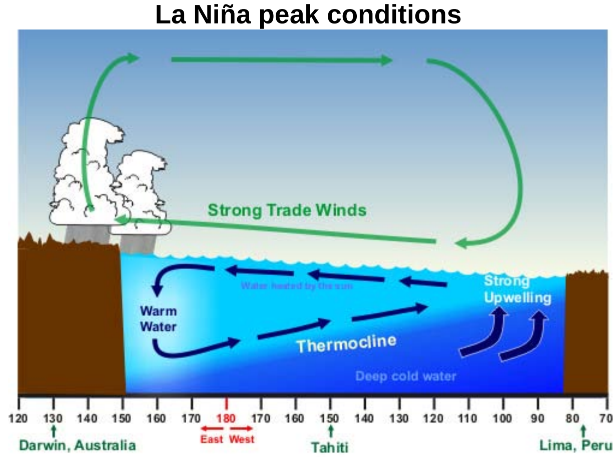
(from http://www.srh.noaa.gov/jetstream//tropics/enso_patterns.htm)

El Niño peak conditions



(Same source)

La Niña peak conditions



(Same source)

In El Niño conditions compared to average, the "warm pool" in the W Pacific extends closer to S America, and thunderstorms are shifted from the W more to the mid-Pacific. The cooler upwelling current along the coast of S America is much weakened or absent (contributing to warmer temperatures and a decline in fish populations. The surface pressure is lower than average in the E Pacific whereas it is higher than average in the W Pacific.[334] The prevailing surface winds are westward across the E Pacific but eastward across the W Pacific. In the Pacific NW, El Niño is associated with warmer winds coming more from the S, with warming in AK, BC, and WA in the winter months.

La Niña*:* NOAA defines it as: "A phenomenon in the equatorial Pacific Ocean characterized by a negative sea surface temperature departure from normal (for the 1971-2000 base period) in the Niño 3.4 region greater than or equal in magnitude to 0.5C, averaged over three consecutive months."[335] In *La Niña* conditions compared to average, thunderstorms are more prevalent in the W Pacific, the "warm pool" in the W Pacific does not extend as close to S America, and the thermocline slants more steeply upward and approaches the surface near S America, so that the cooler upwelling nutrient–laden current along the coast of S America is strong (contributing to a strong bloom of phytoplankton and prospering fish populations). The surface pressure is average to slightly above average in the E Pacific whereas it is below average in the W Pacific. The prevailing surface winds are westward across the Pacific.

Correlating ocean surface temperatures and surface air pressures in ENSO:

The 2 graphs from NOAA that follow show the correlation between ENSO-related ocean temperatures and the SOI (which compares Tahiti to Darwin Australia surface temperatures):

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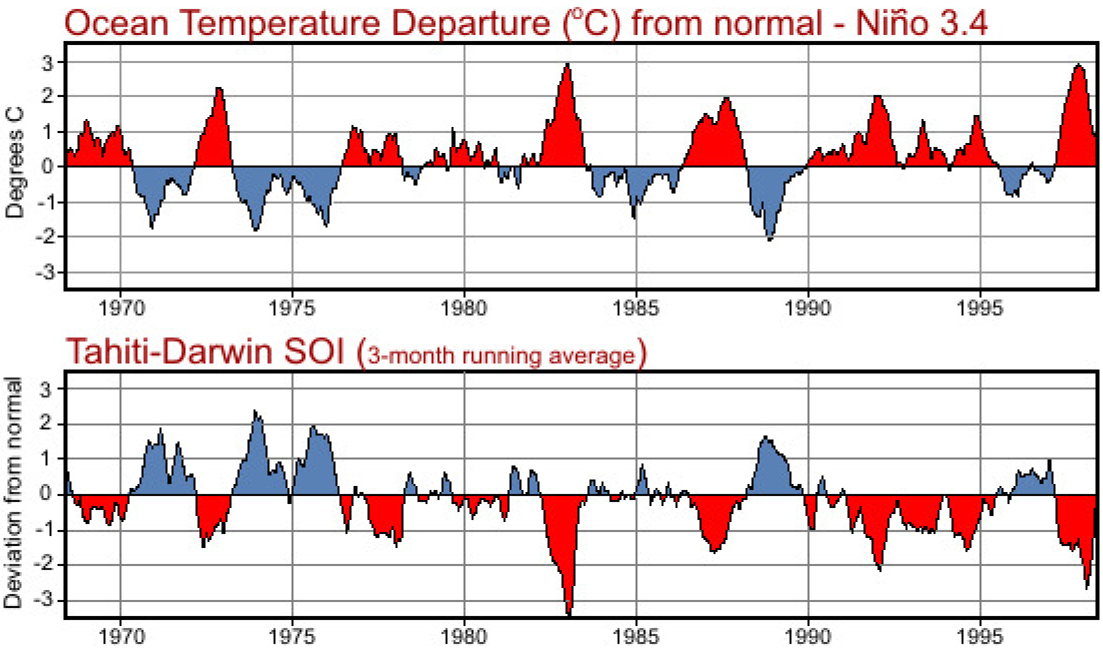
[334] Pressure data from slide presented by graduate student Anthony Didlake.

[335] http://usgovinfo.about.com/cs/spacescience/a/elnino.htm



The top graph shows the change in water temperature from average for ENSO index area Niño 3.4. The bottom graph shows the Southern Oscillation Index SOI for the same period. When the pressure in Tahiti is lower than Darwin (negative SOI), the temperature in Niño 3.4 is higher than normal, and an El Niño event is occurring—the warm episode of ENSO.[336] Conversely, when the pressure in Tahiti is higher than Darwin, the temperature in Niño 3.4 is lower than normal, and a La Niña event is occurring—the cool episode of ENSO.

Weather impacts of ENSO:

There are extensive global effect of ENSO, best appreciated with graphs such as are illustrated and discussed *here.*[337] "As the position of the warm water along the equator shifts back and forth across the Pacific Ocean, the position where the greatest evaporation of water into the atmosphere also shifts with it. This has a profound effect on the average position of the jet stream which, in turn, [a]ffects the storm track. During El Niño (warm phase of ENSO), the jet stream's position shows a dip [trough] in the Eastern Pacific. The stronger the El Niño, the farther east in the Eastern Pacific the dip in the [jet stream] occurs. Conversely, during La Niña's, this dip in the jet stream shifts west of its normal position toward the Central Pacific. The position of this dip in the jet stream, called a trough, can have a huge effect on the type of weather experienced in North America. During the warm episode of ENSO (El Niño) the eastern shift in the trough typically sends the storm track, with huge amounts of tropical moisture, into California, south of its normal position of the Pacific Northwest. Very strong El Niños will cause the trough to shift further south with the average storm track position moving into Southern California. During these times, rainfall in California can be significantly above normal, leading to numerous occurrences of flash flood and debris flows. With the storm track shifted south, the Pacific Northwest becomes drier and drier as the tropical moisture is shunted south of the region." The same webpage also presents a table summarizing the correlation of ENSO with tropical cyclones.

Monsoons and Deserts

We did not spend much time on this topic and did not discuss deserts.

Monsoon Definition and Scope: A monsoon is, "a major wind system that seasonally reverses its direction—such as one that blows for approximately six months from the northeast and six months from the southwest. The most prominent monsoons occur in South Asia, Africa, Australia, and the Pacific coast of Central America. Monsoonal tendencies also are apparent along the Gulf Coast of the United States and in central Europe; however, true monsoons do not occur in those regions."[338] "The word 'monsoon' is derived from the

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[336] http://www.srh.noaa.gov/jetstream//tropics/enso.htm
[337] http://www.srh.noaa.gov/jetstream//tropics/enso_impacts.htm
[338] http://www.britannica.com/EBchecked/topic/390302/monsoon

Arabic word 'mausim' which means season. Ancient traders sailing in the Indian Ocean and adjoining Arabian Sea used it to describe a system of alternating winds which blow persistently from the northeast during the northern winter and from the opposite direction, the southwest, during the northern summer. Thus, the term monsoon actually refers solely to a seasonal wind shift, and not to precipitation."[339]

Monsoon Prediction: Global monsoon prediction is presented by the Climate Prediction Center of NOAA *here*.[340]

Monsoons in Arizona: "Even though the term monsoon was originally defined for the Indian subcontinent, monsoon circulations exist in other locations of the world as well, such as in Europe, Africa, and the west coasts of Chile and the United States. Arizona happens to be located in the area of the United States that experiences a monsoonal circulation. During the summer months, winds shift from a west or northwest direction to a south or southeasterly direction. This allows moisture from the Gulf of California and the Gulf of Mexico to stream into the state. This shift in the winds, or monsoonal circulation, produces a radical change in moisture conditions statewide. This monsoonal circulation is typically referred to … in Arizona as the Arizona monsoon. What [Arizona experiences] during the summer months, however, is only a small part of a much larger circulation that encompasses not only Arizona, but much of the southwestern United States and northwestern Mexico. Thus, it sometimes is also known as the Mexican monsoon. Others call it the North American Monsoon."[341]

Tropical Cyclones, Typhoons, and Hurricanes

I can only touch on a few aspects of this important and fascinating subject, and am omitting forecasting, impacts on human life and property, and the effects of global warming on hurricane frequency and intensity. Tropical cyclones including hurricanes are discussed extensively in *ASI* chapter 8 "Weather Systems" and *MT8* chapter 15.

Definitions and Terminology: A tropical cyclone is a low pressure storm system of tropical origin, often associated with numerous thunderstorms that produce strong winds and heavy rain.[342]

"The terms 'hurricane' and 'typhoon' are regionally specific names for a strong 'tropical cyclone'. A tropical cyclone is the generic term for a non-frontal synoptic scale low-pressure system over tropical or sub-tropical waters with organized convection (i.e. thunderstorm activity) and definite cyclonic surface wind circulation (Holland 1993). [Most definitions for *tropical cyclone* as a generic term do not refer to wind speed.]

"Tropical cyclones with maximum sustained surface winds of less than 17 m/s (34 kt, 39 mph) are called *tropical depressions*… Once the tropical cyclone reaches winds of at least 17 m/s (34 kt, 39 mph), they are typically called a *tropical storm* and assigned a name. If winds reach 33 m/s (64 kt, 74 mph)), then they are called:
• *hurricane* (in the North Atlantic Ocean, the Northeast Pacific Ocean east of the dateline, or the South Pacific Ocean east of 160E)
• *typhoon* (in the Northwest Pacific Ocean, west of the dateline)
• *severe tropical cyclone* (in the Southwest Pacific Ocean west of 160E or Southeast Indian Ocean east of 90E)
• *severe cyclonic storm* (in the North Indian Ocean)
• *tropical cyclone* (in the Southwest Indian Ocean)"[343]

A *gale* is a very strong sustained surface wind. The US NWS defines a gale as 34-47 knots (39-54 miles/hour) of sustained surface winds.[344] "Other sources use minimums as low as 28 knots (52 km/h) and maximums as high as 90 knots (170 km/h)… A common alternative definition of the maximum is 55 knots (102 km/h)."[345]

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[339] http://www.wrh.noaa.gov/fgz/science/monsoon.php?wfo=fgz
[340] http://www.cpc.noaa.gov/products/Global_Monsoons/Global-Monsoon.shtml
[341] http://www.wrh.noaa.gov/fgz/science/monsoon.php?wfo=fgz
[342] Tropical Cyclones and Hurricanes:
• RAH notes
• http://en.wikipedia.org/wiki/Tropical_cyclone
• http://hurricanes.noaa.gov/pdf/hurricanebook.pdf
[343] http://www.aoml.noaa.gov/hrd/tcfaq/A1.html drawing on Neumann 1993
[344] http://www.nws.noaa.gov/glossary/index.php?letter=g
[345] http://en.wikipedia.org/wiki/Gale

Comparison with Extra-tropical cyclone: "An *extra-tropical cyclone* is a storm system that primarily gets its energy from the horizontal temperature contrasts that exist in the atmosphere. Extra-tropical cyclones (also known as mid-latitude or baroclinic storms) are low pressure systems with associated cold fronts, warm fronts, and occluded fronts. Tropical cyclones, in contrast, typically have little to no temperature differences across the storm at the surface and their winds are derived from the release of energy due to cloud/rain formation from the warm moist air of the tropics."[346]

Mid-latitude (Extra-Tropical, Baroclinic) Cyclones	Tropical Cyclones
Low pressure systems with cyclonic motion at the surface arising in mid-latitudes	Low-pressure systems with cyclonic motion at the surface arising in the tropical latitudes. Isobars are more circular, pressure gradient is steeper.
Wind speeds not distinguishing, but generally strongest aloft in the jet stream. Some resemble hurricanes in wind force. (*MT8*-418)	Winds are strongest at the surface and stronger than mid-latitude cyclones. (*MT8*-418) Tropical Cyclones are divided into: *tropical depression*≡max. sustained surface wind ≤ 38 mph (33 kt, 17 m s^{-1}) *tropical storm*≡max. sust. surface wind 39-73 mph (34–63 kt, 17.5 to 32.4 m s^{-1}) *severe tropical storm*≡max. sust. surface wind ≥ 74 mph (64 kt, 32.9 m s^{-1}) *typhoon, hurricane*≡same
Cold core low, usually intensify with increasing height. Cold upper-level low or trough often existing above, or to the W of the surface low. (*MT8*-413)	Warm core low, with warm central column. Weakens with height. (*MT8*-413)
Fronts present. Extract energy from horizontal temperature gradients associated with fronts.	No fronts required. Extract energy from warm moist ocean water.

"Structurally, tropical cyclones have their strongest winds near the earth's surface , while extra-tropical cyclones have their strongest winds near the tropopause - about 8 miles (12 km) up. These differences are due to the tropical cyclone being 'warm-core' in the troposphere (below the tropopause) and the extra-tropical cyclone being 'warm-core' in the stratosphere (above the tropopause) and 'cold-core' in the troposphere. 'Warm-core' refers to being relatively warmer than the environment at the same pressure surface... Often, a tropical cyclone will transform into an extra-tropical cyclone as it recurves poleward and to the east. Occasionally, an extra-tropical cyclone will lose its frontal features, develop convection near the center of the storm and transform into a full-fledged tropical cyclone. Such a process is most common in the North Atlantic and Northwest Pacific basins. The transformation of tropical cyclone into an extra-tropical cyclone (and vice versa) is currently one of the most challenging forecast problems..."[347]

"Tropical cyclones strengthen when water evaporated from the ocean [condenses] ... as the saturated air rises... The characteristic that separates tropical cyclones from other cyclonic systems is that any height in the atmosphere, the center of a tropical cyclone will be warmer than its surrounds; a phenomenon called 'warm core' storm systems."[348]

"The term 'tropical' refers to both the geographic origin of these systems, which form almost exclusively in tropical regions of the globe, and their formation in maritime tropical air masses. The term 'cyclone' refers to such storms' cyclonic nature, with counterclockwise rotation in the Northern Hemisphere and clockwise rotation in the Southern Hemisphere..."[349]

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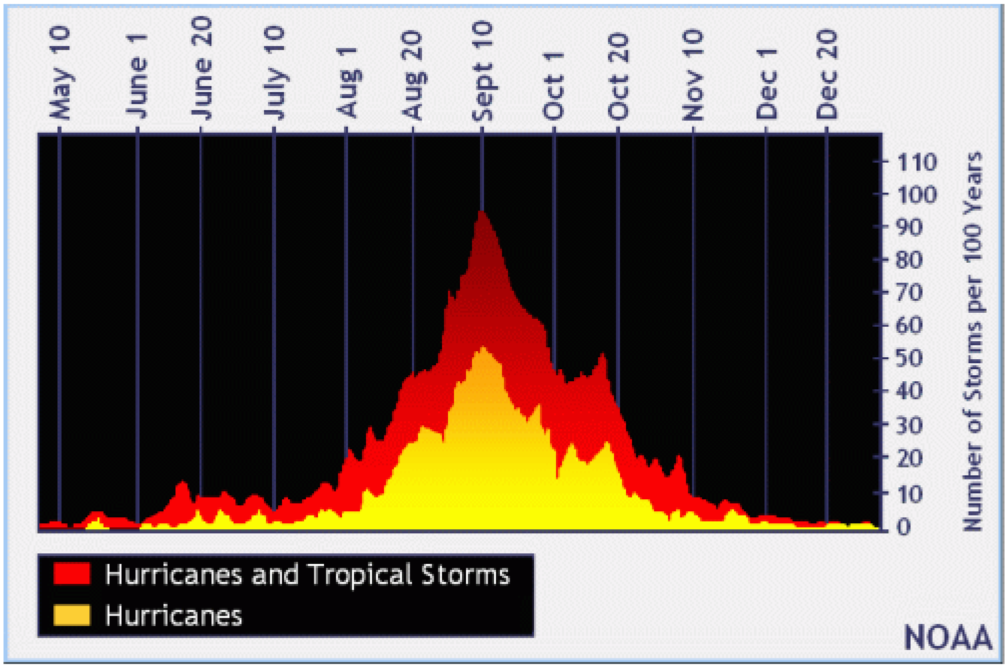
[346] http://www.aoml.noaa.gov/hrd/tcfaq/A7.html
[347] http://en.wikipedia.org/wiki/Tropical_cyclone
[348] ibid.
[349] ibid.

“While tropical cyclones can produce extremely powerful winds and torrential rain, they are also able to produce high waves and damaging storm surge as well as spawning tornadoes. They develop over large bodies of warm water, and lose their strength if they move over land due to increased surface friction and loss of the warm ocean as an energy source. This is why coastal regions can receive significant damage from a tropical cyclone, while inland regions are relatively safe from receiving strong winds. Heavy rains, however, can produce significant flooding inland, and storm surges can produce extensive coastal flooding up to 40 kilometres (25 mi) from the coastline. Although their effects on human populations can be devastating, tropical cyclones can also relieve drought conditions. They also carry heat and energy away from the tropics and transport it toward temperate latitudes, which makes them an important part of the global atmospheric circulation mechanism. As a result, tropical cyclones help to maintain equilibrium in the Earth's troposphere, and to maintain a relatively stable and warm temperature worldwide… Many tropical cyclones develop when the atmospheric conditions around a weak disturbance in the atmosphere are favorable. The background environment is modulated by climatological cycles and patterns such as the Madden-Julian oscillation, El Niño-Southern Oscillation, and the Atlantic multidecadal oscillation. Others form when other types of cyclones acquire tropical characteristics. Tropical systems are then moved by steering winds in the troposphere; if the conditions remain favorable, the tropical disturbance intensifies, and can even develop an eye. On the other end of the spectrum, if the conditions around the system deteriorate or the tropical cyclone makes landfall, the system weakens and eventually dissipates.”[350]

Factors predisposing to tropical cyclone formation and propagation: Tropical cyclones form in the following conditions:

(1) Tropical ocean latitudes, especially at the ITCZ. Here convection is strong and strong solar heating produces warm water leading to warm very humid air. Hurricanes get their energy from the warmed ocean and moist air, and are most likely to form in the Atlantic NH from June 1 to Nov. 30 (“hurricane season”), especially from mid-August to late October when the surface water is at its warmest. Hurricanes need moist air that can condense out moisture when convecting, releasing latent heat of condensation/vaporization, thereby furthering the convective instability that drives the hurricane. By slowly migrating, the cyclone can continue to move over new warm water (instead of remaining stationary and gradually depleting the heat stored in the underlying and now cooling surface ocean water).
(2) But not right at the equator ($\sin \varphi = 0$, no Coriolis force to cause spinning)
(3) Vertical wind shear which is weak (to prevent disrupting vertical structure of the hurricane). For instance, hurricanes do not arise in the jet streams because they would blow them apart.

[350] ibid.



"The official hurricane season for the Atlantic Basin (the Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico) is from 1 June to 30 November. As seen in the graph above, the peak of the season is from mid-August to late October. However, deadly hurricanes can occur anytime in the hurricane season."
from http://www.nhc.noaa.gov/pastprofile.shtml

Direction of Hurricane Tracks in the NH Atlantic: In general, trade winds (and the clockwise rotation of the southern circulation of the Bermuda High) tend to blow Atlantic hurricanes in the NH to the W or WNW, but as they move further N, they curve more northward and often eventually blow toward the E after encountering the westerlies.[351] The northward and eastward deviation is not as frequent for E Pacific hurricanes. Prediction of hurricane tracks has improved significantly in the last 20 years, but predicting hurricane intensity (kts) has not improved.

from http://www.nhc.noaa.gov/pastprofile.shtml
High res image at http://www.nhc.noaa.gov/gifs/1851_2008_mjrhurr_1350x888.jpg

351 http://www.nhc.noaa.gov/pastprofile.shtml

Hurricane Strength: The Saffir-Simpson Hurricane Scale[352] defines hurricane strength by maximum sustained surface wind speed categories. A Category 1 storm is the weakest hurricane, a Category 5 hurricane is the strongest. In the US, the NWS measures *sustained wind speeds*[353] by averaging wind speed over a period of only one minute, measured as usual at 10 meters height above the ground surface. In other parts of the world and the WMO, the average is made over 10 minutes and this method yields somewhat lower maximum sustained wind speeds:

- Tropical Storm – winds 39-73 mph (34-63 kt)
- Category 1 – winds 74-95 mph (64-82 kt)
- Category 2 – winds 96-110 mph (83-95 kt)
- Category 3 – winds 111-130 mph (96-113 kt)
- Category 4 – winds 131-155 mph (114-135 kt)
- Category 5 – winds 156 mph and up (135+ kt)

The Worst US Hurricanes:

(Extracted from *here*[354] except as noted)

• The deadliest US hurricane, 1851 - 2006, was Galveston 1900 (8,000-12,000 deaths). [Wikipedia lists the earlier "Great Hurricane" of 1780, producing 22,000 fatalities.][355]
• The most intense by lowest surface pressure, 1851 - 2006, was the hurricane of the Florida Keys 1935, category 5, pressure 892 mb.
• The costliest, 1900 - 2006, was Katrina 2005 (in $ unadjusted for inflation and economics)
• The costliest, 1900 - 2006, was SE Florida/Alabama 1926 (in $ after adjustment for inflation and other economic factors)[356]
• The largest US hurricane, as determined by gale force winds diameter, was Igor 2010 (920 miles). (See above for definition of gale.)
• The most intense landfalling hurricane (having the greatest Hurricane Severity Index=17) was Carla 1961, with wind speeds of 175 mph and 931 mbar lowest pressure.

Statistics for past hurricanes etc. (Tropical Cyclone Climatology): See *here*[357] for storm tracks and other statistical information.

Vertical Structure of a Hurricane:

In brief, warm moist air at the surface spirals in along the pressure gradient toward the central surface Low, deviated by the Coriolis force in the usual cyclonic (counterclockwise in NH) direction. These winds spiral inward but eventually they also rise in the spiral rainbands (which may extend as much as 500 miles from the center as with hurricane Gilbert) and in the eyewall. The adiabatic cooling of the rising moist air leads to saturation, dense cloud formation, and heavy precipitation. Rising air emerges aloft at or near the eyewall, and as it spreads out from the center it spirals outward in the usual anti-cyclonic (clockwise in NH) direction. Some rising air emerges into the upper eye itself, and descends down the eye, moving along the gradient from the High aloft to the Low at the surface. This subsiding air has no or minimal clouds and accounts for the frequent transparency of the eye.

Graduate student Anthony Didlake, who taught part of our class, presented a fine diagram which I have not otherwise found, of hurricane vertical structure. A similar diagram however is in the textbook at *ASI*-367 (and *MT8*-411). The following NOAA diagram is not as detailed, as it omits the contours of θ_e, azimuthal [tangential] wind speed, and angular momentum:

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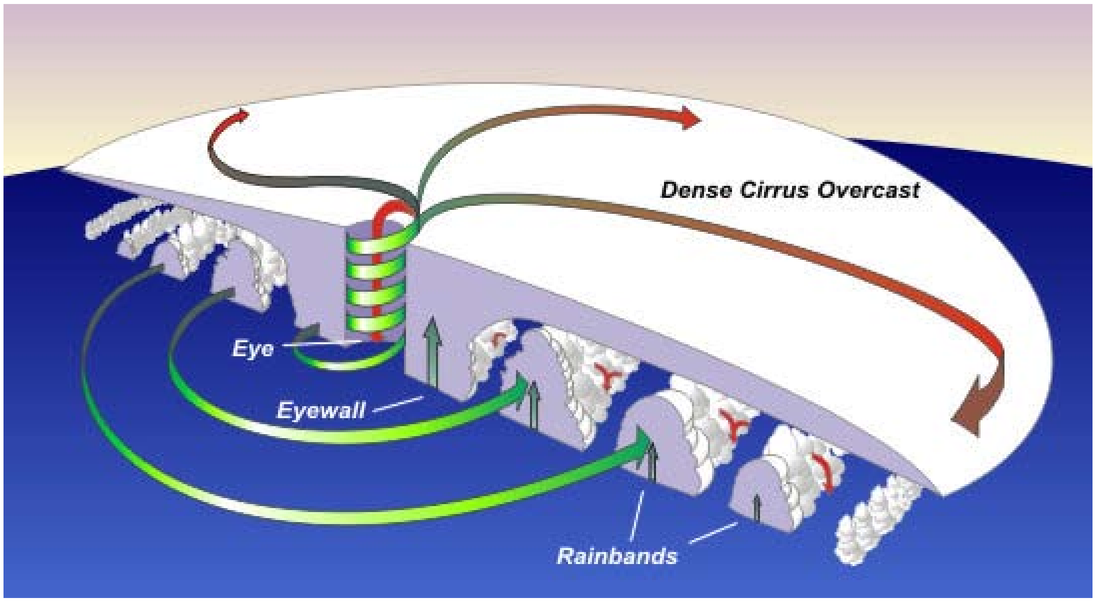
[352] Saffir-Simpson Hurricane Scale:
• http://www.prh.noaa.gov/hnl/cphc/
• http://en.wikipedia.org/wiki/Saffir%E2%80%93Simpson_Hurricane_Scale
[353] http://en.wikipedia.org/wiki/Maximum_sustained_wind
[354] http://www.nhc.noaa.gov/pdf/NWS-TPC-5.pdf
[355] http://en.wikipedia.org/wiki/List_of_tropical_cyclones
[356] http://www.nhc.noaa.gov/pdf/NWS-TPC-5.pdf
[357] http://www.nhc.noaa.gov/pastprofile.shtml



Vertical structure of a hurricane in Northern Hemisphere
Source: http://www.srh.noaa.gov/srh/jetstream/tropics/tc_structure.htm

"The main parts of a tropical cyclone are the rainbands, the eye, and the eyewall. Air spirals in toward the center in a counter-clockwise pattern in the northern hemisphere (clockwise in the southern hemisphere), and out the top in the opposite direction. In the very center of the storm, air sinks, forming an "eye" that is mostly cloud-free.

The Eye: The hurricane's center is a relatively calm, generally clear area of sinking air and light winds that usually do not exceed 15 mph (24 kph) and is typically 20-40 miles (32-64 km) across. An eye will usually develop when the maximum sustained wind speeds go above 74 mph (119 kph) and is the calmest part of the storm… But why does an eye form?.. It probably has to do with the combination of "the conservation of angular momentum" and centrifugal force. The conservation of angular momentum means is objects will spin faster as they move toward the center of circulation… In [a] tropical cyclone, as the air moves toward the center, the speed must increase… However, as the speed increases, an outward-directed force, called the centrifugal force, occurs because the wind's momentum wants to carry the wind in a straight line… The sharper the curvature, and/or the faster the rotation, the stronger is the centrifugal force… Around 74 mph (119 kmph) the strong rotation of air around the cyclone balances inflow to the center, causing air to ascend about 10-20 miles (16-32 km) from the center forming the eyewall. This strong rotation also creates a vacuum of air at the center [a Low pressure], causing some of the air flowing out the top of the eyewall to turn inward and sink to replace the loss of air mass near the center… This sinking air suppresses cloud formation, creating a pocket of generally clear air in the center. People experiencing an eye passage at night often see stars. Trapped birds are sometimes seen circling in the eye, and ships trapped in a hurricane report hundreds of exhausted birds resting on their decks. The landfall of hurricane Gloria (1985) on southern New England was accompanied by thousands of birds in the eye… The sudden change of very strong winds to a near calm state is a dangerous situation for people ignorant about a hurricane's structure… The storm is only half over with dangerous eyewall winds returning, this time from the opposite direction within a few minutes.

The Eyewall: Where the strong wind gets as close as it can [to the center] is the eyewall. The eyewall consists of a ring of tall thunderstorms that produce heavy rains and usually the strongest winds. Changes in the structure of the eye and eyewall can cause changes in the wind speed, which is an indicator of the storm's intensity. The eye can grow or shrink in size, and double (concentric) eyewalls can form.

[*Spiral*] *Rainbands*: Curved bands of clouds and thunderstorms that trail away from the eye wall in a *spiral* fashion. These bands are capable of producing heavy bursts of rain and wind, as well as tornadoes. There are sometimes gaps in between spiral rain bands where no rain or wind is found… In fact, if one were to travel between the outer edge of a hurricane to its center, one would normally progress from light rain and wind, to dry and weak breeze, then back to increasingly heavier rainfall and stronger wind, over and over again with each period of rainfall and wind being more intense and lasting longer…"[358] Note that air may be descending

[358] http://www.srh.noaa.gov/srh/jetstream/tropics/tc_structure.htm

between the rainbands, or at least between the old inner eyewall and a new outer eyewall, as shown for in fig. 2 of Prof. Houze's 2007 paper.[359]

Storm surge: "*Storm surge* is an abnormal rise of water generated by a storm, over and above the predicted astronomical tides. Storm surge should not be confused with *storm tide*, which is defined as the water level rise due to the combination of storm surge and the astronomical tide. This rise in water level can cause extreme flooding in coastal areas particularly when storm surge coincides with normal high tide, resulting in storm tides reaching up to 20 feet or more in some cases... Storm surge is produced by water being pushed toward the shore by the force of the winds moving cyclonically around the storm. [MCM: Thus the greatest effect is on the right side of the eye of a counterclockwise rotating Atlantic hurricane approaching the Gulf Coast, where onshore winds are at their greatest.] The impact on surge of the low pressure associated with intense storms is minimal [about 5%] in comparison to the water being forced toward the shore by the wind... Storm surge is a very complex phenomenon because it is sensitive to the slightest changes in storm intensity, forward speed, size (radius of maximum winds-RMW), angle of approach to the coast, central [barometric] pressure (minimal contribution in comparison to the wind), and the shape and characteristics of coastal features such as bays and estuaries."[360] Storm surge is modeled and predicted by the computer program SLOSH (Sea, Lake and Overland Surges from Hurricanes).[361]

Hurricane Loops of interest:
• Radar loop of Hurricane Katrina2005 showing the eye and rainbands.[362] The full horizontal extent of the hurricane is cut off by the image display method.
• Hurricane Isabel 2003 from GOES-12 satellite (visible light, showing a well defined flaring upper eye, and a hint of visible anti-cyclonic flow at the far periphery).[363]
• Hurricane Isidore 2002 from GOES-8, water vapor image showing some visible spiraling anti-cyclonic flow at the periphery.[364]

Glossary and Miscellaneous Mini-Topics

Topics and terms are included here for added emphasis or for when they are not fully treated in the body of this summary. Emphasis such as *italics* may be added by MCM in quoted material.

Adiabat and Adiabatic Lapse Rates:

"A line plotted on a thermodynamic diagram ... showing as a continuous sequence the temperature and pressure states of a parcel of air with changing height. *Dry adiabats* show temperature change at the *dry adiabatic lapse rate,*"[365] which represent the adiabatic sequence for dry air lacking water vapor [or moist air that does not attain saturation]. It's value is approximately Γ_d = 9.8 °C per 1,000 m.[366] The name implies an absence of input or output of heat by the parcel.

Aerovane:

"An aerovane is used to measure both wind direction and speed. The tail orients the instrument into the wind for direction while the propellers measure the wind speed."[367]

Albedo:

"The albedo of an object is a measure of how strongly it reflects light from light sources such as the Sun. It is therefore a more specific form of the term reflectivity [which is directional]. Albedo is defined as the ratio of total reflected [in any direction and without absorption] to incident electromagnetic radiation. It is a unitless measure indicative of a surface's or body's diffuse reflectivity. The word is derived from Latin albedo 'whiteness'... The range of possible values is from 0 (dark) to 1 (bright)... The average albedo of the

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[359] Robert A. Houze Jr., et al. "Hurricane Intensity and Eyewall Replacement". *Science* 2 March 2007: Vol. 315 no. 5816 pp. 1235-1239
[360] http://www.nhc.noaa.gov/ssurge/index.shtml
[361] SLOSH:
•http://www.fema.gov/plan/prevent/nhp/slosh_link.shtm
•http://en.wikipedia.org/wiki/SLOSH
[362] http://www.srh.noaa.gov/srh/jetstream/tropics/katrinaloop.htm (requires Java)
[363] http://www.srh.noaa.gov/srh/jetstream/tropics/isabel.htm
[364] http://www.esl.lsu.edu/demos/hurricanes/ISIDORE.gif
[365] http://www.answers.com/topic/adiabat
[366] http://en.wikipedia.org/wiki/Adiabatic_lapse_rate
[367] http://www.uwsp.edu/geo/faculty/ritter/glossary/A_D/aerovane.html

Earth is about 0.3."[368] There are several types of albedo distinguished in technical treatments, such as "bond albedo" and "geometric albedo".[369]

Arctic and Antarctic Circle:

"The Arctic Circle is one of the five major circles of latitude that mark maps of the Earth. For Epoch 2010, it is the parallel of latitude that runs 66° 33′ 44″ (or 66.5622°) north of the Equator. The region north of this circle is known as the Arctic, and the zone just to the south is called the Northern Temperate Zone. The equivalent polar circle in the Southern Hemisphere is called the Antarctic Circle. The Arctic Circle marks the southern extremity of the polar day (24-hour sunlit day, often referred to as the "midnight sun") and polar night (24-hour sunless night). North of the Arctic Circle, the sun is above the horizon for 24 continuous hours at least once per year and below the horizon for 24 continuous hours at least once per year. On the Arctic Circle those events occur, in principle, exactly once per year, at the June and December solstices, respectively. In fact, because of atmospheric refraction and because the sun appears as a disk and not a point, part of the midnight sun may be seen on the night of the northern summer solstice up to about 50′ (90 km (56 mi)) south of the Arctic Circle; similarly, on the day of the northern winter solstice, part of the sun may be seen up to about 50′ north of the Arctic Circle. … The position of the Arctic Circle is not fixed, but directly depends on the Earth's axial tilt, which fluctuates within a margin of 2° over a 40,000 year period, notably due to tidal forces resulting from the orbit of the Moon. The Arctic Circle is currently drifting northwards at a speed of about 15 m (49 ft) per year…"[370]

Barometer:

OED3: Gr. weight + measure. "An instrument for determining the weight or pressure of the atmosphere, and hence for judging of probable changes in the weather, ascertaining the height of an ascent, etc." *Anaeroid barometer*: "Specifying a barometer, in which the pressure of the air is measured, not by the height of a column of mercury or other fluid which it sustains, but by its action on the elastic lid of a box exhausted of air."

Baroclinic wave or disturbance:

Baroclinic wave "describes the synoptic-scale disturbance that grows in midlatitudes due to baroclinic instability." "Any migratory cyclone more or less associated with strong baroclinicity of the atmosphere, evidenced on synoptic charts by temperature gradients in the constant-pressure surfaces, vertical wind shear, tilt of pressure troughs with height, and concentration of solenoids in the frontal surface near the ground. Baroclinic disturbances play an important role in atmospheric energy conversion from potential energy to kinetic energy."[371] *ASI-12* implies that these waves are eastward propagating waves superimposed on the tropospheric jet streams or mid-latitude westerlies. Also called Rossby waves.[372]

Barotropic Disturbance (or barotropic wave):

"A wave disturbance in a two-dimensional flow, the driving mechanism for which lies in the variation of vorticity of the basic current and/or in the variation of the vorticity of the earth about the local vertical… Such wave disturbances are also known as Rossby waves."[373]

Coriolis Effect (or "Force"):

"In physics, the Coriolis effect is an apparent deflection of moving objects when they are viewed from a rotating reference frame. In a reference frame with clockwise rotation [such as the SH of the Earth], the deflection is to the left of the motion of the object; in one with anti-clockwise rotation [such as the NH of the Earth], the deflection is to the right. The mathematical expression for the Coriolis force appeared in an 1835 paper by a French scientist Gaspard-Gustave Coriolis in connection with hydrodynamics, and also in the tidal equations of Pierre-Simon Laplace in 1778.

Perhaps the most important instance of the Coriolis effect is in the large-scale dynamics of the oceans and the atmosphere. In meteorology and oceanography, it is convenient to use a rotating frame of reference where the Earth is stationary. The fictitious centrifugal and Coriolis forces must then be introduced. Their relative importance is determined by the Rossby number… The Rossby number is the ratio of inertial to Coriolis forces. A small Rossby number signifies a system which is strongly affected by Coriolis forces, and a large Rossby number signifies a system in which inertial forces dominate. For

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[368] http://en.wikipedia.org/wiki/Albedo
[369] http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/albedo.html
[370] http://en.wikipedia.org/wiki/Arctic_circle
[371] http://amsglossary.allenpress.com/glossary/search?id=baroclinic-disturbance1
[372] http://en.wikipedia.org/wiki/Rossby_wave
[373] http://amsglossary.allenpress.com/glossary/search?id=barotropic-disturbance1

example, in tornadoes, the Rossby number is large, [whereas] in low-pressure systems it is low... As a result, in tornadoes the Coriolis force is negligible, and balance is between pressure and centrifugal forces. In low-pressure systems, centrifugal force is negligible and balance is between Coriolis and pressure forces...

If a *low-pressure* area forms in the atmosphere, air will tend to flow in towards it, but will be deflected perpendicular to its velocity by the Coriolis force. A system of equilibrium can then establish itself creating circular movement, or a *cyclonic flow*. Because the Rossby number is low, the force balance is largely between the pressure gradient force acting towards the low-pressure area and the Coriolis force acting away from the center of the low pressure... Instead of flowing down the gradient, large scale motions in the atmosphere and ocean tend to occur perpendicular to the pressure gradient [thus parallel to the isobar or isohypse contours]. This is known as *geostrophic flow*. On a non-rotating planet, fluid would flow along the straightest possible line, quickly eliminating pressure gradients. Note that the geostrophic balance is thus very different from the case of "inertial motions" which explains why mid-latitude cyclones are larger by an order of magnitude than inertial circle flow would be... This pattern of deflection, and the direction of movement, is called *Buys-Ballot's law*. In the atmosphere, the pattern of flow [associated with a low-pressure area] is called a *cyclone*. In the Northern Hemisphere the direction of movement around a low-pressure area is anticlockwise. In the Southern Hemisphere, the direction of movement [around a low-pressure area] is clockwise because the rotational dynamics [are] a mirror image there... Cyclones rarely form along the equator due to the weak Coriolis effect present in this region...

High pressure systems rotate in a direction [resulting from the Coriolis force being directed radially inwards, and nearly balanced by the outwardly directed radial pressure gradient]. This direction is clockwise in the northern hemisphere and counter-clockwise in the southern hemisphere. Low pressure systems rotate in the opposite direction, so that the Coriolis force is directed radially outward and nearly balances an inwardly radial pressure gradient. In each case a slight imbalance between the Coriolis force and the pressure gradient accounts for the [resultant] radially inward acceleration of the system's circular motion."[374]

MCM + Wikipedia: The formula for the Coriolis Force $\mathbf{F_C}$ is $\mathbf{F_C} = -2m\boldsymbol{\Omega}\times\mathbf{v}$, where $\boldsymbol{\Omega}$ is the angular velocity vector which has magnitude equal to the rotation rate ω and is directed along the axis of rotation of the rotating reference frame, $\mathbf{v}$ is the instantaneous velocity of the particle in the rotating system, and the × symbol represents the cross product operator. Using the right hand rule for cross products, if the angular velocity axis is parallel to the thumb, and the unperturbed velocity down the pressure gradient is parallel to the index finger, the middle finger points in the $-\mathbf{F_C}$ vector direction. (In other words, the Coriolis force points opposite the direction that the middle finger points.) For low Rossby number, the $\mathbf{F_C}$ vector direction predominates . Because of the minus sign, the resulting direction for $\mathbf{F_C}$ for flow into a low pressure area in the NH is opposite the direction pointed at with the middle finger, thus a veering to the right when looking down on flow in the NH. Consider the magnitude of the vector component of $\boldsymbol{\Omega}$ which is perpendicular to the locally horizontal plane in which v is defined. This magnitude is maximal at the poles and is 0 at the equator, and correspondingly the Coriolis force is maximal at the poles and zero at the equator.

Cyclone, Tropical Cyclone, and Anticyclone:

Cyclone: These are a counterclockwise closed rotation in the NH about a low pressure area, clockwise in the SH. See also discussion with Coriolis Effect. "An atmospheric cyclonic circulation, a closed circulation... A cyclone's direction of rotation (*counterclockwise in the Northern Hemisphere*) is opposite to that of an anticyclone. While modern meteorology restricts the use of the term cyclone to the so-called cyclonic-scale circulations, it is popularly still applied to the more or less violent, small- scale circulations such as tornadoes, waterspouts, dust devils, etc. (which may in fact exhibit anticyclonic rotation)... The first use of this term was in the very general sense as the generic term for all circular or highly curved wind systems. Because cyclonic circulation and relative low atmospheric pressure usually coexist, in common practice the terms *cyclone* and *low* are used interchangeably..."

Tropical Cyclone: "A *tropical cyclone* is a storm system characterized by a large low-pressure center and numerous thunderstorms that produce strong winds and heavy rain. Tropical cyclones strengthen when

[374] Coriolis Effect and Geostrophic flow:
- http://en.wikipedia.org/wiki/Coriolis_effect
- http://en.wikipedia.org/wiki/Geostrophic_wind
- http://en.wikipedia.org/wiki/Right-hand_rule

water evaporated from the ocean is released as the saturated air rises, resulting in condensation of water vapor contained in the moist air. They are fueled by a different heat mechanism than other cyclonic windstorms such as nor'easters, European windstorms, and polar lows. The characteristic that separates tropical cyclones from other cyclonic systems is that [at] any height in the atmosphere, the center of a tropical cyclone will be warmer than its surrounds; a phenomenon called "warm core" storm systems... The term "tropical" refers to both the geographic origin of these systems, which form almost exclusively in tropical regions of the globe, and their formation in maritime tropical air masses. The term "cyclone" refers to such storms' cyclonic nature, with counterclockwise rotation in the Northern Hemisphere and clockwise rotation in the Southern Hemisphere. The opposite direction of spin is a result of the Coriolis force. Depending on its location and strength, a tropical cyclone is referred to by names such as *hurricane*, *typhoon*, *tropical storm*, *cyclonic storm*, *tropical depression*, and simply *cyclone*."[375]

NOAA states, "The terms "hurricane" and "typhoon" are regionally specific names for a strong "tropical cyclone". A tropical cyclone is the generic term for a non-frontal synoptic scale low-pressure system over tropical or sub-tropical waters with organized convection (i.e. thunderstorm activity) and definite cyclonic surface wind circulation (Holland 1993)...Tropical cyclones with maximum sustained surface winds of less than 17 m/s (34 kt, 39 mph) are called "*tropical depressions*"... Once the tropical cyclone reaches winds of at least 17 m/s (34 kt, 39 mph) they are typically called a "*tropical storm*" and assigned a name. If winds reach 33 m/s (64 kt, 74 mph)), then they are called:

* "*hurricane*" (the North Atlantic Ocean, the Northeast Pacific Ocean east of the dateline, or the South Pacific Ocean east of 160E)
* "*typhoon*" (the Northwest Pacific Ocean west of the dateline)
* "*severe tropical cyclone*" (the Southwest Pacific Ocean west of 160E or Southeast Indian Ocean east of 90E)
* "*severe cyclonic storm*" (the North Indian Ocean)
* "*tropical cyclone*" (the Southwest Indian Ocean)"[376]

Anticyclone: "An atmospheric anticyclonic circulation, a closed circulation. The wind in an anticyclone is in the *clockwise direction in the Northern Hemisphere* and *counterclockwise in the Southern Hemisphere*. With respect to the relative direction of its rotation, it is the opposite of a cyclone. Because anticyclonic circulation and relative high atmospheric pressure usually coexist, the terms *anticyclone* and *high* are used interchangeably in common practice."[377]

Equinoxes and Solstices:

Equinox: "An *equinox* occurs twice a year, when the tilt of the Earth's axis is inclined neither away from nor towards the Sun, the center of the Sun being in the same plane as the Earth's equator..."[378] They are termed Vernal (March) equinox and autumnal (September) equinoxes... The equinoxes are currently in the constellations of Pisces and Virgo.

Solstice: "A *solstice* is an astronomical event that happens twice each year when the Sun's apparent position in the sky reaches its northernmost or southernmost extremes. The name is derived from the Latin sol (sun) and sistere (to stand still), because at the solstices, the Sun stands still in declination; that is, the apparent movement of the Sun's path north or south comes to a stop before reversing direction."[379]
They are termed Summer (or less ambiguously Northern or June) Solstice and Winter (or less ambiguously Southern or December) solstices.
Their precise times in UT are given *here*:[380]
In 2010, Perihelion is Jan 3 at 00h, Equinoxes Mar 20 at 17:32 and Sept 23 at 03:09
In 2010, Aphelion is July 6 at 12h, Solstices are June 21 at 11:28 and Dec 21 at 23:38.

Geopotential Height Z, Reference Ellipsoid for Mean Sea Level, and Geoid:

Geopotential Height is usually symbolized by upper case Z rather than ordinary "geometric" height z. It is "the height of a given point in the atmosphere in units proportional to the potential energy of unit mass

[375] http://en.wikipedia.org/wiki/Tropical_cyclone
[376] http://www.aoml.noaa.gov/hrd/tcfaq/A1.html
[377] http://amsglossary.allenpress.com/glossary/search?id=cyclone1
[378] http://en.wikipedia.org/wiki/Equinox
[379] http://en.wikipedia.org/wiki/Solstice
[380] http://www.usno.navy.mil/USNO/astronomical-applications/data-services/earth-seasons

(geopotential) at this height relative to sea level. The relations, in SI units, between the geopotential, the geopotential height Z, and the geometric height z are:

$$\Phi = \int_0^z g(\phi, z)\,dz$$

$$Z = \frac{\Phi}{g_0}$$

$$Z = \frac{1}{g_0} \int_0^z g(\phi, z)\,dz$$

where Φ = Geopotential
g(φ,z) = acceleration of gravity, varying with φ and z
φ = Latitude
z = geometric height
Z = Geopotential Height

The two heights are numerically interchangeable for most meteorological purposes."[381] Sample maps of geopotential height at 500 hPa may be seen *here*.[382]

The datum surface used to define mean sea level, and therefore the surface for which z = Z = 0, is commonly taken to be the reference ellipsoid (oblate spheroid) known as the *World Geodetic System 84 Reference Ellipsoid* ["*WGS 84"*]. The "WGS84 datum" is the reference system used by the used by the Global Positioning System.[383]

In contrast, the *geoid* is "that *equipotential surface* which would coincide exactly with the mean ocean surface of the Earth, if the oceans were in equilibrium, at rest, and extended through the continents (such as with very narrow canals [or tunnels])… It is a smooth but highly irregular surface that corresponds not to the actual surface of the Earth's crust, but to a surface which can only be known through extensive gravitational measurements and calculations."[384] "Presently WGS 84 uses the 1996 Earth Gravitational Model (EGM96) geoid, revised in 2004. The deviations of the EGM96 geoid from the WGS 84 reference ellipsoid range from about –105 m to about +85 m."[385]

Geosynchronous and Geostationary Satellites (particularly NOAA's GOES System):
According to Kepler's Third Law, the square of the orbital period of a planet (or Earth satellite) is directly proportional to the cube of the semi-major axis of its orbit about the Sun (or Earth). "Space stations and Shuttles in Low Earth orbit (LEO), typically two or four hundred miles above the Earth's surface make between fifteen and sixteen revolutions per day. The Moon, at an altitude of about 238,900 miles (384,400 km), takes about 27 days 7 hours to make a complete revolution. Between those extremes lies the "magic" altitude of 22,236 miles (*35,786 km*) at which a satellite's orbital period matches … the [sidereal] period at which the Earth rotates: once every sidereal day (23 hours 56 minutes 4 seconds). In that case, the satellite is said to be *geosynchronous*… There are approximately 300 operational geosynchronous satellites… Radio signals take approximately 0.25 of a second to reach and return from the satellite, resulting in a small but significant signal delay."[386]

"The special case of a geosynchronous orbit that is circular (or nearly circular) and at zero (or nearly zero) inclination, that is, directly above the equator… is customarily called a *geostationary* orbit… A perfect stable geostationary orbit is an ideal that can only be approximated. In practice the satellite drifts out of this orbit (because of perturbations such as the solar wind, radiation pressure, variations in the Earth's gravitational field, and the gravitational effect of the Moon and Sun), and thrusters are used to maintain the orbit in a process known as station-keeping."[387] Note that polar orbiting satellites cannot be

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[381] http://amsglossary.allenpress.com/glossary/search?id=geopotential-height1
[382] http://www.ecmwf.int/research/era/ERA-40_Atlas/docs/section_D15/parameter_ga500hpa.html
[383] http://en.wikipedia.org/wiki/Global_Positioning_System
[384] http://en.wikipedia.org/wiki/Geoid
[385] http://en.wikipedia.org/wiki/World_Geodetic_System
[386] http://en.wikipedia.org/wiki/Geosynchronous_satellite
[387] http://en.wikipedia.org/wiki/Geosynchronous_orbit

geostationary. The POES satellite system is used by NASA to provide coverage of the entire Earth from low orbit.[388]

All satellite positions can be tracked at this NASA site.[389]

Detailed information on NOAA's GOES geostationary weather satellites,[390] such as GOES 11 (GOES West) and GOES 12, may be seen *here.*[391]

"Four GOES satellites are currently [in 2010] available for operational use:
• *GOES-11* [formerly GOES-L or NSSDC ID 2000-022A] is designated *GOES-West* [*GOES West*], currently located at 135°W over the Pacific Ocean.
• *GOES-12* [formerly GOES-M or NSSDC ID 2001-031A] is designated *GOES-South* [*GOES South*], currently located at 75°W over the Amazon River.
• *GOES-13* [formerly GOES-N] is designated *GOES-East* [*GOES East*], currently located at 105°W. It provides most of the U.S. weather information.
• GOES 14 [formerly GOES-O] was placed in … on-orbit storage…
The GOES I–M series of spacecraft are the principal observational platforms for covering such dynamic weather events and the near-earth space environment for the 1990s and into the 21st century… Before being launched, GOES satellites are designated by letters (-A, -B, -C…). Once a GOES satellite is launched successfully, it is redesignated with a number (-1, -2, -3…)"

The GOES I-M series of satellites is discussed fully *here*,[392] including channel numbers, wavelengths observed, and objectives of these measurements. The GOES *Imager* has the following spectral band (channel) capabilities. (The GOES *Sounder* radiometer has 19 spectral bands or channels:[393] Long wave IR channels 1–7, Medium wave IR channels 8–12; Short wave IR channels 13–18; and Visible 19):

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[388] http://www.oso.noaa.gov/poes/
[389] http://science.nasa.gov/realtime/jtrack/NOAA.html [requires JAVA plug-in Enabled]
[390] http://en.wikipedia.org/wiki/List_of_GOES_satellites
[391] GOES satellites
• *GOES 11 (GOES West,* formerly *GOES-L)*: "The Geostationary Operational Environmental Satellite (GOES-L) is the fourth satellite in a series of next generation geosynchronous spacecraft, referred to as GOES-NEXT and represented by the GOES I through GOES M spacecraft. The GOES-NEXT series is a joint effort on the part of NASA and NOAA to provide continued operational monitoring of weather systems primarily over the United States…. The GOES I-M spacecraft will be placed over the equator at 135 deg West or 75 deg West. The spacecraft structure is based on the Space Transportation System (STS)-launched, three-axis stabilized Insat (geostationary satellite for India) meteorological satellite design… The GOES-NEXT instruments consist of the following: (1) Earth Imaging System, a 5-channel visible and infrared radiometer which provides Earth imagery 24 hours a day; (2) Sounding System, a 19-channel discrete-filter radiometer for obtaining atmospheric temperature and moisture soundings; (3) a Space Environment Monitor (SEM), which consists of a magnetic field sensor, a solar X-ray sensor, an energetic particle sensor (EPS), and a High Energy Proton and Alpha Detector…" http://science.nasa.gov/realtime/satlookup.aspx?sc=2000-022A
• *GOES 12 (GOES South,* formerly *GOES-M)*: "GOES 12 is an American geosynchronous weather satellite that was launched … on 23 July 2001. The spacecraft carries an IR imager, a "sounder", and an X-ray imager. The IR imager is a Cassegrain telescope covering five wavelength channels, 0.55-0.75, 3.80-4.00, 6.50-7.00, 10.20-11.20, and 11.50-12.50 microns. It can provide images covering 3,000 km x 3,000 km every 41 seconds, by scanning the area in 16 square kilometer sections. The "sounder" is to provide vertical distribution of temperature, moisture and ozone, by passive monitoring in 18 depth-dependent wavelengths. (Long wave IR: 14.71, 14.37, 14.06, 13.64, 13.37, 12.66, and 12.02 microns. Medium wave IR: 11.03, 9.71, 7.43, 7.02, and 6.51 microns. Short wave IR: 4.57, 4.52, 4.45, 4.13, 3.98, and 3.74 microns. There is also another band at visible wavelength 0.7 microns, just to provide pictures of cloud tops.) The sounder covers an area of 3,000 km x 3,000 km in about 42 minutes…"
http://science.nasa.gov/realtime/satlookup.aspx?sc=2001-031A
[392] http://goes.gsfc.nasa.gov/text/goes.databook.html
[393] http://noaasis.noaa.gov/NOAASIS/ml/sounder.html

Imager Channel	Wavelength Range µm	Range of Measurements	Objective and Maximum Temp. Range
1	0.55 to 0.75 [visible light]	1.6% to 100% albedo	Cloud cover
2: I/J/L	3.80 to 4.00 [near IR]	4 to 320 K	Nighttime clouds (space – 340 K)
2: L/M	3.80 to 4.00 [near IR]	4 to 335 K	Nighttime clouds (space – 340 K)
3: I/J/K/L	6.50 to 7.00 [near IR]	4 to 320 K	Water vapor (space – 290 K)
3: M	13.0 to 13.7 [mid IR]	4 to 320 K	Cloud cover and height
4	10.2 to 11.2 [mid IR "IR 1"]	4 to 320 K	Sea surface temperature and water vapor (space – 335 K)
5 I/J/K/L	11.5 to 12.5 [mid IR "IR 2"]	4 to 320 K	Sea surface temperature and water vapor (space – 335 K)
5 M	5.8 to 7.3 [near IR "IR 2"]	4 to 320 K	Water vapor

Geostrophic wind/flow:

"is the theoretical wind that would result from an exact balance between the Coriolis effect and the pressure gradient force. This condition is called *geostrophic balance*. The geostrophic wind is directed parallel to isobars (lines of constant pressure at a given height). This balance seldom holds exactly in nature. The true [actual observed] wind almost always differs from the geostrophic wind due to other forces such as friction from the ground. Thus, the actual wind would equal the geostrophic wind only if there were no friction and the isobars were perfectly straight. Despite this, much of the atmosphere outside the tropics is close to geostrophic flow much of the time and it is a valuable first approximation."[394] See also detailed discussion in Dynamics above.

Gravity Anomaly:

This topic interests me but has limited relevance to atmospheric science, aside from its contribution to geopotential. Deviations are measured in mGal. The Bouguer anomalies usually are negative in the mountains because of isostasy. For the complete-Bouger anomaly (usual abbreviation ΔgB), the digital terrain model is considered as accurate as possible.[395]

"Gravity anomaly maps depict the difference between theoretical computed gravity values and observed gravity values for a region of the earth's crust. The difference between these values may be positive or negative. P. Bouguer first observed this anomaly in 1735, noting that the deviation of a plumb-line in gravitational observations was less than a calculated value. He attributed the anomaly to isostatic compensation resulting from a deficiency of mass in the earth's crust where it underlies mountain ranges.

The anomaly is mapped with isolines (lines of equal value) that represent gravity (*isogals*). The contour interval uses *milligals* (1/1000th of a gal) as gravitational units of measure. A gal is a unit of acceleration named after Galileo, equivalent to 1 cm/sec/sec, but is too large to measure the earth's gravitational field anomalies and so it has been divided into milligals to facilitate measurement. Bouguer anomalies are calculated for a sea-level datum using density values of 2.67 grams per centimeter cubed for rock density and 1.00 grams per centimeter cubed for water."[396]

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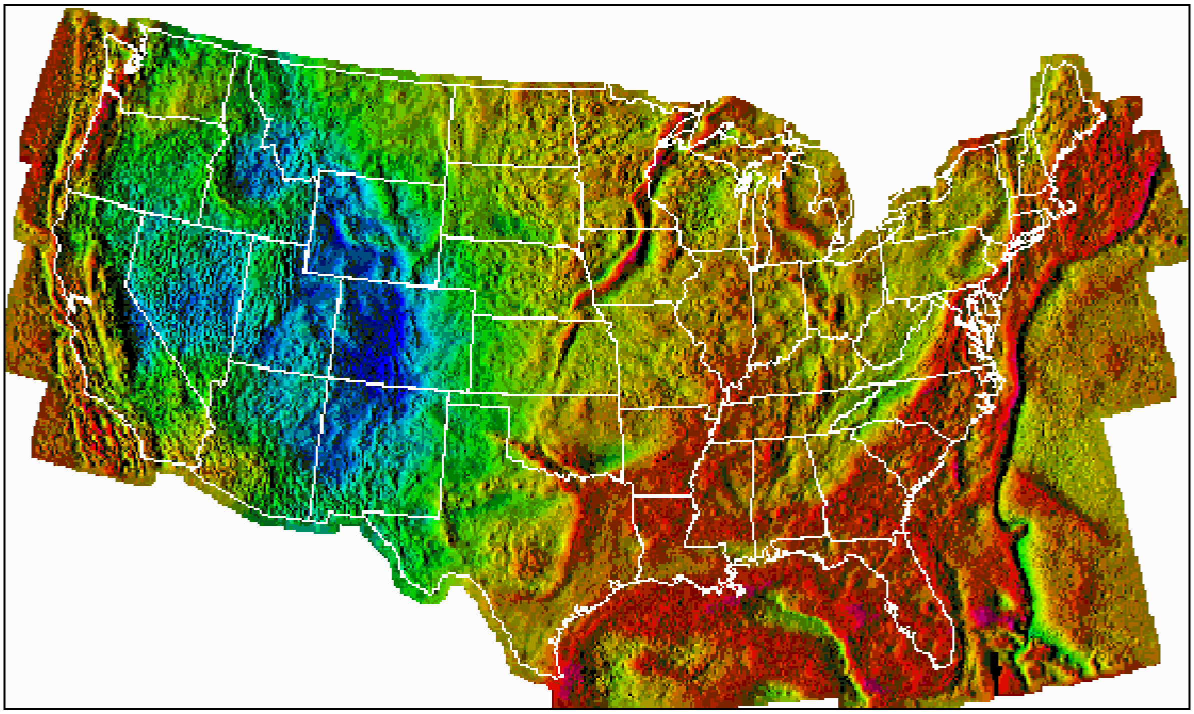
[394] http://en.wikipedia.org/wiki/Geostrophic_wind
[395] http://en.wikipedia.org/wiki/Gravity_anomaly
[396] http://www.sco.wisc.edu/maps/gravityanomaly.php



Complete-Bouguer gravity anomaly data for the CONUS and free-air gravity anomaly data offshore. Red shades indicate areas of high gravity values produced by high average densities in the Earth's crust and upper mantle; blue shades indicate areas of low gravity values produced by low average densities.
http://pubs.usgs.gov/fs/fs-0078-95/FS078-95.html

Hygrometer:

"Hygrometers are instruments used for measuring relative humidity. A simple form of a hygrometer is specifically known as a *psychrometer* and consists of two thermometers, one of which includes a dry bulb and one of which includes a bulb that is kept wet to measure wet-bulb temperature. Modern electronic devices use temperature of condensation, changes in electrical resistance, and changes in electrical capacitance to measure humidity changes… One device that uses the wet/dry bulb method is the *sling psychrometer*, where the thermometers are attached to a handle or length of rope and spun around in the air for a few minutes… Humidity measurement is among the more difficult problems in basic meteorology… Hygrometers must be calibrated in air, which is a much less effective heat transfer medium than is water, and many types are subject to drift…"[397]

OED3: *psychro–* is a combining form meaning "of or relating to cold"

Isobar:

A contour line of equal pressure, usually expressed as surface level pressure after adjustment to mean sea-level (SLP). Surface pressure readings that are not corrected to SLP would have little predictive usefulness, as pressure over the mountains would always be low and pressure over lowlands would always be high. "An isobar … is a line of equal or constant pressure on a graph, plot, or map; an isopleth [isoline] or contour line of pressure. More accurately, isobars are lines drawn on a map joining places of equal average atmospheric pressure reduced to sea level for a specified period of time. In meteorology, the barometric pressures shown are reduced to sea level, not the surface pressures at the map locations. The distribution of isobars is closely related to the magnitude and direction of the wind field, and can be used to predict future weather patterns…"[398]

Wind blows to some extent across isobars from higher to toward lower pressure (but see discussion with Coriolis effect as to how wind is deflected by this effect).

Isoentropic (Isentropic) process:

"In thermodynamics, an isentropic process or isoentropic process … is one in which for purposes of

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[397] http://en.wikipedia.org/wiki/Hygrometer
[398] http://en.wikipedia.org/wiki/Contour_line

engineering analysis and calculation, one may assume that the process takes place from initiation to completion without an increase or decrease in the entropy of the system, i.e., the entropy of the system remains constant. It can be proved that any reversible adiabatic process is an isentropic process."[399]

Isohypse:

A contour line on a constant pressure height surface (e.g., the 500 mb surface) for which line the height above sea level (typically, the geopotential height above mean sea level) is constant. The pressure along the contour line also happens to be constant, but this applies to the entire constant pressure surface by definition, whereas the different isohyspe contours have different geopotential heights. Thus on such a surface, there would only be one isobar.

Isopleth (Isoline):

In meteorology, the word *isopleth* is used for any type of contour line, and is synonymous with *isoline*. In contrast, "In geography, the word isopleth (from plethos, meaning 'quantity') is used for contour lines that depict a variable which cannot be measured at a point, but which instead must be calculated from data collected over an area. An example is population density."[400]

Isotach and Isogon:

Isotach: "A line of equal or constant wind speed on a graph or chart, such as a weather map."[401] The wind direction is not indicated and may change along an isotach.

Isogon: In meteorology, an **isogon** refers to a line of constant wind direction. (The term may refer to constant direction of other quantities in other disciplines).[402]

Isotherm:

A contour line of constant temperature.

Latitude Zones: Tropics of Cancer and Capricorn, Meteorological Tropical Zone, etc.:

Wikipedia: "**The Tropic of Cancer**, also referred to as the Northern tropic, is the circle of latitude on the Earth that marks the most northerly position at which the Sun may appear directly overhead at its zenith. This event occurs once per year, at the time of the June solstice, when the Northern Hemisphere is tilted toward the Sun to its maximum extent… Its Southern Hemisphere counterpart, marking the most southerly position at which the Sun may appear directly overhead, is the **Tropic of Capricorn**. These tropics are two of the five major degree measures or major circles of latitude that mark maps of the Earth, besides the Arctic and Antarctic Circles and the Equator. The positions of these circles of latitude (other than the Equator) are dictated by the tilt of the Earth's axis of rotation relative to the plane of its orbit."[403]

RAH: In contrast, meteorologists use roughly ±30 degrees to demarcate the *Tropical Latitudes*, the latitudes between 30 and 60 degrees to demarcate the *Extratropical Storm Latitudes*, and presumably the latitudes above 60 are the high latitude zones or *Polar latitudes*.

Mesoscale (1 or 10 km to 1000 km) and Microscale (< 10 km or < 1 km) meteorology:

Mesoscale: AMS: Mesoscale meteorology is "…pertaining to atmospheric phenomena having horizontal scales ranging from a few to several hundred kilometers, including thunderstorms, squall lines, fronts, precipitation bands in tropical and extratropical cyclones, and topographically generated weather systems such as mountain waves and sea and land breezes."[404]

Merriam Webster: "approximately 10 to 1000 km in horizontal extent."[405]

Wikipedia: Mesoscale meteorology "is the study of weather systems smaller than synoptic scale systems [thus <1000 km] but larger than microscale [thus >1 km]… and storm-scale cumulus systems [MCM: i.e., the size of individual thunderstorms, inconsistent with other definitions above]. Horizontal dimensions generally range from around 5 kilometers to several hundred kilometers. Examples of mesoscale weather systems are sea breezes, squall lines, and mesoscale convective complexes… Vertical velocity often equals

399 http://en.wikipedia.org/wiki/Isentropic_process
400 http://en.wikipedia.org/wiki/Contour_line#Isopleths
401 http://en.wiktionary.org/wiki/isotach
402 http://en.wikipedia.org/wiki/Contour_line
403 http://en.wikipedia.org/wiki/Tropic_of_Cancer
404 http://amsglossary.allenpress.com/glossary/search?p=1&query=mesoscale&submit=Search
405 http://www.merriam-webster.com/dictionary/mesoscale

or exceeds horizontal velocities in mesoscale meteorological systems due to nonhydrostatic processes such as buoyant acceleration of a rising thermal or acceleration through a narrow mountain pass."[406]

Microscale: "Microscale meteorology is the study of short-lived atmospheric phenomena smaller than mesoscale, about 1 km or less. These two branches of meteorology are sometimes grouped together as 'mesoscale and microscale meteorology' (MMM) and together study all phenomena smaller than synoptic scale; that is they study features generally too small to be depicted on a weather map. These include small and generally fleeting cloud "puffs" and other small cloud features. Microscale meteorology controls the most important mixing and dilution processes in the atmosphere. Important topics in microscale Meteorology include heat transfer and gas exchange between soil, vegetation, and/or surface water and the atmosphere caused by near-ground turbulence. Measuring these transport processes involves use of micrometeorological (or flux) towers. Variables often measured or derived include net radiation, sensible heat flux, latent heat flux, ground heat storage, and fluxes of trace gases important to the atmosphere, biosphere, and hydrosphere."[407]

Radar Reflectivity Z and dBZ:

NWS JetStream: dBZ is "a logarithmic expression for reflectivity factor, referenced to ($1\ mm^6$ / $1\ m^3$).
$dBZ = 10 \log (z / 1\ mm^6\ m^3)$."

NOAA: "When the 'z' is large (many drops in a cubic meter), the reflected power is large. A small 'z' means little returned energy. In fact, 'z' can be less than $1\ mm^6/m^3$ and since it is logarithmic, dBz values will become negative, as often in the case when the radar is in clear air mode and indicated by earthtone colors."

Wikipedia: "dBZ stands for decibels of Z. It is a meteorological measure of equivalent reflectivity (Z) of a radar signal reflected off a remote object. The reference level for Z is $1\ mm^6\ m^{-3}$, which is equal to $1\ \mu m^3$. It is related to the number of drops per unit volume and the sixth power of drop diameter… Reflectivity of a cloud is dependent on the number and type of hydrometeors, which includes rain, snow, and hail, and the hydrometeors' size. A large number of small hydrometeors will reflect the same as one large hydrometeor. The signal returned to the radar will be equivalent in both situations, so a group of small hydrometeors is virtually indistinguishable from one large hydrometeor on the resulting radar image. A meteorologist can determine the difference between one large hydrometeor and a group of small hydrometeors as well as the type of hydrometeor through knowledge of local weather condition contexts. One dBZ-scale of rain: 40=heavy; 24–39 moderate; 8–23 light; 0–8 barely anything."[408]

Radiosonde, Rawinsonde, and Dropwindsonde System:

OED3 etymology of *sonde*: French for 'sounding-line, sounding'…"A radiosonde or similar device that is sent aloft to transmit or record information on conditions in the atmosphere. Orig. only as the second element in [combinations] (as ballon-sonde, ionosonde, radiosonde, etc.)"

Edward J. Hopkins: "The radiosonde is a balloon-borne instrument platform with radio transmitting capabilities. Originally named a radio-meteorograph, the instrument is now referred to as a radiosonde, a name apparently derived by H. Hergesell from a combination of the words *radio* for the onboard radio transmitter and *sonde* [see above] … The radiosonde contains instruments capable of making direct in-situ measurements of air temperature, humidity and pressure with height, typically to altitudes of approximately 30 km. These observed data are transmitted immediately to the ground station by a radio transmitter located within the instrument package. The ascent [and translation] of a radiosonde provides an indirect measure of the wind speed and direction at various levels throughout the troposphere. Ground based radio direction finding antenna equipment track the motion of the radiosonde during its ascent through the air. The recorded elevation and azimuth information are converted to wind speed and direction at various levels by triangulation techniques… A *rawinsonde* (or radio wind sonde) is a radiosonde package with an attached radar reflector that permits radio-direction finding equipment to

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[406] http://en.wikipedia.org/wiki/Mesoscale_meteorology
[407] http://en.wikipedia.org/wiki/Microscale_meteorology
[408] dBZ:
- http://en.wikipedia.org/wiki/DBZ_%28meteorology%29
- http://www.srh.noaa.gov/jetstream/append/glossary_d.htm
- http://www.srh.noaa.gov/jetstream/doppler/radarfaq.htm#diff

determine the wind direction and wind speed at various altitudes during the ascent of the package."[409]

Wikipedia: Transmission is at ~403 MHz or ~1680 MHz "The first true radiosonde that sent precise encoded telemetry from weather sensors was invented in France by Robert Bureau… Worldwide there are more than 800 radiosonde launch sites… Nearly all routine radiosonde launches occur 45 minutes before the official observation time of 0000 UTC and 1200 UTC, so as to provide an instantaneous snapshot of the atmosphere… Sometimes radiosondes are deployed by being dropped from an aircraft… [and] are called *dropsondes* [or more commonly *dropwindsones*]."

Well-annotated sample sounding data may be seen *here*[410] by selecting a station[411] (e.g., 72797 UIL = Quillayute, 72786 OTX = Spokane, 72694 SLE = Salem, 72597 MFR = Medford, 72672 RIW = Riverton WY), the text or graph type (such as "GIF: to 10 mb"), and desired date. The

Rossby (planetary) waves:

AMS: "A wave on a uniform current in a two-dimensional nondivergent fluid system, rotating with varying angular speed about the local vertical (beta plane)… This is a special case of a barotropic disturbance, conserving absolute vorticity. Applied to atmospheric flow, it takes into account the variability of the Coriolis parameter while assuming the motion to be two-dimensional. The wave speed c is given by [formula] where μ is the mean westerly flow, β is the Rossby parameter, and $K^2 = k^2 + l^2$, the total wavenumber squared. (This formula is known as the Rossby formula, long-wave formula, or planetary-wave formula.) A stationary Rossby wave is thus of the order of the distance between the large-scale semipermanent troughs and ridges in the middle troposphere. The Rossby wave moves westward relative to the current, in effect slowing the eastward movement of long-wave components relative to the short-wave components in a barotropic flow. This effect is important in a numerical forecast with a barotropic model, but attempts to apply the formula to actual contour patterns considered as waves have less dynamic justification and correspondingly less success."[412]

Wikipedia: "…are giant meanders in high-altitude winds that are a major influence on weather. Their emergence is due to shear in rotating fluids, so that the Coriolis force changes along the sheared coordinate. In planetary atmospheres, they are due to the variation in the Coriolis effect with latitude. The waves were first identified in the Earth's atmosphere in 1939 by Carl-Gustaf Arvid Rossby who went on to explain their motion… Most work on Rossby waves has been done on those in Earth's atmosphere. The special identifying feature of the Rossby waves is [that] its phase velocity (that of the wave crests) always has a westward component. However, the wave's group velocity (associated with the energy flux) can be in any direction. In general: shorter waves have an eastward group velocity and long waves a westward group velocity. The terms "barotropic" and "baroclinic" Rossby waves are used to distinguish their vertical structure. *Barotropic Rossby waves* do not vary in the vertical [direction], and have the fastest propagation speeds. The *baroclinic wave* modes are slower, with speeds of only a few centimetres per second or less… Rossby waves in the atmosphere are easy to observe as (usually 4-6) large-scale meanders of the jet stream. When these loops become very pronounced, they detach the masses of cold, or warm, air that become cyclones and anticyclones and are responsible for day-to-day weather patterns at mid-latitudes."[413]

Standard Atmospheres:

These are defined by national and international standards organizations. They define idealized atmospheres (dry ideal gas) by composition, P, T, density, g, variations with height, etc.
(1) U.S. Standard Atmosphere 1976 (ref.[414])

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409 Radiosonde:
• http://www.meteor.wisc.edu/~hopkins/wx-inst/wxi-raob.htm
• http://en.wikipedia.org/wiki/Radiosonde
410 http://weather.uwyo.edu/upperair/sounding.html
411 http://www.ua.nws.noaa.gov/nws_upper.htm
412 http://amsglossary.allenpress.com/glossary/search?p=1&query=Rossby+wave&submit=Search
413 http://en.wikipedia.org/wiki/Rossby_wave
414 US Standard Atmosphere:
• Full description: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19770009539_1977009539.pdf
• Wikipedia: http://en.wikipedia.org/wiki/U.S._Standard_Atmosphere

(2) International Standard Atmosphere (ISA)[415]
(3) International Civil Aviation Organization (ICAO) Standard Atmosphere (an extension of the ISA).[416] This is the standard utilized in the Skew-T Log P diagram.

Surface Weather Observation Stations and Upper-air stations:

Measurements made at ground level stations include the ASOS systems (Automated Surface Observing System) and Automated Weather Observing System (AWOS).[417] This is as opposed to upper-air stations that use the rawinsonde system of radiosondes or other methods for making higher altitude observations. Also, "supplementing the radiosondes, a network of aircraft [data] collection is organized by the World Meteorological Organization."[418]

Well-annotated upper air rawinsonde soundings as text or graphs may be seen *here*[419] by selecting a station, the text or graph type (such as "GIF: to 10 mb"), and the desired date/time. Closest stations to Seattle with approximate air mileages[420] from downtown Seattle (122.33306° W / 47.60972° N) are:

72797 UIL = Quillayute WA	106 mi
72786 OTX = Spokane WA	220 mi
72694 SLE = Salem OR	189 mi
72597 MFR = Medford OR	363 mi
72681 BOI = Boise ID	407 mi
72776 TFX Great Falls MT	516 mi
71203 YLW Kelowna BC	212 mi
71109 YZT Port Hardy BC	312 mi
72672 RIW = Riverton WY	744 mi

There are no upper-air stations closer to Seattle than those I have listed here. The US upper-air level soundings graphs typically extend to 100 mb (16 km) or even as high as to 10 mb (31 km).

Synoptic Scale Meteorology (aka Large or Cyclonic Scale, > 1000 km):

"The synoptic scale in meteorology (also known as large scale or cyclonic scale) is a horizontal length scale of the order of *1000 kilometres* (about 620 miles) or more. This corresponds to a horizontal scale typical of mid-latitude depressions. Most high and low pressure areas seen on weather maps such as surface weather analyses are synoptic-scale systems, driven by the location of Rossby waves in their respective hemisphere. Low pressure areas and their related frontal zones occur on the leading edge of a trough within the Rossby wave pattern, while surface highs form on the back edge of the trough. Most precipitation areas occur near frontal zones. The word synoptic is derived from the Greek word *sunoptikos* meaning seen together."[421]

Time: Coordinated Universal Time UTC, Universal Time UT, Universal [Astronomical] Time UT1, and Greenwich Mean Time GMT:

Wikipedia on UTC:[422] "*Coordinated Universal Time (UTC)* is a time standard based on *International Atomic*

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[415] International Standard Atmosphere (ISA):
http://en.wikipedia.org/wiki/International_Standard_Atmosphere

[416] ICAO Standard Atmosphere
• Full Description: ICAO publication *Manual of the ICAO Standard Atmosphere: extended to 80 kilometres (262 500 feet)*, 1993 (not available free online)
• Wikipedia: http://en.wikipedia.org/wiki/International_Civil_Aviation_Organization

[417] ASOS/AWOS of FAA:
• http://www.faa.gov/air_traffic/weather/asos/
• http://www.allweatherinc.com/aviation/awos_dom.html

[418] http://en.wikipedia.org/wiki/Meteorology

[419] http://weather.uwyo.edu/upperair/sounding.html

[420] http://boulter.com/gps/distance/?from=47.60972%2C+122.33306&to=47.95%2C+124.55+&units=m

[421] http://en.wikipedia.org/wiki/Synoptic_scale

[422] UTC, UT, and UT1:
• Wikipedia: http://en.wikipedia.org/wiki/Coordinated_Universal_Time
• Wikipedia on UT1: http://en.wikipedia.org/wiki/Universal_Time
• USNO: http://www.usno.navy.mil/USNO/astronomical-applications/astronomical-information-center/universal-time
• USNO on precise time: http://www.usno.navy.mil/USNO/time/time
• NIST: http://www.nist.gov/pml/general/time/index.cfm

Time (TAI) with leap seconds added at irregular intervals to compensate for the Earth's slowing rotation. Leap seconds are used to allow UTC to closely track UT1, which is mean solar time at the Royal Observatory, Greenwich. Since the difference between UTC and UT1 is not allowed to exceed 0.9 seconds, if high precision is not required, the general term *Universal Time (UT)* may be used… In casual use, when fractions of a second are not important, *Greenwich Mean Time (GMT)* can be considered equivalent to UTC or UT1. Saying "GMT" often implies either UTC or UT1 when used within informal or casual contexts. In technical contexts, usage of "GMT" is avoided; the unambiguous terminology "UTC" or "UT1" is preferred. Time zones around the world can be expressed as positive or negative offsets from UTC… UTC replaced GMT as the basis for the main reference time scale or civil time in various regions on 1 January 1972." The acronym UTC is a compromise between English CUT = *coordinated universal time* and French TUC =*temps universel coordonné*.

USNO: "The times of various events, particularly astronomical and weather phenomena, are often given in *Universal Time* (abbreviated *UT*) which is sometimes referred to, now colloquially, as *Greenwich Mean Time* (abbreviated *GMT*). The two terms are often used loosely to refer to time kept on the Greenwich meridian (longitude zero)… Times given in UT are almost always given in terms of a 24-hour clock. Thus, 14:42 (often written simply 1442) is 2:42 p.m., and 21:17 (2117) is 9:17 p.m. Sometimes a Z is appended to a time to indicate UT, as in 0935Z…. When a precision of one second or better is needed, however, it is necessary to be more specific about the exact meaning of UT. For that purpose different designations of Universal Time have been adopted. In astronomical and navigational usage, UT often refers to a specific time called *UT1*, which is a measure of the rotation angle of the Earth as observed astronomically. It is affected by small variations in the rotation of the Earth, and can differ slightly from the civil time on the Greenwich meridian. Times which may be labeled "Universal Time" or "UT" in data provided by the U.S. Naval Observatory (for example, in the annual almanacs) conform to this [astronomical] definition… However, in the most common civil usage, UT refers to a time scale called *Coordinated Universal Time* (abbreviated *UTC*), which is the basis for the worldwide system of civil time. This time scale is kept by time laboratories around the world, including the U.S. Naval Observatory, and is determined using highly precise atomic clocks. The International Bureau of Weights and Measures makes use of data from the timing laboratories to provide the international standard UTC which is accurate to approximately a nanosecond (billionth of a second) per day. The length of a UTC second is defined in terms of an atomic transition of the element cesium under specific conditions, and is not directly related to any astronomical phenomena. UTC is the time distributed by standard radio stations that broadcast time, such as WWV and WWVH. It can also be obtained readily from the Global Positioning System (GPS) satellites. The difference between UTC and UT1 is made available electronically and broadcast so that navigators can obtain UT1. UTC is the basis for civil standard time in the U.S. and its territories. Standard time within U.S. time zones is an integral number of hours offset from UTC… One can think of UT1 as being a time determined by the rotation of the Earth, over which we have no control, whereas UTC is a human invention. It is relatively easy to manufacture highly precise clocks that keep UTC, while the only "clock" keeping UT1 precisely is the Earth itself. Nevertheless, it is desirable that our civil time scale not be very different from the Earth's time, so, by international agreement, UTC is not permitted to differ from UT1 by more than 0.9 second. When it appears that the difference between the two kinds of time may approach this limit, a one-second change called a *leap second* is introduced into UTC. This occurs on average about once every year to a year and a half."

Wikipedia on UT1: "UT1 is the principal form of Universal Time. While conceptually it is mean solar time, precise measurements of the Sun are difficult. Hence, it is computed from observations of distant quasars using long baseline interferometry, laser ranging of the Moon and artificial satellites as well the determination of GPS satellite orbits. UT1 is the same everywhere on Earth, and is proportional to the rotation angle of the Earth with respect to distant quasars, specifically, the International Celestial Reference Frame (ICRF), neglecting some small adjustments. The observations allow the determination of a measure of the Earth's angle with respect to the ICRF, called the Earth Rotation Angle (ERA, which serves as a modern replacement for Greenwich Mean Sidereal Time). UT1 is required to follow the relationship:

$$ERA = 2\pi(0.7790572732640 + 1.00273781191135448T_\mu) \text{ radians}$$

where T_μ = (Julian UT1 date - 2451545.0)."

Trough and Ridge:

Trough: "In meteorology, an elongated area of relatively low atmospheric pressure; the opposite of a ridge. The axis of a trough is the *trough line*. This term [trough] is commonly used to distinguish the previous condition [the elongated area of low pressure] from the closed circulation of a low (or cyclone), but a large-scale trough may include one or more lows, an upper-air trough may be associated with a lower-level low, and a low may have one or more distinct troughs radiating from it…"[423] A trough is usually defined on a constant pressure surface, typically 500 mb.

Ridge: "Sometimes called [a] wedge. In meteorology, an elongated area of relatively high atmospheric pressure, almost always associated with and most clearly identified as an area of maximum anticyclonic curvature of wind flow… The locus of this maximum curvature [e.g., along pressure height contours] is called the *ridge line*. Sometimes, particularly in discussions of atmospheric waves embedded in the westerlies, a ridge line is considered to be a line drawn through all points at which the anticyclonically curved isobars or contour lines are tangent to a latitude circle. The most common use of this term is to distinguish it from the closed circulation of a high (or anticyclone); but a ridge may include a high (and an upper-air ridge may be associated with a surface high) and a high may have one or more distinct ridges radiating from its center. The opposite of a ridge is a trough…"[424] A ridge is usually defined on a constant pressure surface, typically 500 mb.

Wind speed at Surface: Ten 10-meter (surface) wind speed:
"Wind speed ten meters (33 feet) above the surrounding vegetation… In most of the world, the standard height above the surrounding vegetation for measuring open wind speed is ten meters (33 feet); in the United States, it is measured 20 feet above the surrounding vegetation (20-ft wind speed). Multiply 20-foot wind speed by 1.15 to estimate 10-meter wind speed; alternately, divide 10-meter wind speed by 1.15 to estimate 20-foot wind speed (Turner and Lawson 1978)."[425]

Surface wind is "wind blowing near the Earth's surface. It is measured, by convention, at a height of 10 m above ground in an area where the [horizontal] distance between the anemometer and any obstruction is at least 10 times the height of the obstruction."[426]

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[423] http://amsglossary.allenpress.com/glossary/search?id=trough1
[424] http://amsglossary.allenpress.com/glossary/search?id=ridge1
[425] http://www.firewords.net/definitions/10-meter_wind_speed.htm
[426] http://nsidc.org/arcticmet/glossary/surface_wind.html