Physical Meteorology

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First Semester, 2004–2005.

Text for the Course

The lectures will be based closely on the text

Atmospheric Science: An Introductory Survey
by
John M. Wallace and Peter V. Hobbs

published by Academic Press (1977).

A second edition of this text is expected to be published next year.

Introduction and Overview

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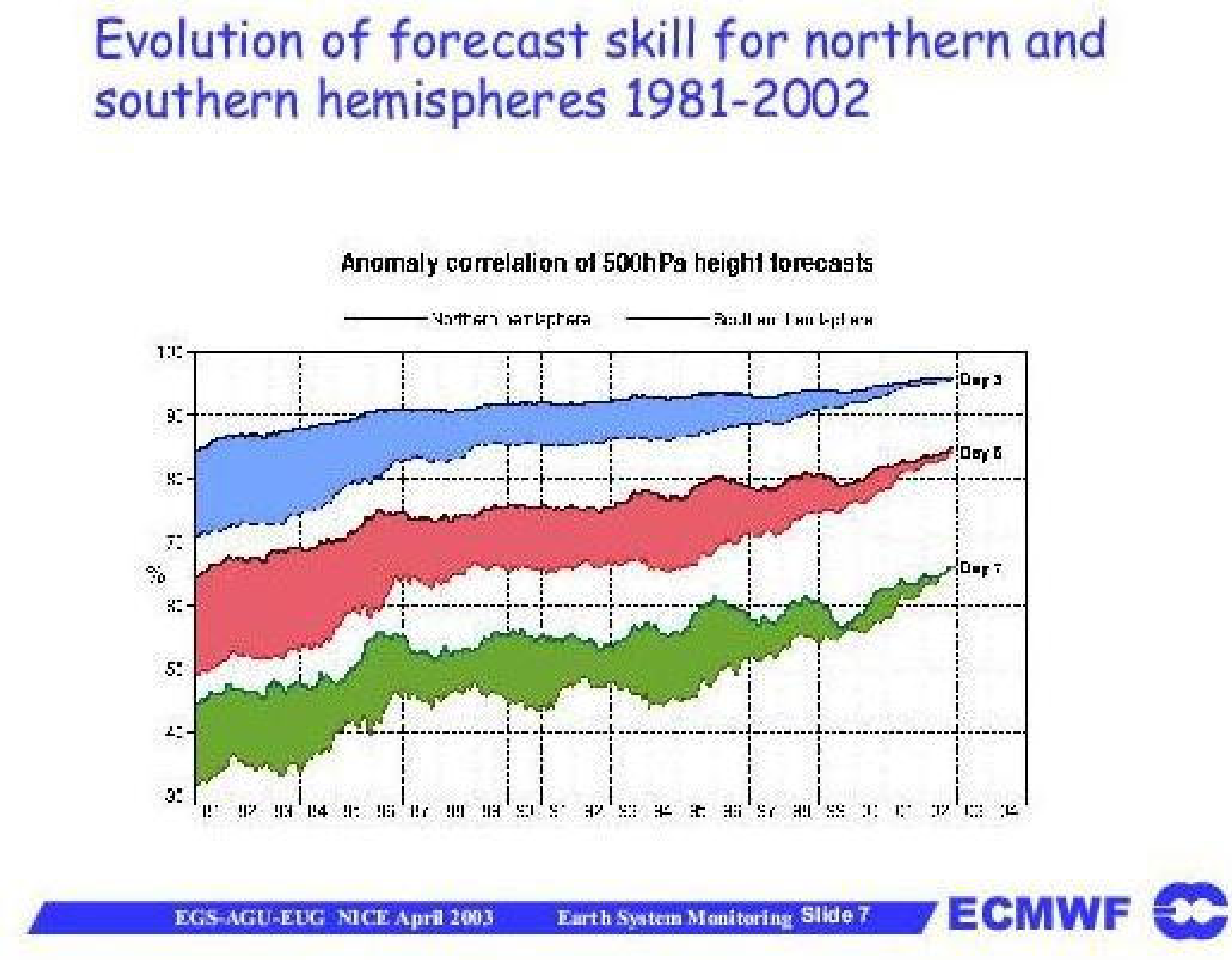
During the past century, weather forecasting has evolved from an *art* that relied solely on experience and intuition, into a *science* that relies on numerical models based on the *conservation of mass, momentum and energy*.

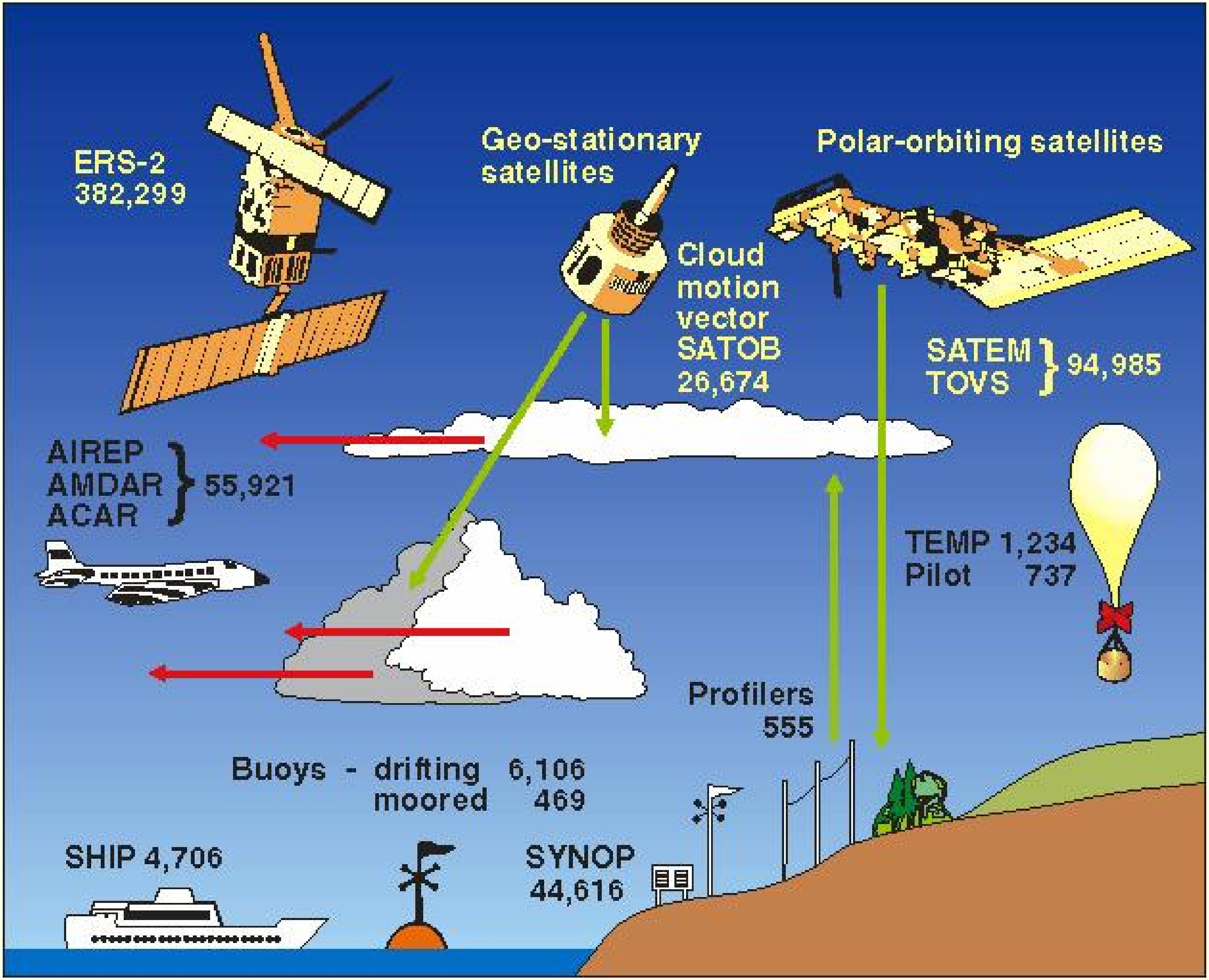
The increasing sophistication of the computer models of the atmosphere has led to dramatic improvements in forecast skill, as shown in the figure which follows.



Forecast Skill. Prediction of 500mb heights.

The Global Observing System

What began in the late 19th century as an assemblage of regional collection centers for real time (synoptic) teletype transmissions of observations of surface weather variables has evolved into an observing system in which satellite and *in situ* measurements of many surface and upper air variables are merged in a consistent way to produce optimal estimates of their respective three-dimensional fields over the entire globe.


ERS-2
382,299
Geo-stationary
satellites
Polar-orbiting satellites
Cloud
motion
vector
SATOB
26,674
SATEM
TOVS
94,985
AIREP
AMDAR
ACAR
55,921
TEMP 1,234
Pilot 737
Profilers
555
Buoys - drifting 6,106
moored 469
SHIP 4,706
SYNOP
44,616

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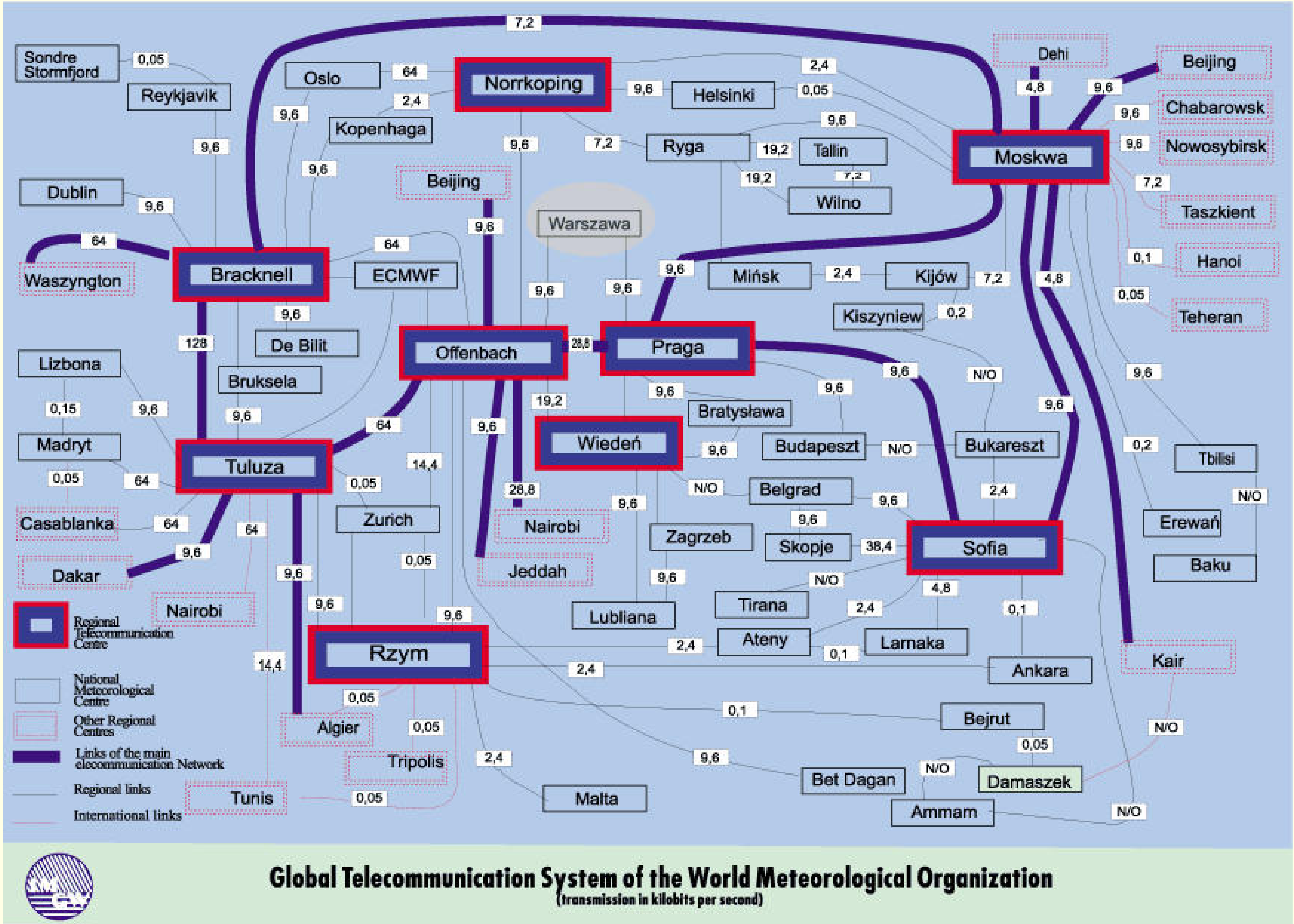

The GTS (Global Telecommunications System)

Atmospheric Chemistry

An increasingly important area of atmospheric science is atmospheric chemistry. Urban air quality has long been a concern. During the 1970's when it was discovered that forests and organisms living in lakes over parts of northern Europe were being killed by acid rain caused by sulfur dioxide emissions from coal-fired electric power plants hundreds of kilometers upwind. The sources of the acidity were gaseous oxides of sulfur and nitrogen (SO_2, NO, NO_2, and N_2O_5) that dissolve in microscopic cloud droplets which may reach the ground as raindrops.

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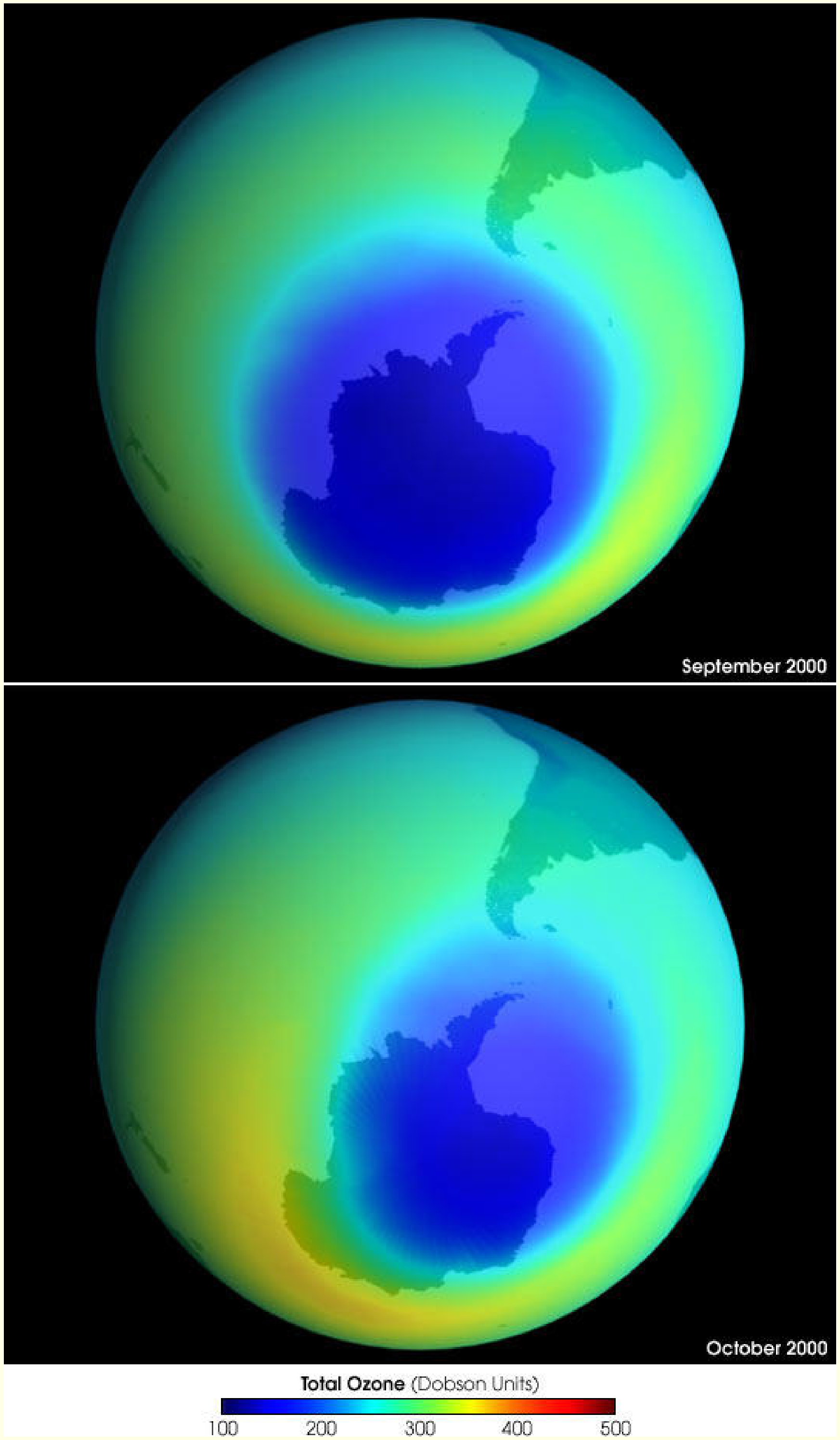
A major discovery of the 1980's was the Antarctic ozone hole, the temporary disappearance of much of the stratospheric ozone layer over the southern polar cap each spring. The ozone destruction was shown to be caused by the breakdown of chloroflurocarbons (CFC's).

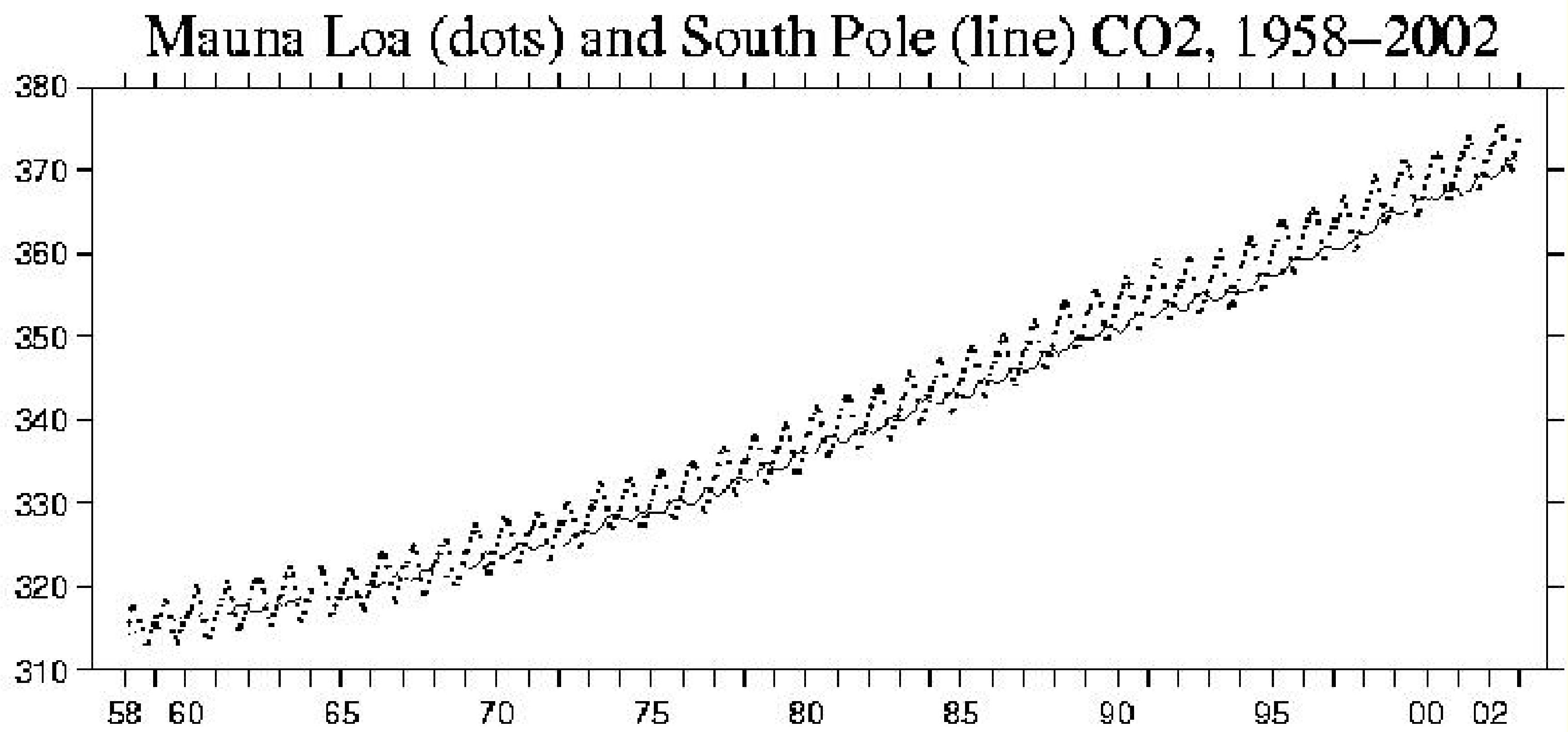


The Antarctic ozone hole due to the build-up of CFC's. Vertically integrated ozone over high latitudes of the southern hemisphere in September and October, 2000. Cool colors represent low values of total ozone.

Greenhouse Warming

The issues surrounding the buildup of atmospheric carbon dioxide and other relatively inert trace gases produced by burning of fossil fuels represent a major challenge for mankind.

The following figure shows the upward trend in atmospheric CO_2 concentrations (in ppmv) at Mauna Loa (black) and South Pole (blue) due to the burning of fossil fuels.



CO_2 variation in Hawaii and Antarctic.

At one time climatic change was viewed by most atmospheric scientists as occurring on such long time scales that, for most purposes, today's climate could be described in terms of a fixed set of statistics, such as January climatological mean (or "normal") temperature.

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The older view was that, on the scale of a human lifetime, the climate could be regarded as *static*. More recent research and indeed general experience has brought us to the realization that this view is not reliable.

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Climate dynamics is inherently multi-disciplinary: the atmosphere must be treated as a component of the Earth system.

The term Earth System Science has been gaining popularity during the last few years.

Some Terms of Reference

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$$dx \equiv r\cos\phi\, d\lambda$$
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Note the (obvious) relationship between r and z

$$r = z + a$$

where a is the radius of the Earth.

[Figure to follow: Draw on board.]

Spherical coordinate system used in atmospheric science

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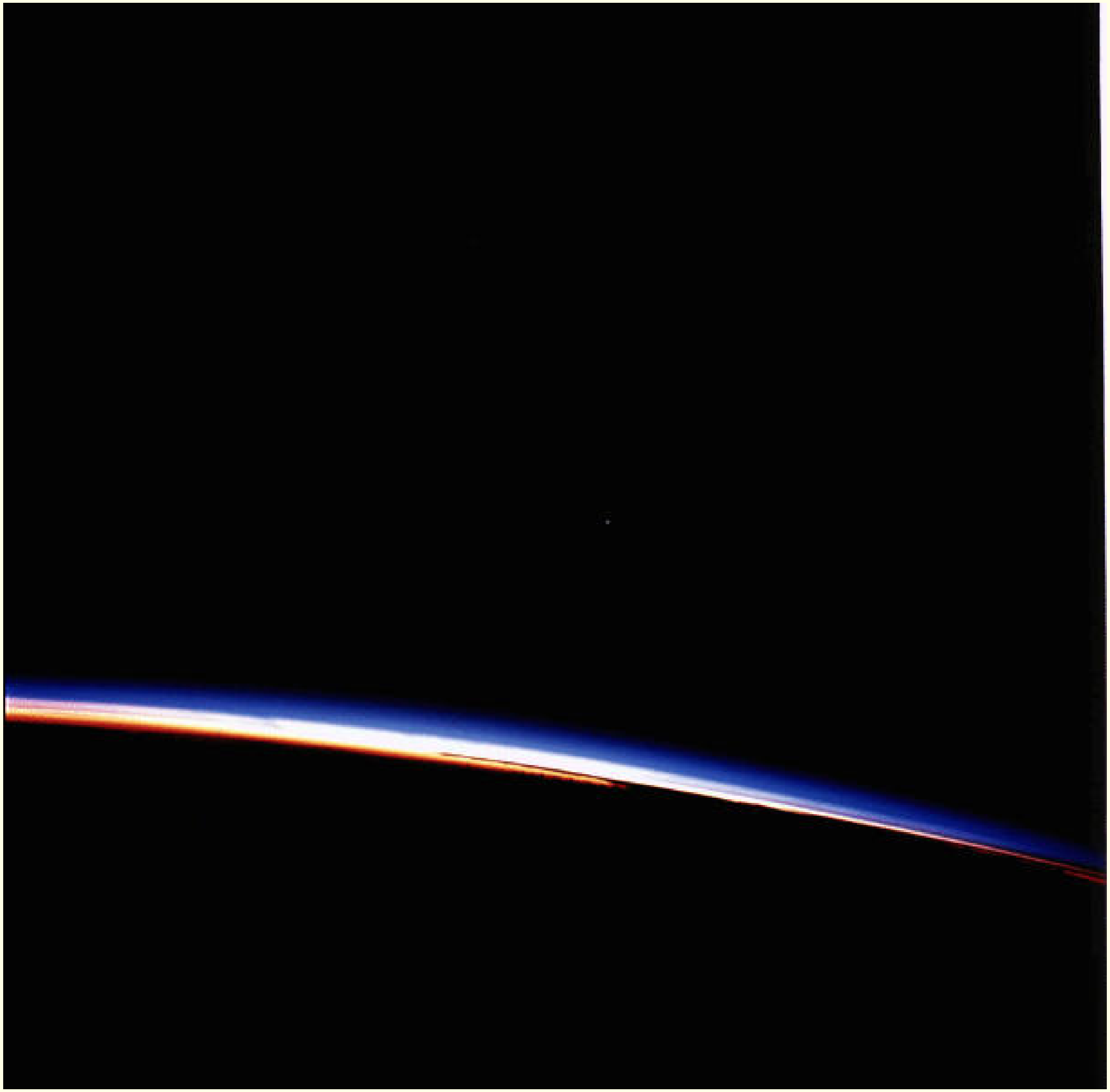
Satellite images of the atmosphere, as viewed edge on emphasize how thin the atmosphere really is.



The limb of the earth, as viewed from space in visible satellite imagery.

The three velocity components are defined as

$$u \equiv \frac{dx}{dt} = a\cos\phi\,\frac{d\lambda}{dt} \qquad \textbf{(the zonal velocity component)}$$

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***Festina lente*.**

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Note that terms such as 'westerly' are frequently misused by those who should know better. For example, an airline pilot may say: "We are taking off in a westerly direction". S/he should say "in a westward direction".

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For vertical velocities, a rough rule of thumb is

$$1\,\mathbf{cm\,s}^{-1} \sim 1\,\mathbf{km\,day}^{-1}$$

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The two derivatives are related by the chain rule

$$\begin{aligned} \frac{d}{dt} &= \frac{\partial}{\partial t} + \frac{dx}{dt}\frac{\partial}{\partial x} + \frac{dy}{dt}\frac{\partial}{\partial y} + \frac{dz}{dt}\frac{\partial}{\partial z} \\ &= \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z} \end{aligned}$$

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We re-write this as

$$\frac{\partial}{\partial t} = \frac{d}{dt} + \left\{ -u\frac{\partial}{\partial x} - v\frac{\partial}{\partial y} - w\frac{\partial}{\partial z} \right\}$$

The terms in the braces are called the *advection*.

At a fixed point in space the Eulerian and Lagrangian rates of change differ by virtue of the advection of air from upstream, which carries with it higher or lower values of the variable in question.

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For the special case of a hypothetical conservative tracer, the Lagrangian rate of change is identically equal to zero, and the Eulerian rate of change is determined entirely by the advection.

Many pollutants can be treated, at least on short time scales, as passive tracers, so their dynamics are governed by advection.

Pressure Units

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Predictability and Chaos

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This *sensitivity to initial conditions* is a characteristic of chaotic nonlinear systems. In fact, it was the growth of errors in an idealized weather forecast model and the long term behavior of extended forecasts carried out with that same model that provided one of the most lucid early demonstrations of the type of behavior signified by the term chaos.

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"Climate is what we expect:
Weather is what we get."

Atmospheric variability on time scales of months or longer is referred to as *climate variability*, and statistics relating to conditions in a typical (as opposed to a particular) season or year are referred to as *climatological statistics*.

Brief Overview of the Atmosphere

The remainder of this introduction provides an overview of the optical properties, composition and vertical structure of the earth's atmosphere, the major wind systems and the climatological-mean distribution of precipitation.

Optical Properties of Atmosphere

The earth's atmosphere is relatively transparent to incoming solar radiation and opaque to outgoing terrestrial radiation.

The blocking of outgoing radiation by the atmosphere, popularly referred to as the *greenhouse effect*, keeps the surface of the earth warm enough so that water in the liquid state is abundant.

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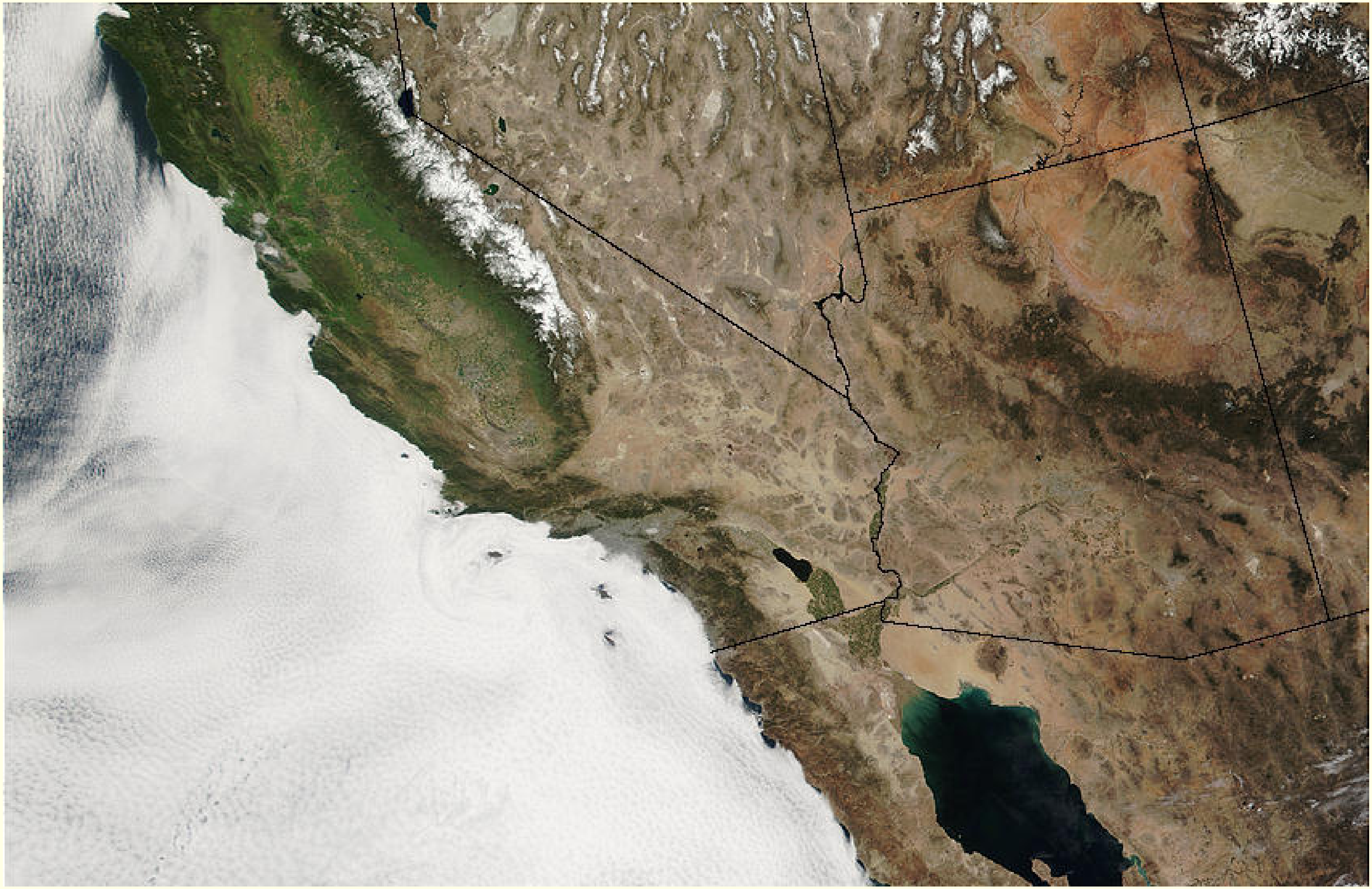
Much of the absorption and reemission of outgoing terrestrial radiation is due to air molecules, but cloud droplets also contribute.

The radiation emitted to space by air molecules and cloud droplets provides a basis for *remote sensing* of the temperature and various atmospheric constituents, using satellite-borne sensors.



A deck of low clouds off the coast of California (viewed in reflected visible radiation)

The back-scattering of solar radiation off the top of the deck of low clouds off the California coast greatly enhances the whiteness (or reflectively) of that region as viewed from space.

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The contribution of clouds to the earth's planetary albedo (i.e., the ratio of backscattered to incoming solar radiation, averaged over the entire planet) is 20%, and atmospheric aerosols also make a significant contribution.

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Since back-scattering depletes the incoming solar radiation as it passes through the atmosphere, it has a cooling effect on climate at the earth's surface.

Mass and Composition

The total mass of the atmosphere can easily be inferred from the mean surface pressure.

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At any point on the earth, the atmosphere exerts a downward force on the underlying surface due to the earth's gravitational attraction. The downward force (the weight) on a unit volume of air with density ρ is

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where g is the acceleration due to gravity.

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$$F = \rho g$$

where g is the acceleration due to gravity.

Integrating this expression from the earth's surface to the "top" of the atmosphere, we obtain the pressure on the earth's surface due to the weight of the air above:

$$p_s = \int_0^\infty \rho g \, dz$$

Assuming for now that g is constant, $g = g_0 = 9.8066\,\mathbf{m\,s}^{-2}$, we get

$$p_s = g_0 \int_0^\infty \rho\, dz = m g_0$$

where m is the vertically integrated mass of the air in the overlying column.

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The globally averaged surface pressure is observed to be $\mathbf{997\,hPa}$. Assuming for simplicity that $g_0 = 10\,\mathbf{m\,s^{-2}}$ and $\bar{p}_s = 10^5\,\mathbf{Pa}$, the mass per unit area is

$$m = \frac{\bar{p}_s}{g_0} = 10^4\,\mathbf{kg\,m^{-2}}$$

Multiplying this value by the surface area of the earth

$$4\pi a^2 = 4\pi \times (6.37 \times 10^6)^2 \approx 5 \times 10^{14}\,\mathbf{m}^2$$

we obtain

$$M \approx 5 \times 10^{18}\,\mathbf{kg}$$

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Exercise: Check this (5 thousand million million tonnes).

Principal Constituents of Air

The atmosphere is composed primarily of nitrogen (80%) and oxygen (20%).

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Ozone concentrations are much smaller than those of water vapor and are also variable.

Because of the large variability of water vapor, it is customary to list the percentages of the various constituents in relation to dry air.

Table 1: **Main Constitutents of the Atmosphere**

Gas		Percentage	Mol. Wt.
Nitrogen	N_2	78%	28
Oxygen	O_2	21%	32
Argon	Ar	0.9%	40
Water	H_2O	variable	18
Air		100%	29

Triatomic Molecules

For reasons that will be explained later, gas molecules comprised of three or more atoms are highly effective at trapping outgoing longwave radiation.

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In the earth's atmosphere, this so-called greenhouse effect is primarily due to water vapor and certain trace gases (CO_2, O_3, CH_4, N_20 and the chlorofluorocarbons or CFC's), all of which are comprised of three or more atoms.

Aerosols

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Averaged over the earth's surface, clouds reflect around 22% of the incoming solar radiation back to space;

Aerosols also contribute to the greenhouse effect.

Vertical Structure

The density of air at sea-level is $1.25\,\mathrm{kg\,m^{-3}}$ to within a few percent. Pressure and density ρ decrease nearly exponentially with height, with an e-folding depth or scale height of 7 or 8 km.

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We will show later that

$$p = p_0 \, e^{-z/H}$$

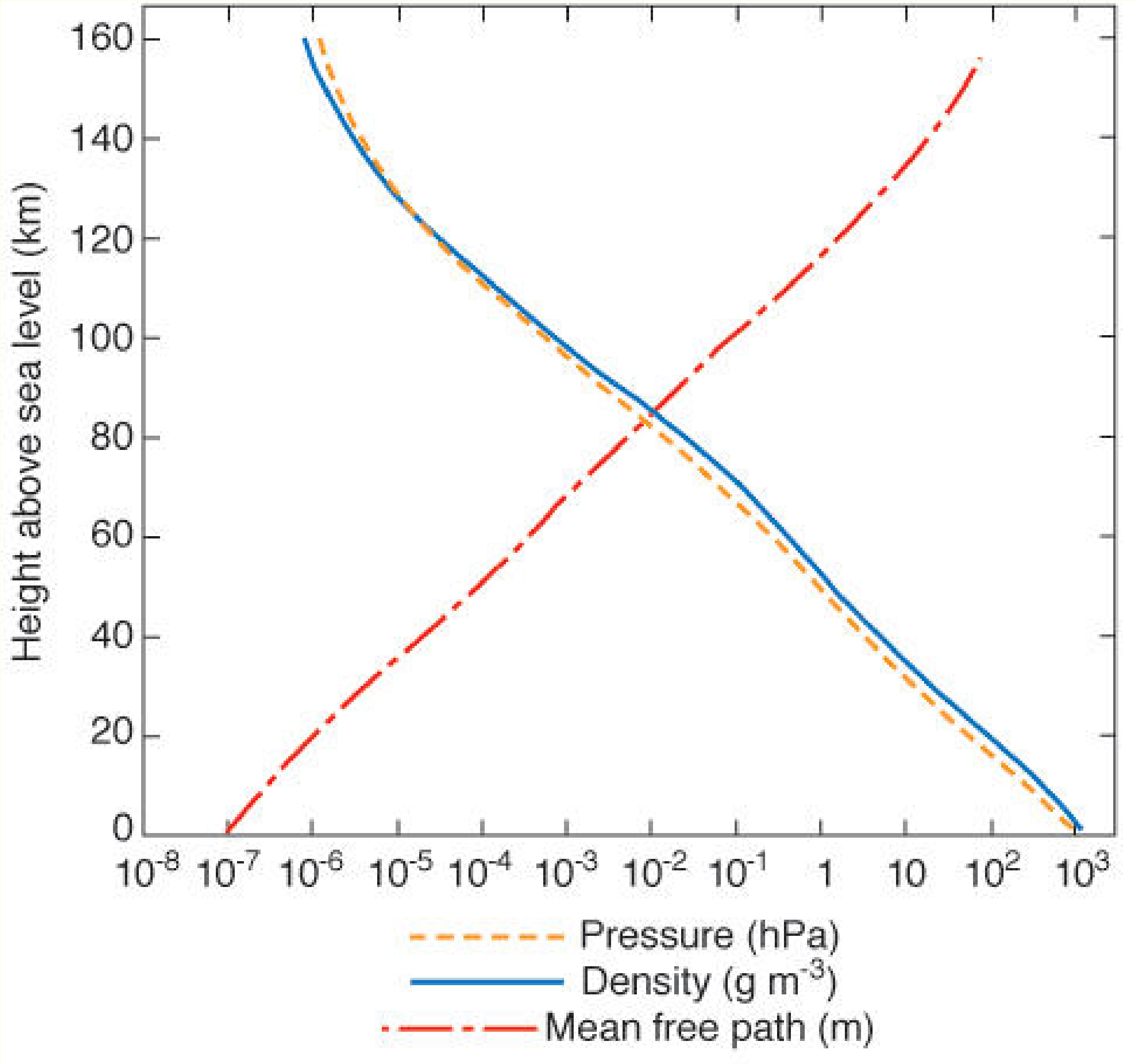
or, equivalently

$$\log\left(\frac{p}{p_0}\right) = -\frac{z}{H}$$

where H is the scale height.

Density decreases with height in the same manner as pressure.

The exponential dependence can be seen from the the fact that the pressure and density curves on a semi-log plot closely resemble straight lines.



Vertical profiles of pressure (hPa), density ($g\,m^{-3}$), and mean free path (m), for the standard atmosphere.

Exercise: **Assuming a scale height of 7.5 km, estimate the heights in the atmosphere at which the air density is equal to 1 $\mathrm{kg\,m^{-3}}$, and the pressure is equal to 1 hPa.**

⋆ ⋆ ⋆

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Because the pressure at a given height in the atmosphere is a measure of the mass that lies above that level, it is sometimes used as a **vertical coordinate** in lieu of height.

For example, the 500-hPa level, situated at a height of around 5.5 km above sea-level is roughly halfway up to the top the atmosphere in terms of mass.

The vertical distribution of temperature for typical conditions in the earth's atmosphere is shown in the following figure. The atmosphere is divided into four layers:

- **troposphere**
- **stratosphere**
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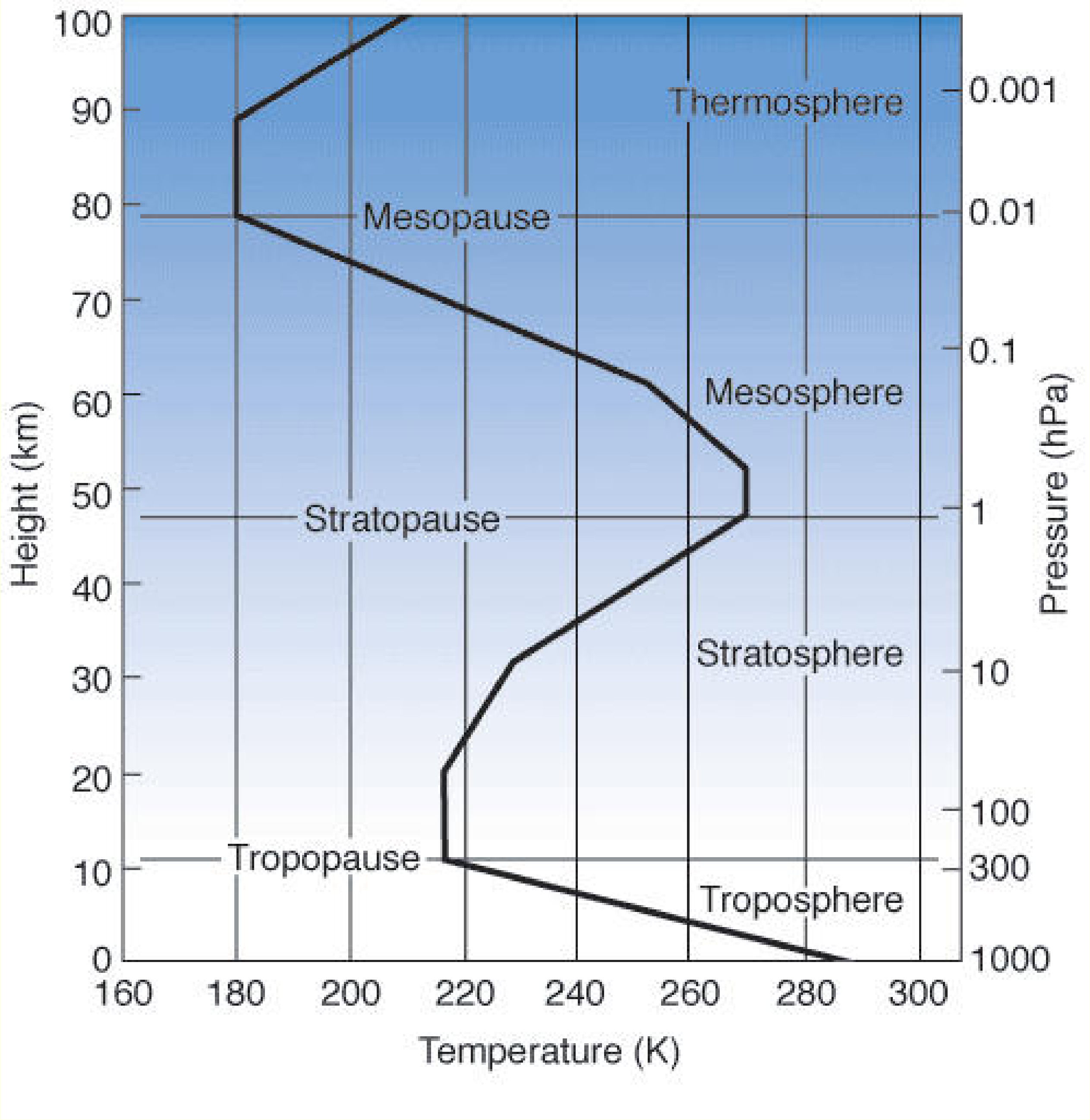
These are separated by surfaces called the

- **tropopause**
- **stratopause**
- **mesopause**



Vertical temperature profile (Standard atmosphere)

The Troposphere

The troposphere (or *turning* or *changing* sphere) is marked by generally decreasing temperatures with height, with an average rate of decrease of temperature with height or lapse rate of about 7°C km^{-1}. That is to say,

$$\Gamma \equiv -\frac{\partial T}{\partial z} \approx 7\,\mathbf{K\,km}^{-1} = 0.007\,\mathbf{K\,m}^{-1}$$

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Tropospheric air, which accounts for about 80% of the mass of the atmosphere, is relatively well mixed and it is continually being cleansed or scavenged of aerosols by cloud droplets and ice particles.

Temperature Inversions

Embedded within the troposphere are thin layers called temperature inversions in which temperature increases with height and vertical mixing is strongly inhibited.

Inversions are not fixed in space or time, but depend strongly on the prevailing weather conditions.

In turn, inversions have a strong effect locally on the atmospheric conditions near the ground.

Cumulonimbus cloud with fully developed anvil.

The Stratosphere (and above)

Within the stratosphere (or *layered* sphere) the increase of temperature with height strongly inhibits vertical mixing, just as it does within the much thinner temperature inversions that often form within the troposphere.

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Cloud processes in the stratosphere play a much more limited role in removing particles injected by volcanic eruptions and human activities than they do in the troposphere.

As a result, residence times for aerosols tend to be much longer in the stratosphere than the troposphere.

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Stratospheric air is extremely dry and it is characterized by relatively high concentrations of ozone. The absorption of solar radiation in the ultraviolet region of the spectrum by this stratospheric ozone layer is critical to the habitability of the earth.

Heating due to the absorption of this ultraviolet radiation gives rise to the temperature maximum that defines the stratopause.

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Temperatures in the earth's outer thermosphere vary widely in response to variations in the emission of ultraviolet and x-ray radiation from the sun's outer atmosphere.

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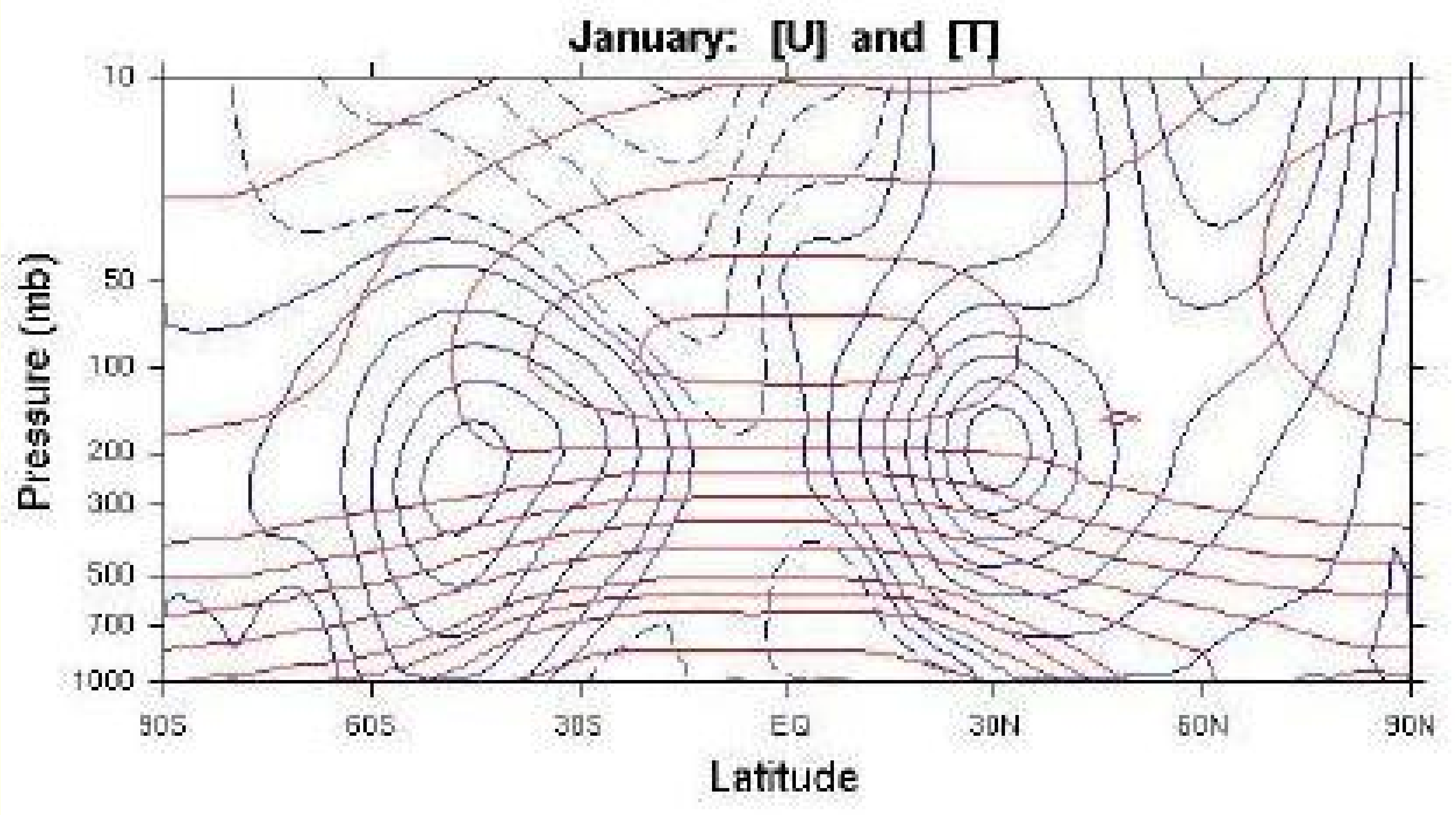
Definition: The Middle Atmosphere is the region of the atmosphere between the tropopause and the mesopause. Thus, it comprises the stratosphere and mesosphere.

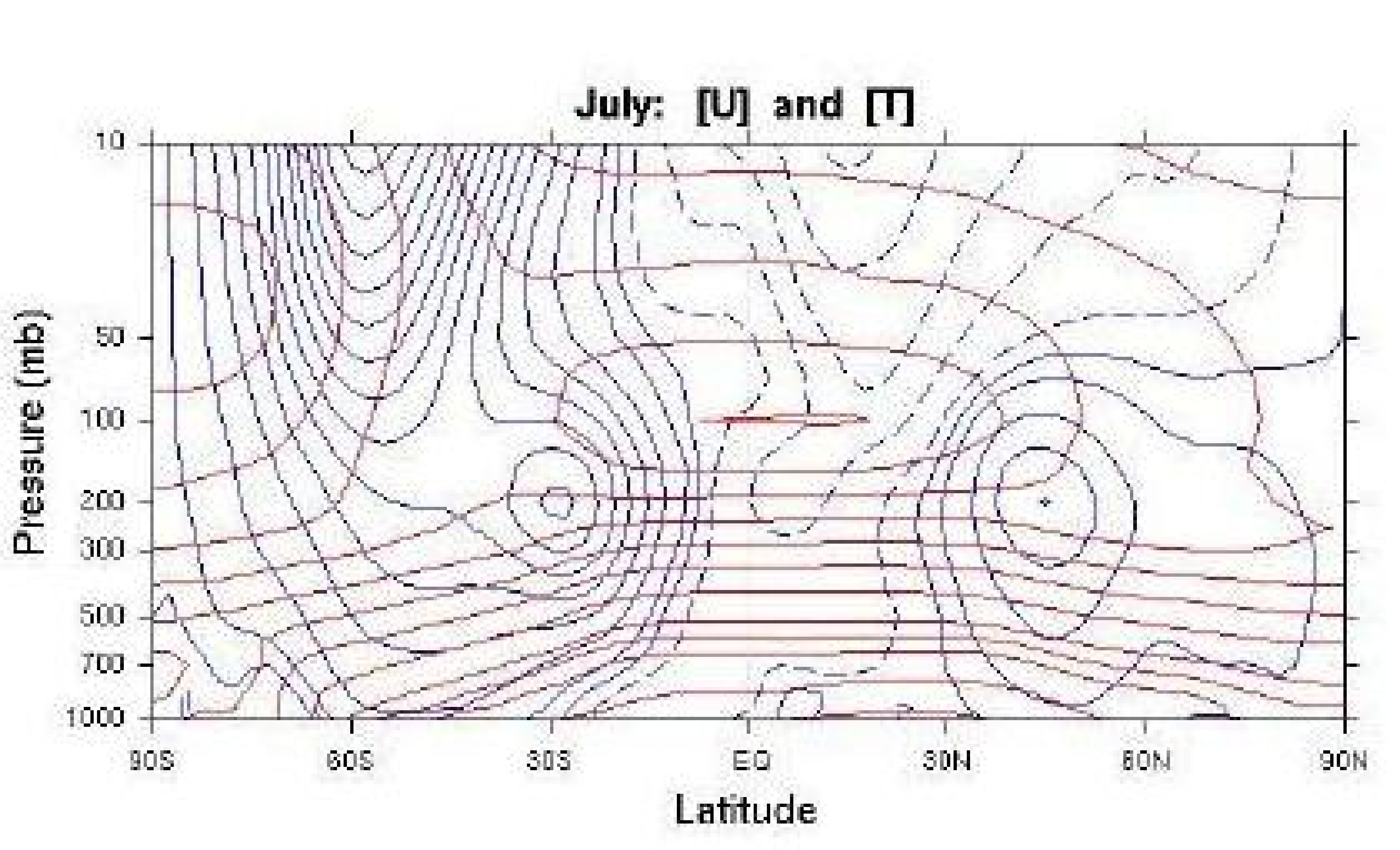
Zonal Mean State

At any given level in the atmosphere temperature varies with latitude. Within the troposphere, the zonally averaged temperature generally decreases with latitude, as seen in the meridional cross section.

The meridional temperature gradient is substantially larger in the winter hemisphere where the polar cap region is in darkness.



Meridional cross section of January mean temperature (red) and zonal wind (blue).



Meridional cross section of July mean temperature (red) and zonal wind (blue).

The tropopause is clearly evident in these figures as a discontinuity in the lapse rate. Note the distinct break between the tropical tropopause, with a mean altitude of 17 km, and the extratropical tropopause, with a mean altitude near 10 km.

The tropical tropopause is remarkably cold, with temperatures on the order of $-80°$C.

Scale of Motions

The horizontal scale of atmospheric motions is defined in various ways.

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Features with scales between 1000 and 6000 km as *synoptic-scale*

Features with scales ranging from 30 to 1000 km as *meso-scale*.

Atmospheric Motions

Differential heating between low and high latitudes gives rise to vigorous large scale horizontal motions on a wide range of scales.

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Prominent features of the atmospheric climatological-mean wind field, which are maintained by this heating gradient are the planetary-scale west-to-east (westerly) mid-latitude *tropospheric jet streams*, centered at the tropopause in mid-latitudes, and the *stratospheric polar-night jet*, which is evident in the meridional cross-section shown already.

The tropospheric jet streams are perturbed by an endless succession of eastward propagating, synoptic scale *baroclinic waves* which feed upon, and tend to limit the north-south temperature contrast.

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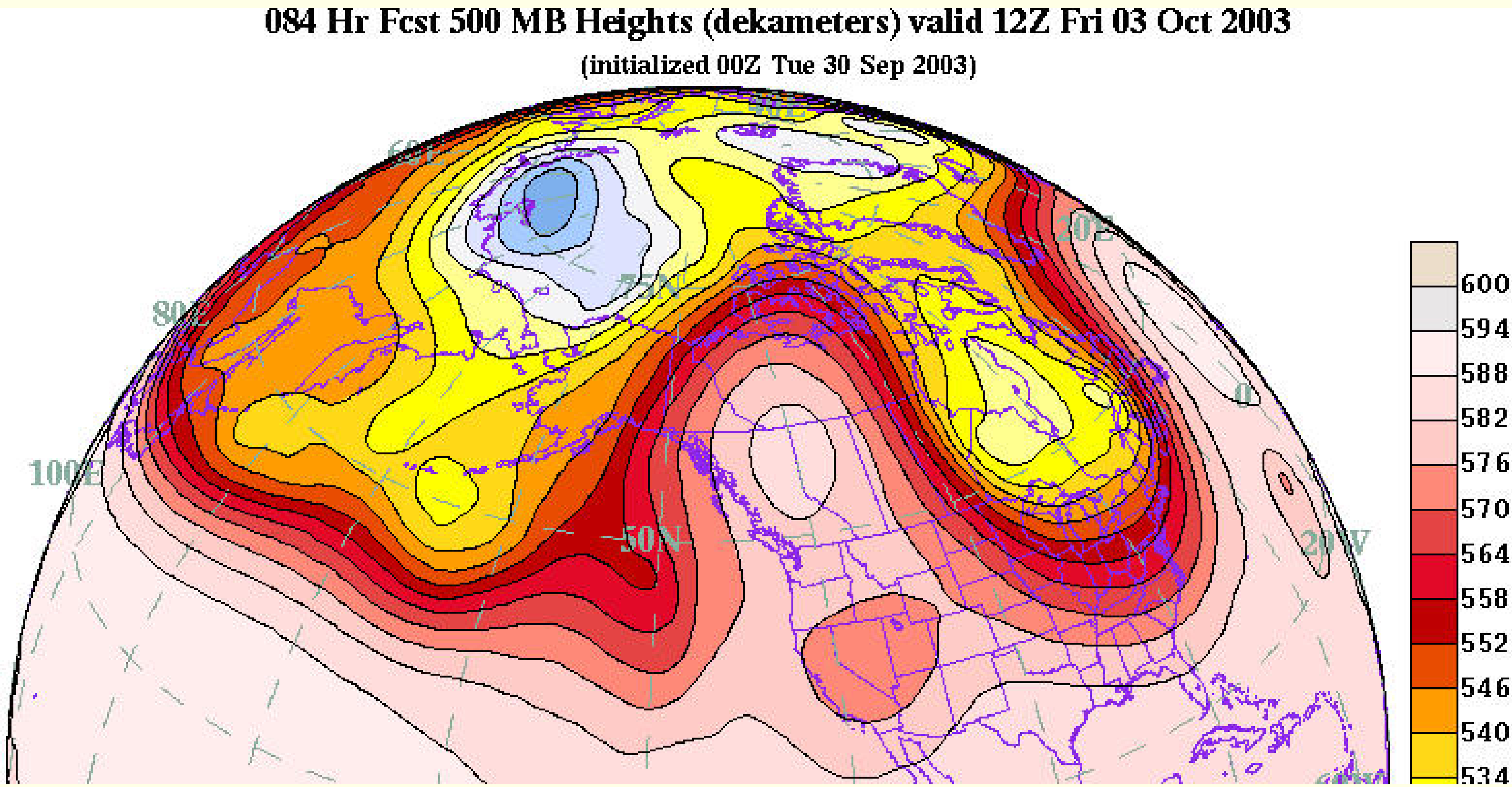
Baroclinic waves are one of a number of types of atmospheric disturbances that develop spontaneously in response to *instabilities* in the large scale flow pattern in which they are embedded.



Large wave-like distortion of the zonal flow.

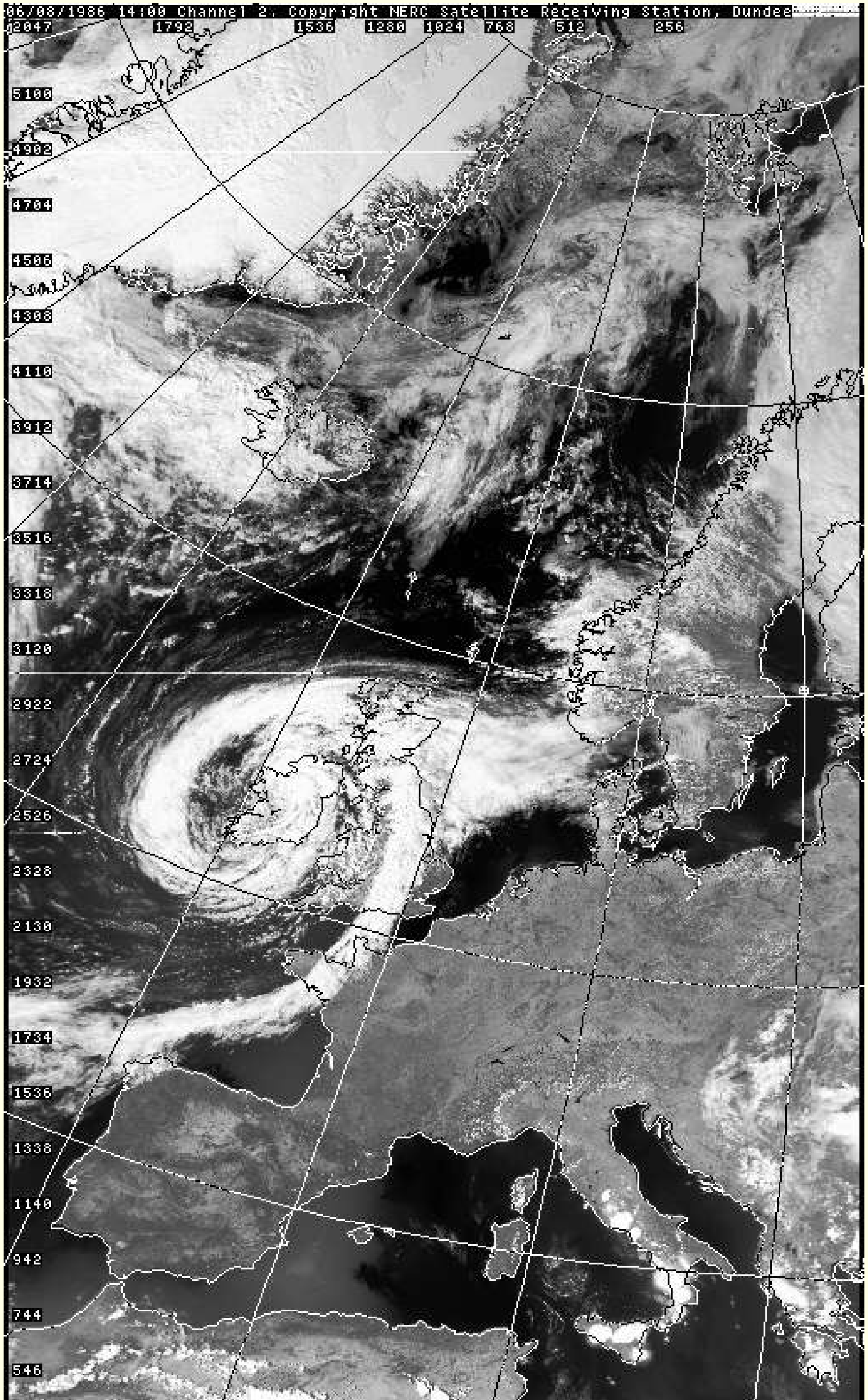
Extratropical Cyclones

The low level wind pattern in these baroclinic waves is dominated by extratropical cyclones, an example of which is shown below.

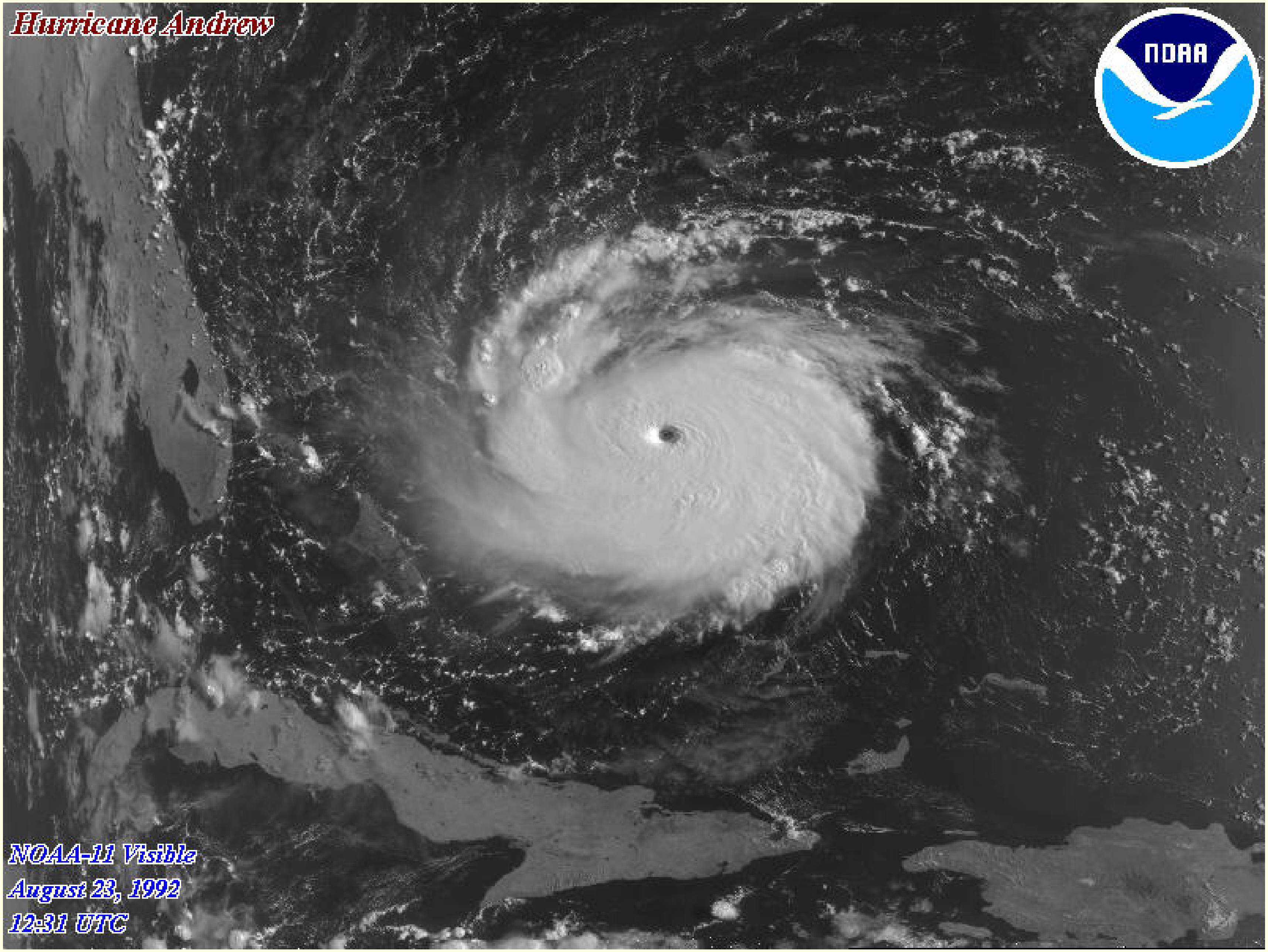
Much of the significant weather associated with these disturbances occurs within *frontal zones*: meso-scale bands of highly concentrated horizontal temperature gradients.

Extratropical cyclones are distinctly different from the tighter and more circular tropical cyclones.

An intense extra-tropical cyclone over the North Pacific, as viewed in visible satellite imagery. The elongated cloud bands spiraling out from the center are the remnants of frontal zones.



An old extratropical cyclone over Ireland (06/08/1986, 14:00, Ch2).

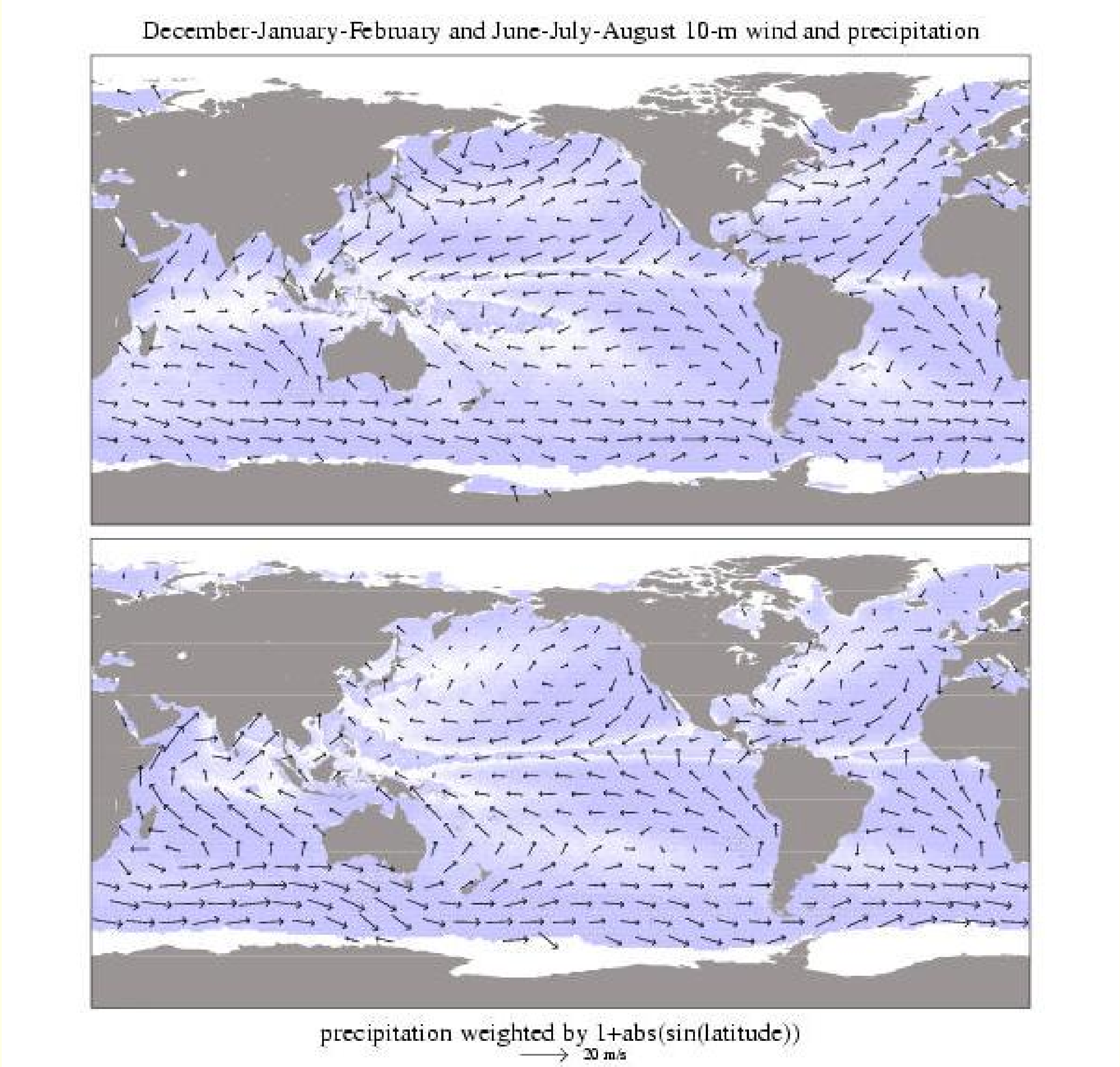


Hurricane Andrew approaching the Florida coast.

Global Surface Winds

The distribution of surface winds over the oceans is shown in the following figure.
Note the following features:

- **Westerlies over the higher latitude oceans**
- **Easterlies (trade winds) over the tropical and subtropical Oceans**
- **The boundary between the northeast trades, and southeast trades, the intertropical convergence zone (ITCZ), located near the equator**
- **Seasonally reversing monsoon circulation over the Indian Ocean**



January and July surface winds over the oceans

[based on three years of Quikscat scatterometer data]

In a time average over the winter season, the northern hemisphere westerly belt is dominated by cyclonic circulations centered over the Aleutians and Iceland.

The flow over the oceans at lower latitudes is dominated by the subtropical anticyclones centered at latitudes near 30°. prominent during summer.

Longitudinally dependent climatic features such as the monsoons and the subtropical anticyclones are driven by contrasts in surface air temperature that develop in response to the widely differing heat capacities of land and sea.

Land-sea contrasts also give rise to a systematic meandering of in the jet streams at higher latitudes, particularly over the northern hemisphere during winter.

Smaller Scale Motions

The heating of the earth's surface by solar radiation gives rise to buoyant plumes, referred to by glider pilots as "thermals".

These plumes of rising air are often visible as cumulus clouds. The overturning circulations are often confined to the lowest 1-2 km of the atmosphere (the so called *mixed layer* or *planetary boundary layer*, in which case they are referred to as *shallow convection*.

Cumulus clouds resulting from plumes of rising air in shallow boundary layer convection.

Deep Convection

Deeper, more vigorous convection is often observed in cold air masses flowing over a warmer surface. Under certain conditions, buoyant plumes originating near the earth's surface can break through the weak temperature inversion that usually caps the mixed layer, giving rise to towering clouds that extend all the way to the tropopause, referred to as *deep convection*.

Deep convective storms can cause locally heavy rain, sometimes accompanied by hail, strong winds, and intense electrical activity.

Boundary Layer Turbulence

Convection is not the only source of small scale atmospheric motions. Large scale flow over small surface irregularities induces small scale, three-dimensional boundary layer turbulence, which is clearly revealed by the distortions and spreading of the plumes from smokestacks.

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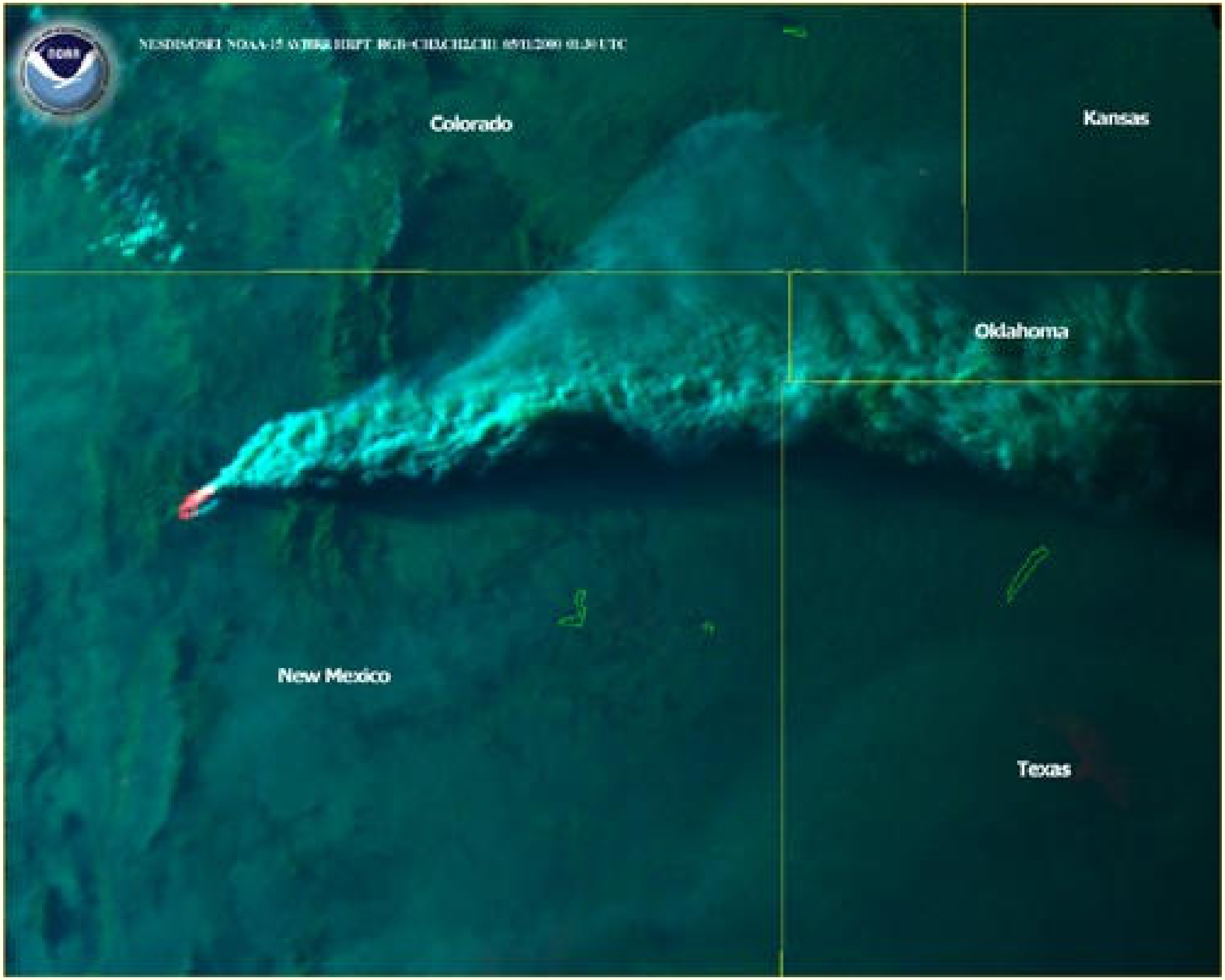
This boundary layer turbulence is instrumental in causing smoke plumes to widen as they move downstream, in limiting the strength of the winds, and in mixing momentum, energy and trace constituents between the atmosphere and the underlying surface.



Smoke plume from a large forest fire widening as it moves downstream under the influence of boundary layer turbulence.

High Level Turbulence

Turbulence is not exclusively a boundary layer phenomenon: it can also be generated by flow instabilities higher in the atmosphere.

The cloud pattern shown below reveals the presence of a overturning circulations know as Kelvin-Helmholtz billows, that develop spontaneously in regions of strong vertical wind shear.

Kelvin-Helmholtz billows

Clear Air Turbulence

Through this succession of instabilities, kinetic energy extracted from the large scale wind field gives rise to a spectrum of smaller scale motions extending down to the molecular scale:

```
Big whirls have smaller whirls that feed on their velocity.
Little whirls have lesser whirls, and so on to viscosity.
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Within localized patches where the energy cascade is particularly intense, eddies on scales of tens of meters can be strong enough to cause discomfort to airline passengers and, in exceptional cases, to pose hazards to aircraft. Turbulence generated by shear instability is referred to as *clear air turbulence*.

Precipitation

So you thought Ireland's climate was wet!!!

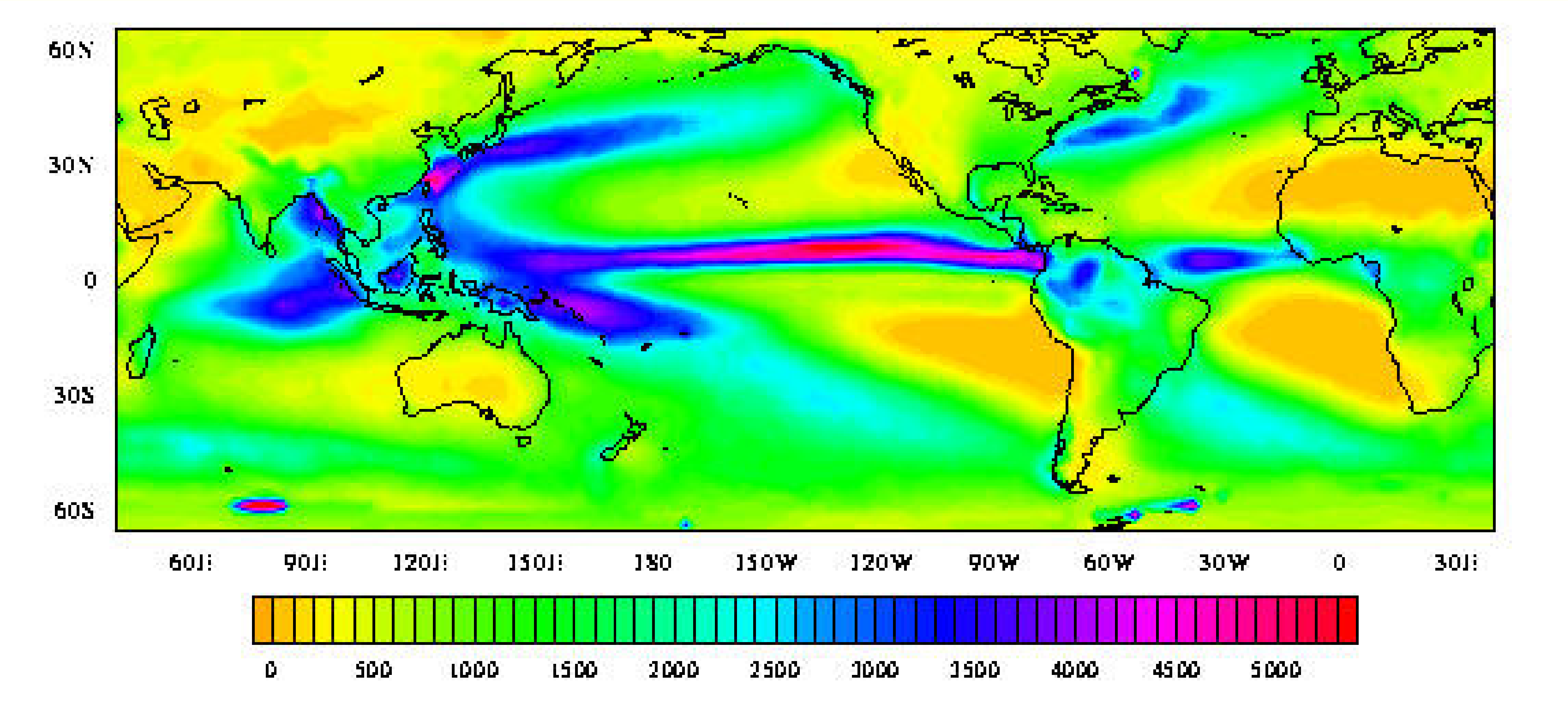
Precipitation

So you thought Ireland's climate was wet!!!

The following figure shows the climatological mean distribution of precipitation.

The narrow bands of heavy rainfall that dominate the tropical Atlantic and Pacific sectors coincide with the ITCZ's in the surface wind field pointed out above.

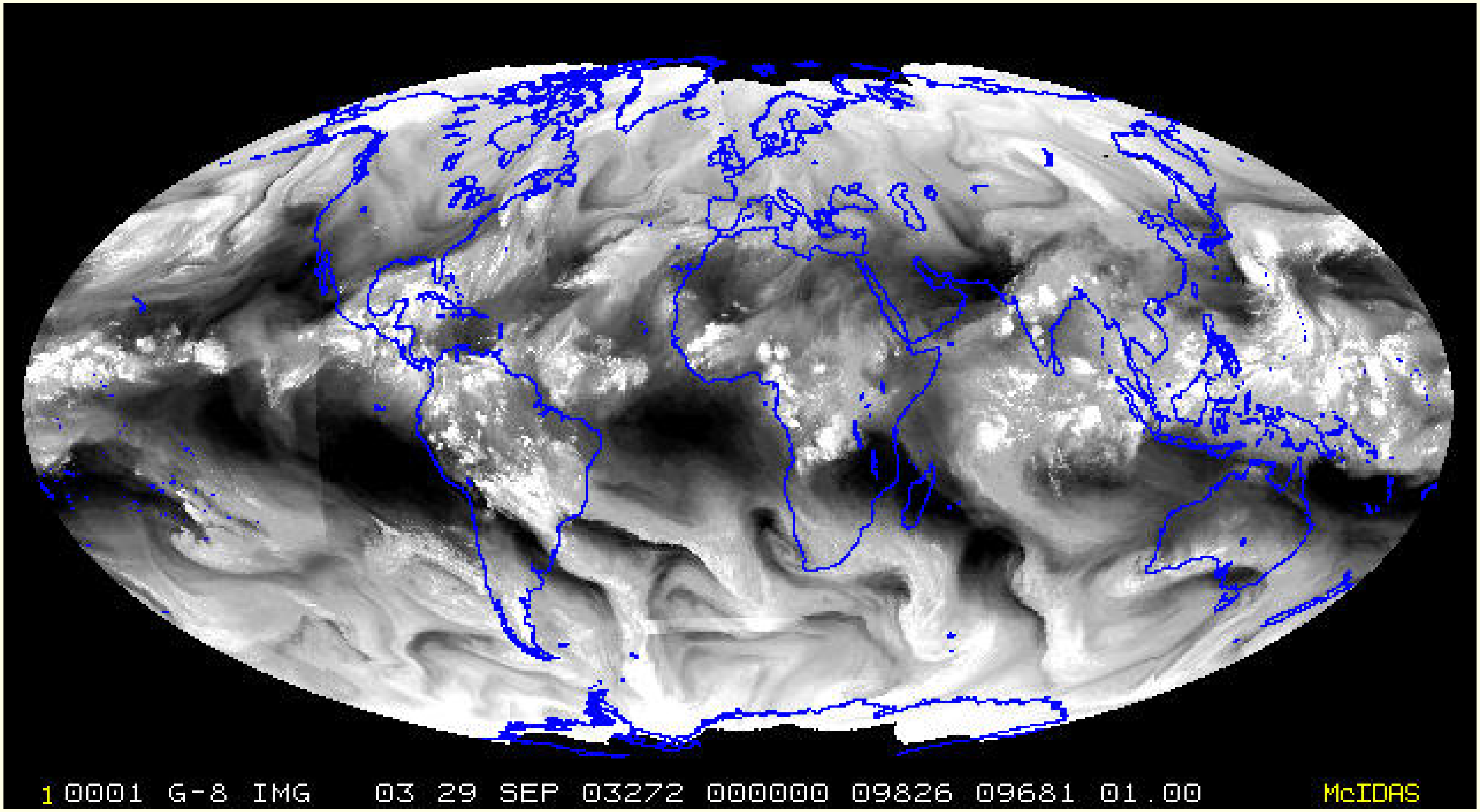
The ITCZ is flanked by pronounced dry zones which extend westward from the continental deserts.



Climatological mean precipitation

A Typical Day

On any given day, the cloud patterns revealed by global satellite imagery exhibit patches of deep convective clouds that can be identified with the ITCZ and the monsoons over the tropical continents of the summer hemisphere; a relative absence of clouds in the subtropical dry zones; and a succession of comma-shaped, frontal cloud bands embedded in the baroclinic waves tracking across the mid-latitude oceans.



Satellite imagery in the water vapour channel. Note the contrast between cloudy ascending air (lighter shades) and clear, dry sinking air (black).

End of Introduction