The Mesosphere

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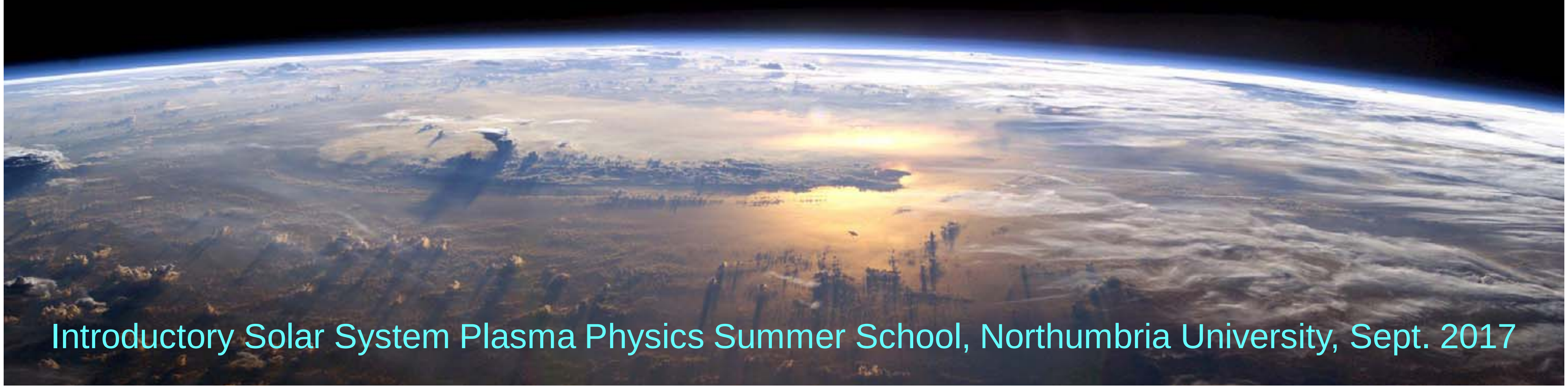
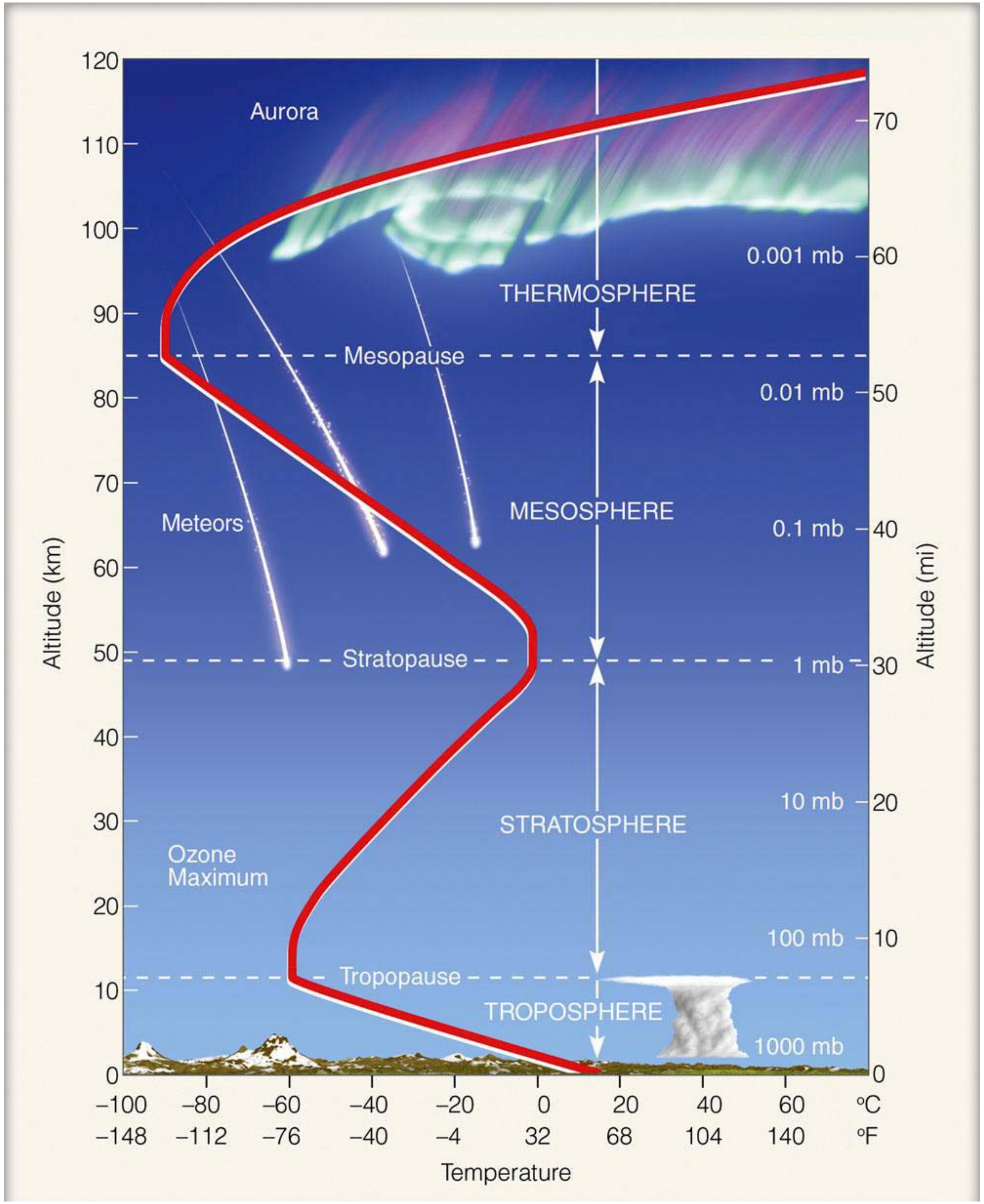


Introductory Solar System Plasma Physics Summer School, Northumbria University, Sept. 2017

In this talk

1. The structure of the atmosphere
2. The mesospheric zoo – sprites, meteors, ghostly noctilucent clouds, giant waves and solar tides
3. The general circulation of the mesosphere – why radiative equilibrium isn’t enough
4. Driving the mesosphere by gravity waves
5. Science questions for the next decade

1. The structure of the atmosphere



2. The structure of the Atmosphere

Spheres defined by temperature gradient

Boundaries are the *pauses*

Thermosphere: “hot sphere”

Mesosphere: “middle sphere”

Stratosphere: “stratified sphere”

Troposphere: “turning sphere”

Atmospheric density and pressure

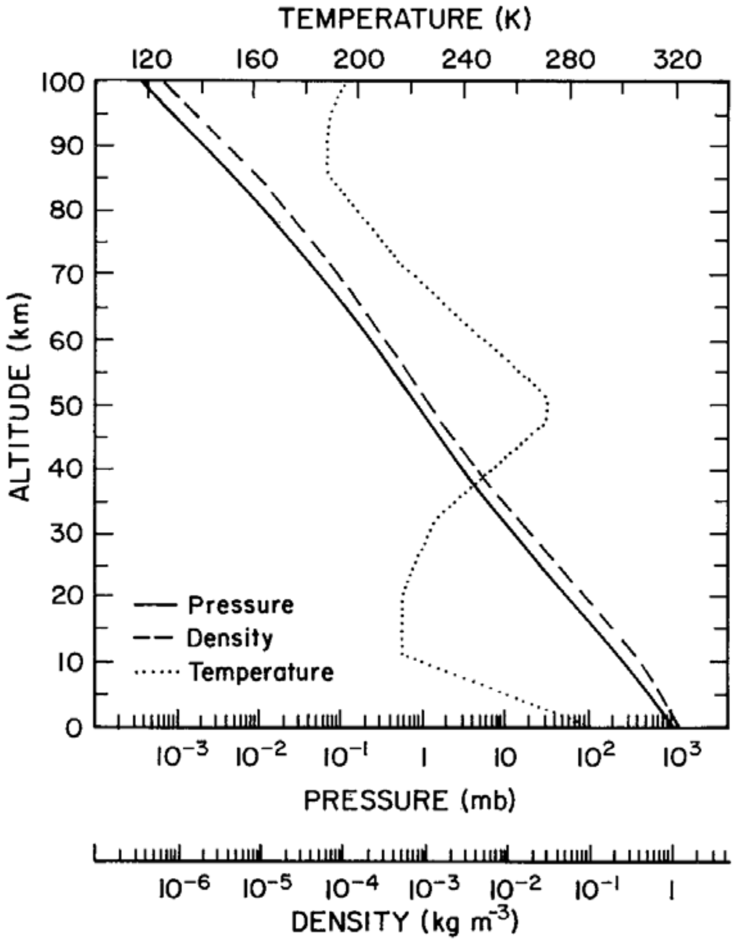
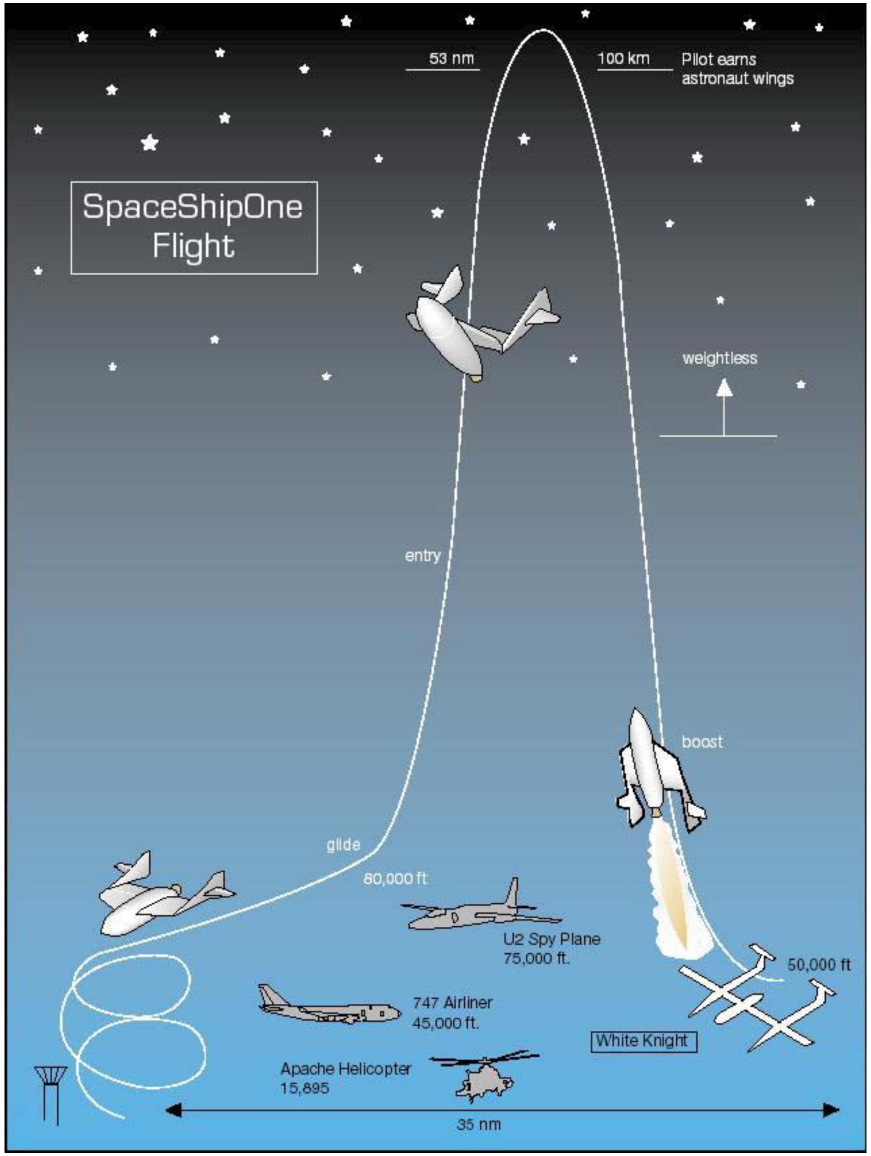


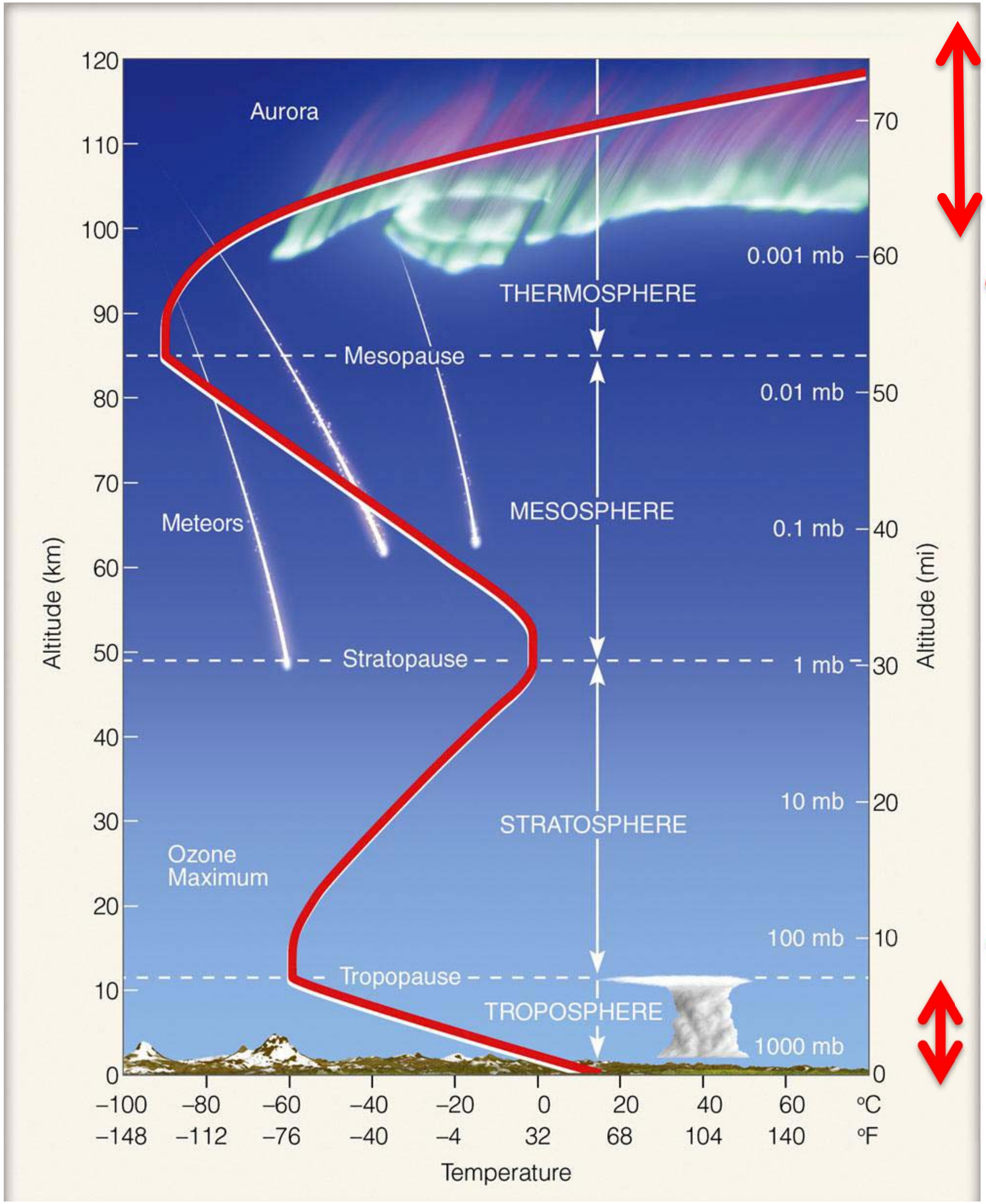
Figure 1.2 Global–mean pressure (solid), density (dashed), and temperature (dotted), as functions of altitude. *Source:* U.S. Standard Atmosphere (1976).

Reaching the mesopause – the edge of space

The X-15 Rocket plane

Spaceship one – a rocket plane to 100 km





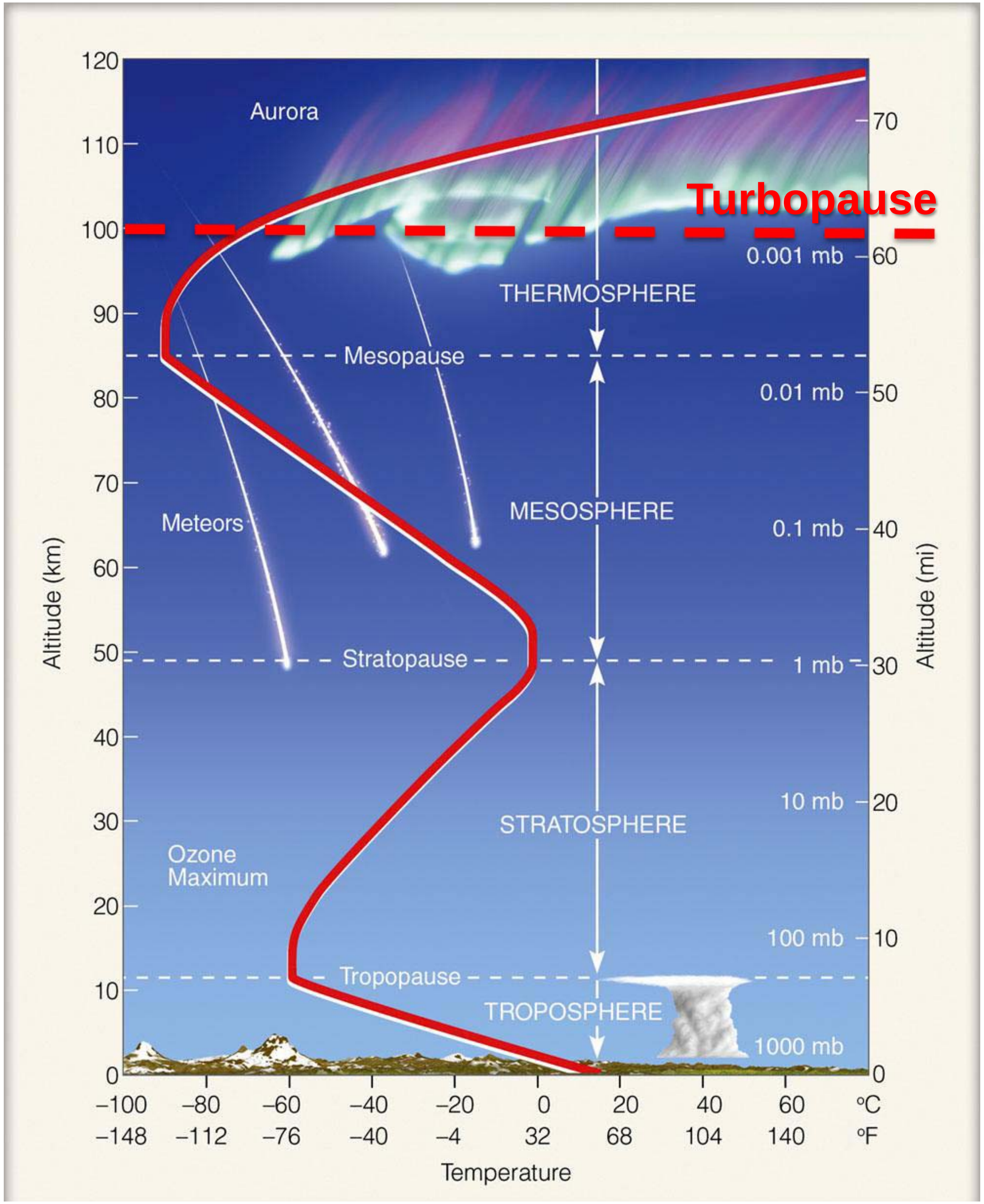
Upper atmosphere > ~ 100 km

2. The structure of the Atmosphere

Common dynamics and chemistry defines **lower**, **middle** and **upper** atmosphere

Middle atmosphere ~ 10 – 100 km

Lower atmosphere ~ 0 – 10 km



2. The structure of the Atmosphere

Turbulent mixing stops at the **turbopause** at ~ 100 km

Below is the homegeneous **homosphere** where turbulent mixing homogenises the major constituents – "well mixed")

Above is the hetrogeneous **hetrosphere** where molecular diffusion dominates and composition changes with height

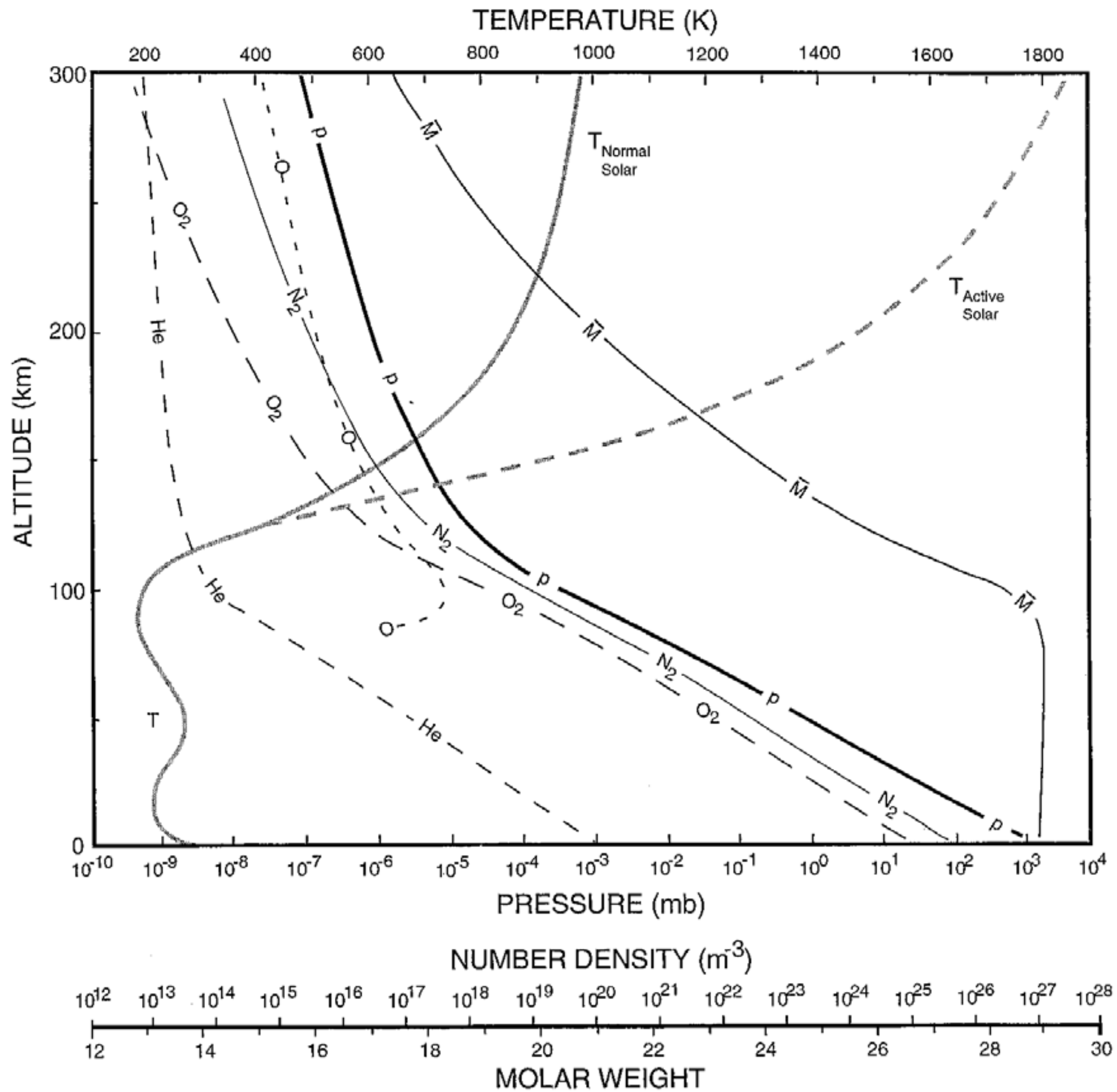
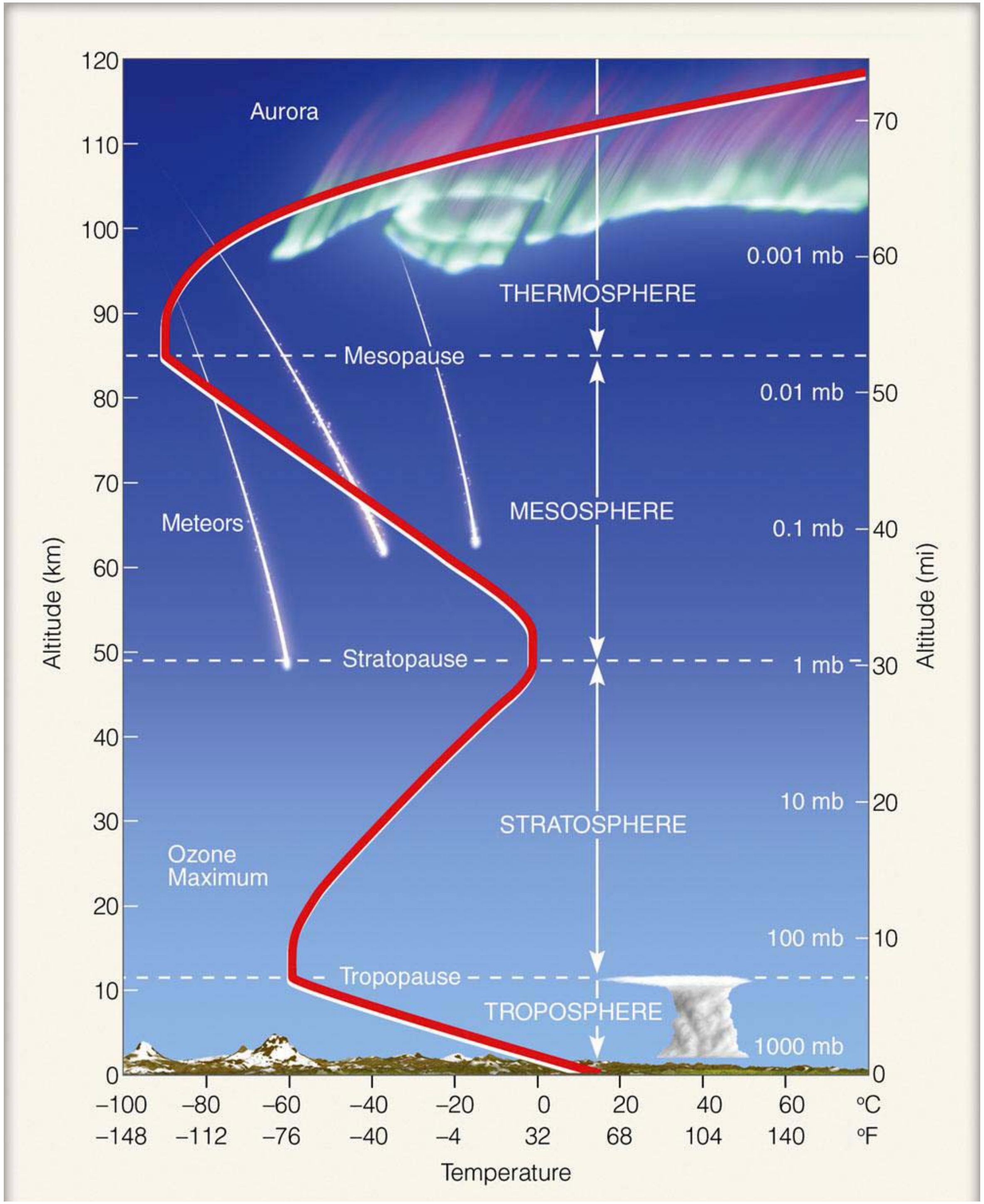


Figure 1.3 Global–mean pressure (bold), temperature (shaded), mean molar weight (solid), and number densities of atmospheric constituents, as functions of altitude. *Source:* U.S. Standard Atmosphere (1976).

Various atmospheric properties as a function of height. Note how the composition changes significantly only at heights above ~ 100 km.

Above ~ 180 km atomic oxygen is the major constituent.



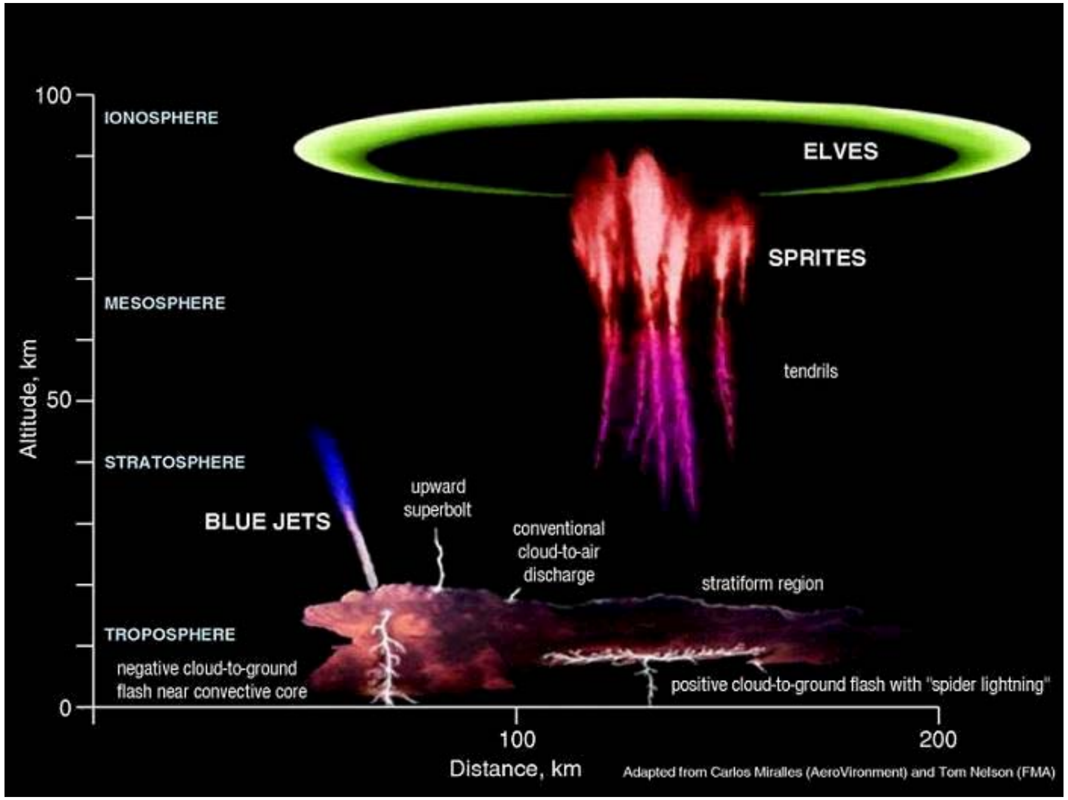
2. The structure of the Atmosphere

The **ionosphere** is the ionised component of the atmosphere, embedded in the **neutral atmosphere**

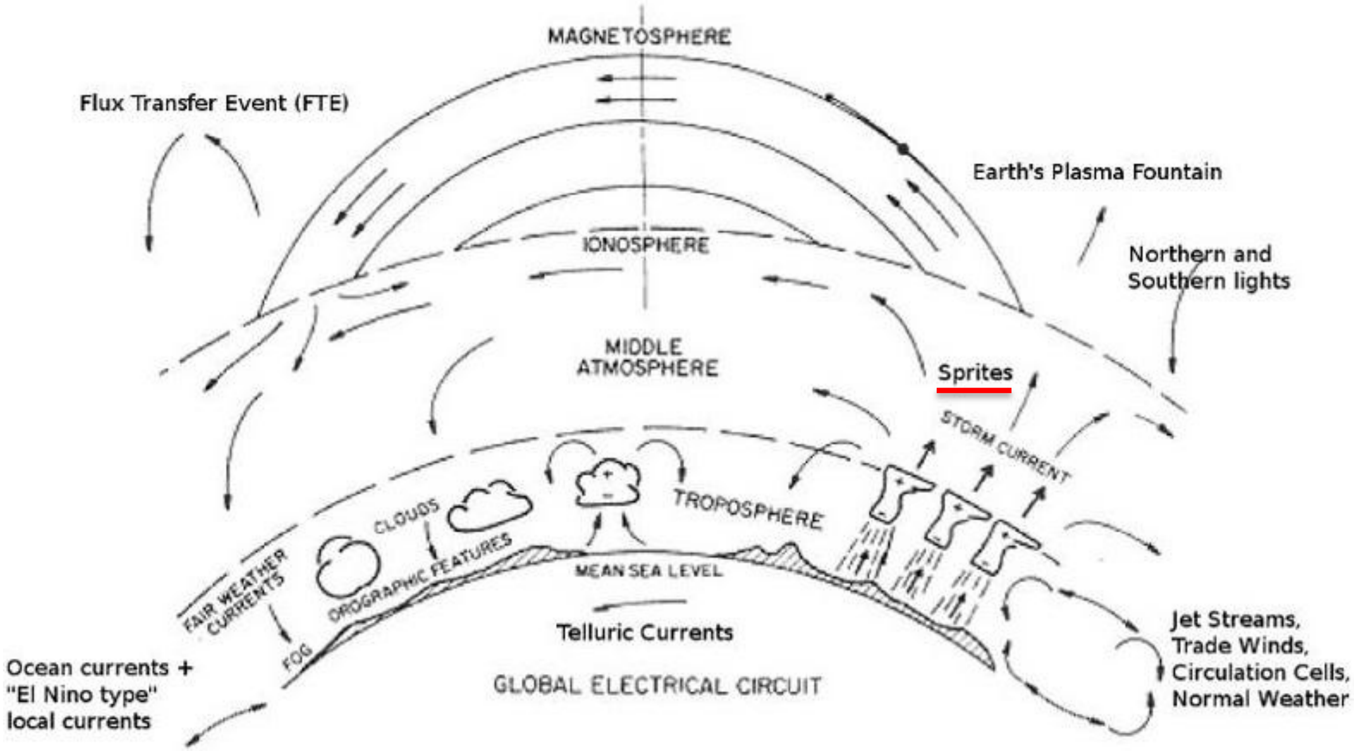
2. The mesospheric zoo – sprites, meteors, ghostly noctilucent clouds, giant waves and solar tides

Sprites – lightning from thunderstorms into the mesosphere

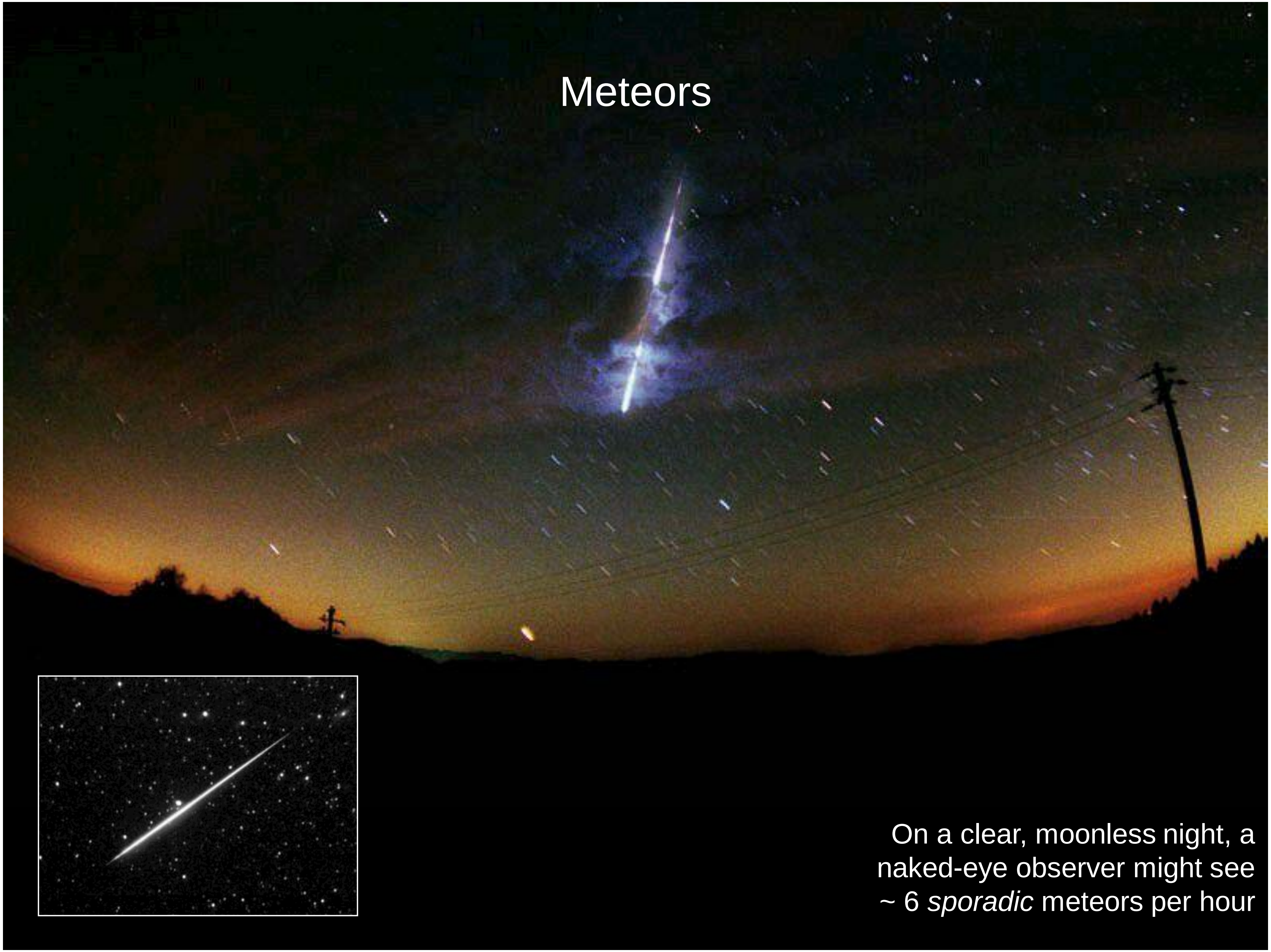
Sprites – lightning from thunderstorms into the mesosphere



Sprites – lightning from thunderstorms into the mesosphere

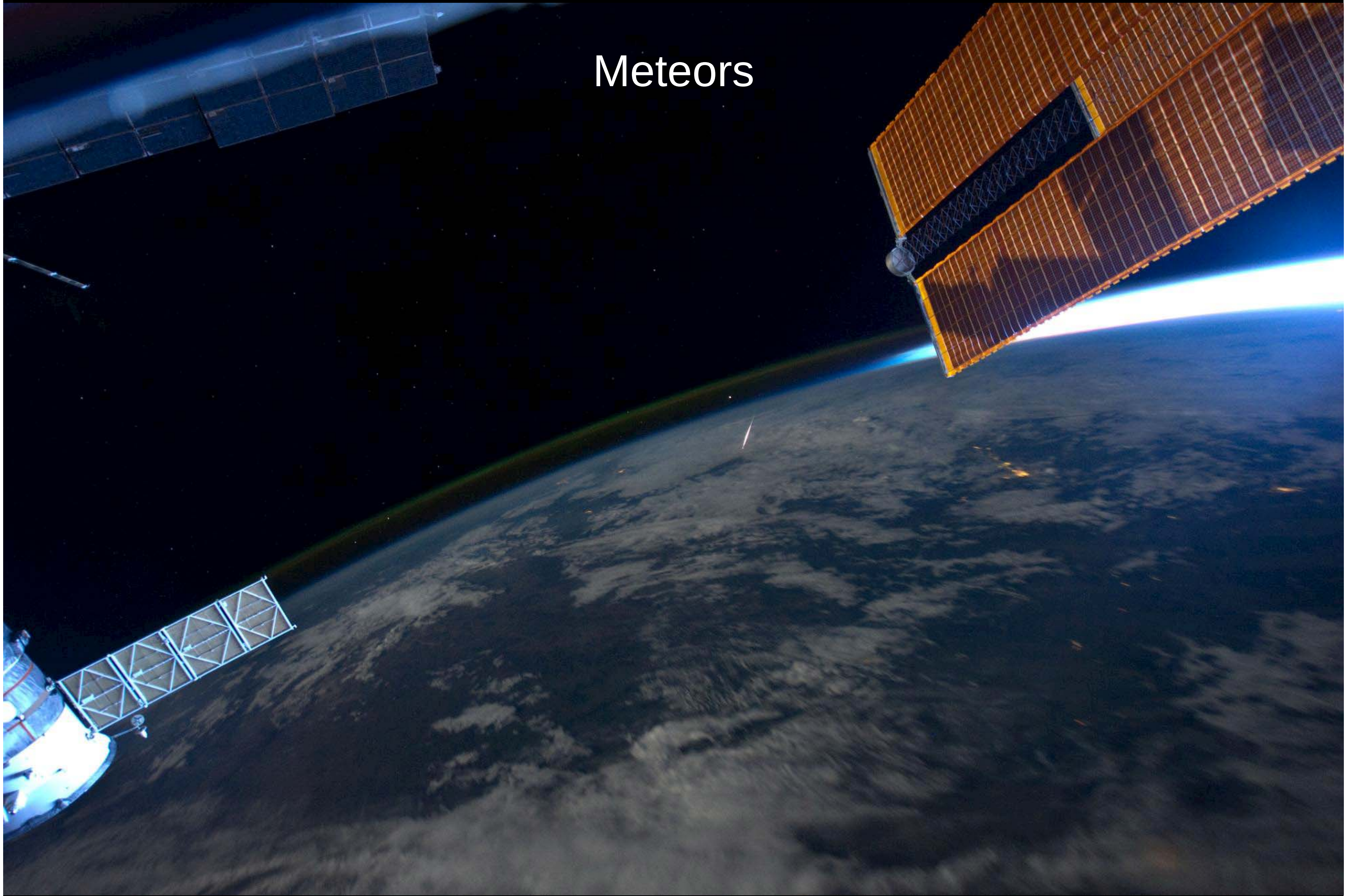


Meteors



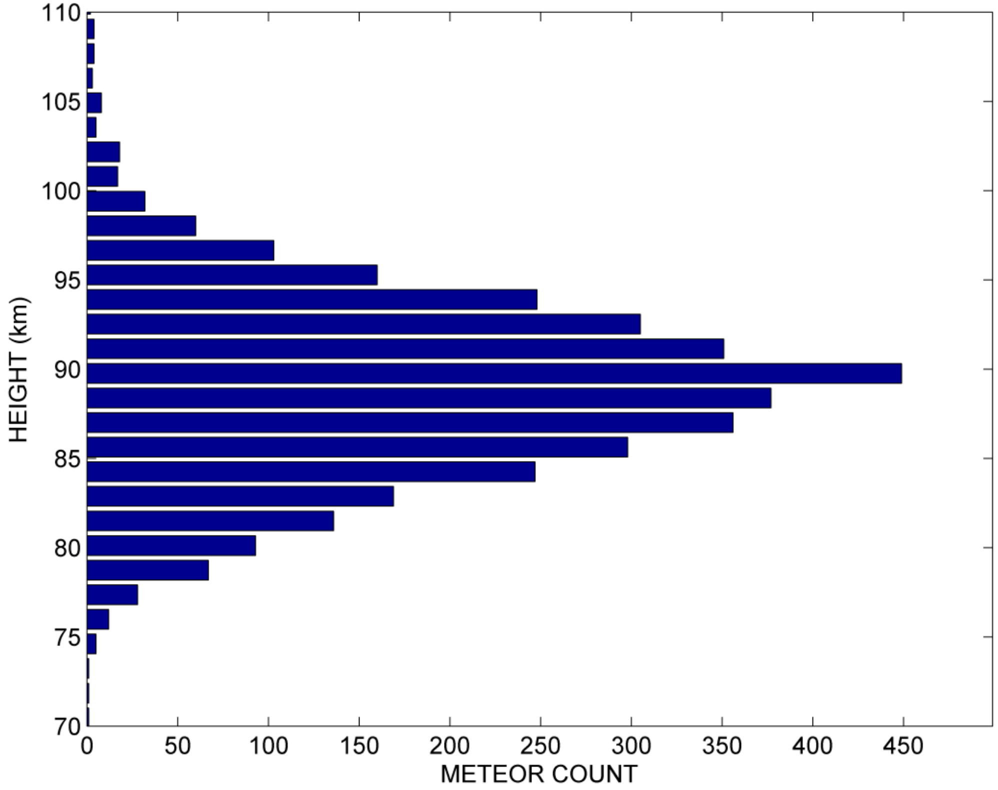
On a clear, moonless night, a naked-eye observer might see ~ 6 *sporadic* meteors per hour

Meteors

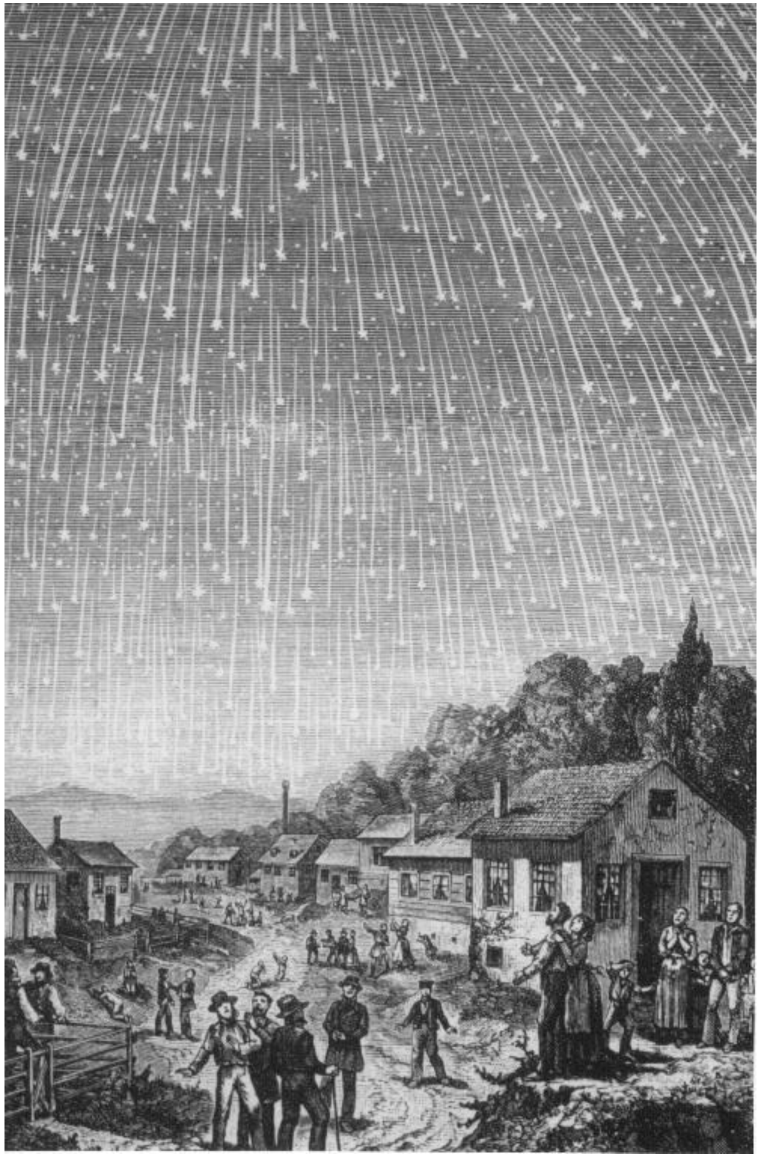


A Perseid meteor photographed from the ISS

Height distribution of meteors



Meteor Showers



The Leonid meteor shower of 1833 was witnessed from Pennsylvania by Joseph Harvey Waggoner.

Under his direction, artist Karl Jauslin produced this drawing.

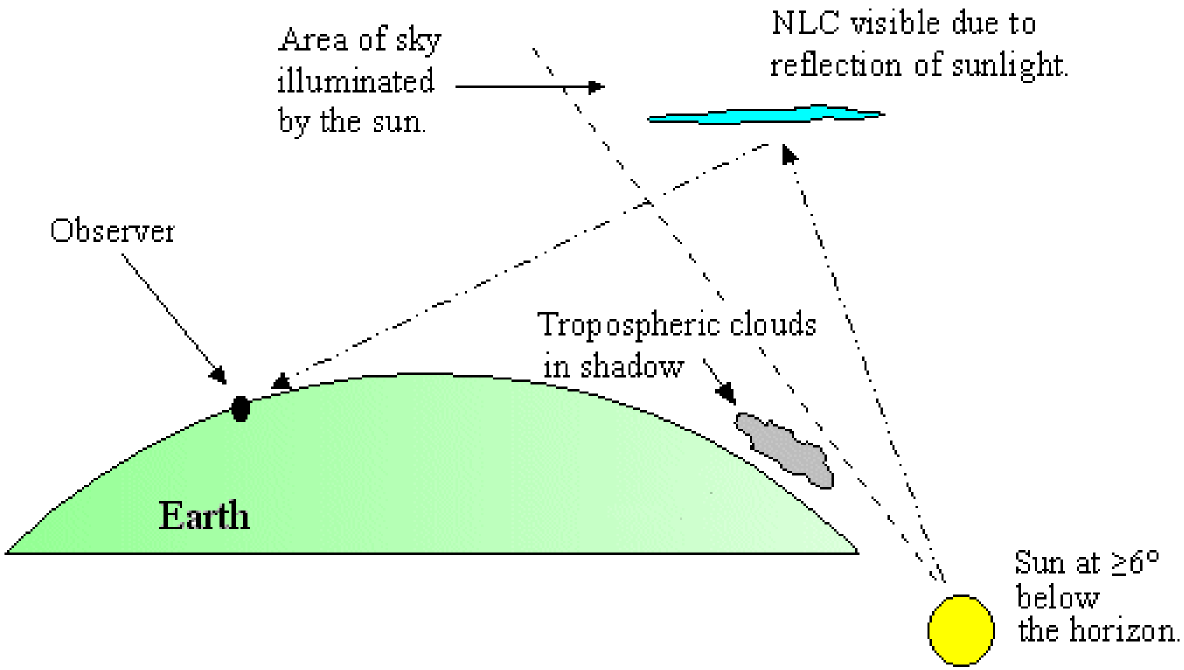
“*Many persons thought that a shower of fire was falling and became exceedingly alarmed.*”

Naked-eye meteor count rates may have exceeded 100,000 per hour.

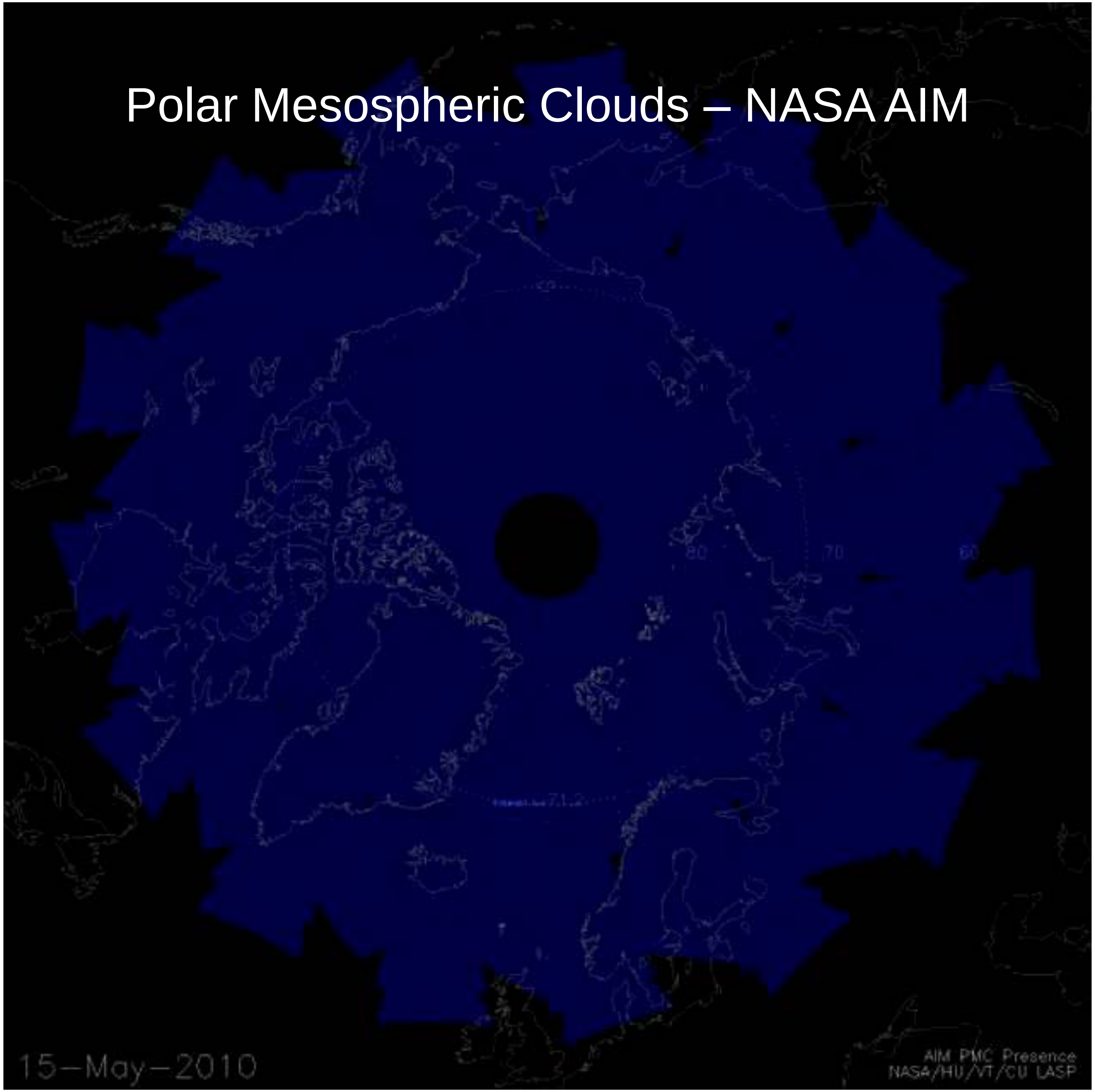
Noctilucent clouds

Noctilucent Clouds

Typical NLC height ~ 82 km



Polar Mesospheric Clouds – NASA AIM

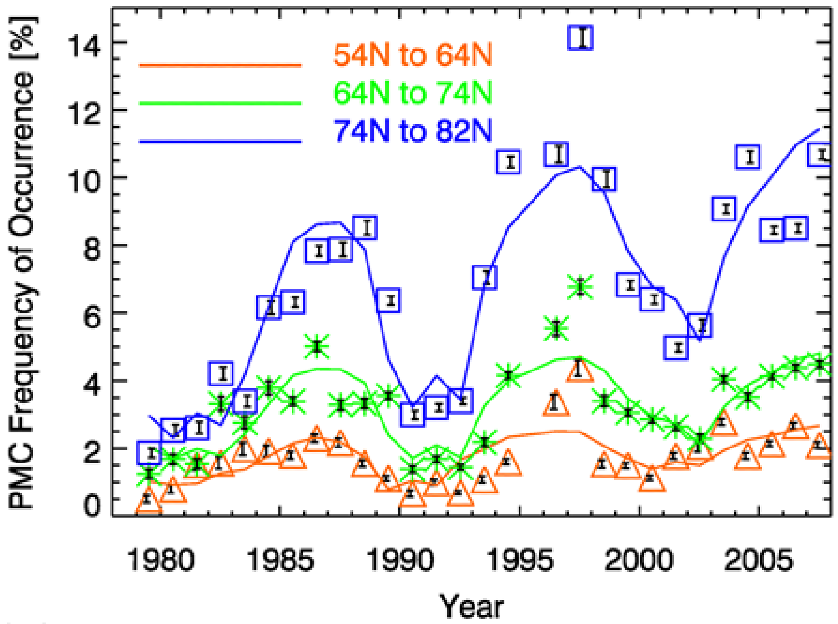


Long-term trends in NLC/PMC?

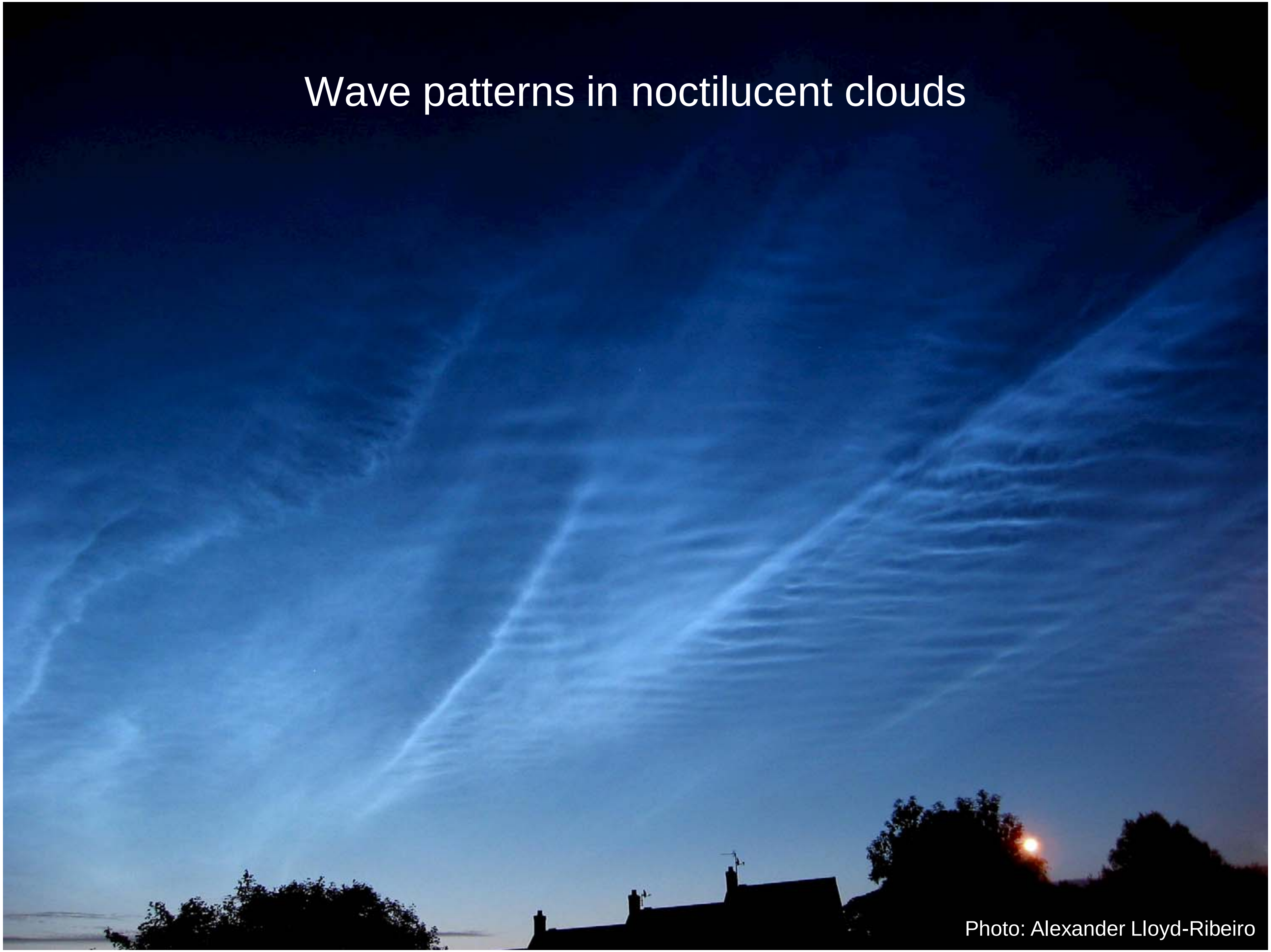
No reliable reports of NLC observed before the late 880s

There is good evidence of long-term trends in NLC/PMC occurrence rates, brightness and equator-ward extent

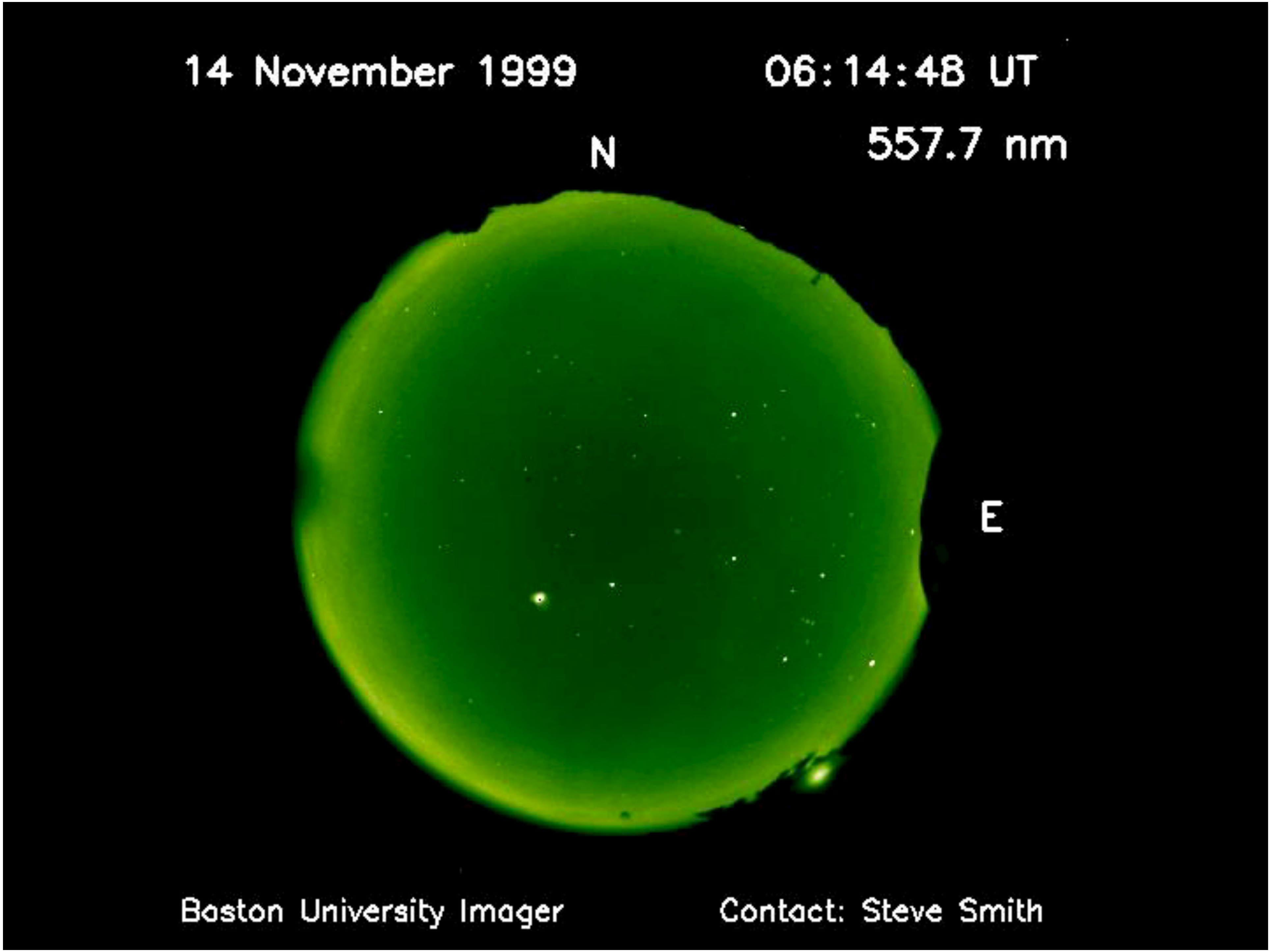
These trends appear to a complex response to long-term trends in temperatures, solar activity and available water vapour



A comparison of the seasonal PMC frequency of occurrence measured by SBUV and the fit to a linear regression in time and solar activity by latitude band (Shettle et al., GRL, 2009)


Wave patterns in noctilucent clouds
Photo: Alexander Lloyd-Ribeiro

Gravity waves in tropospheric clouds (Gulf of Mexico)


14 November 1999
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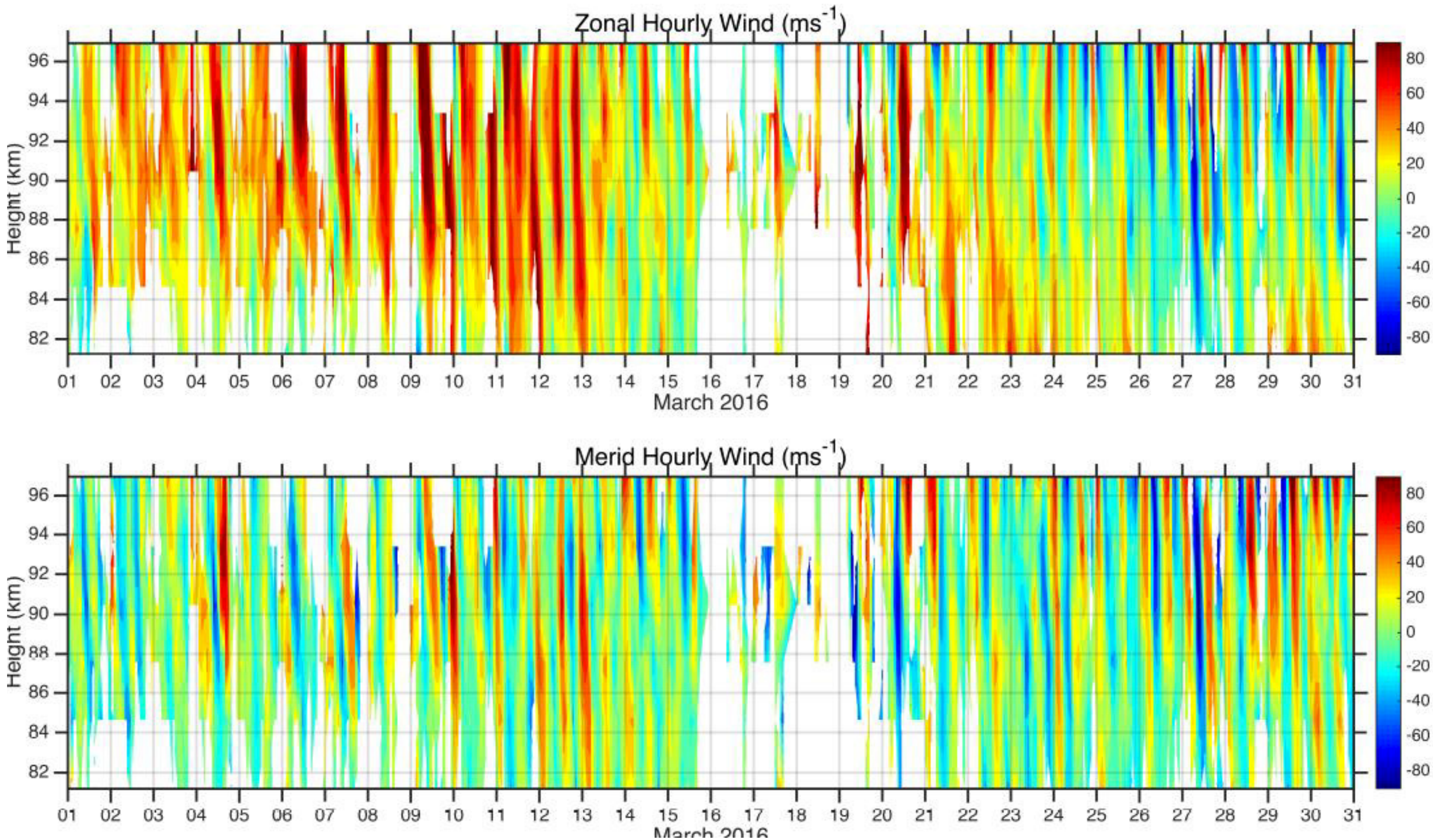
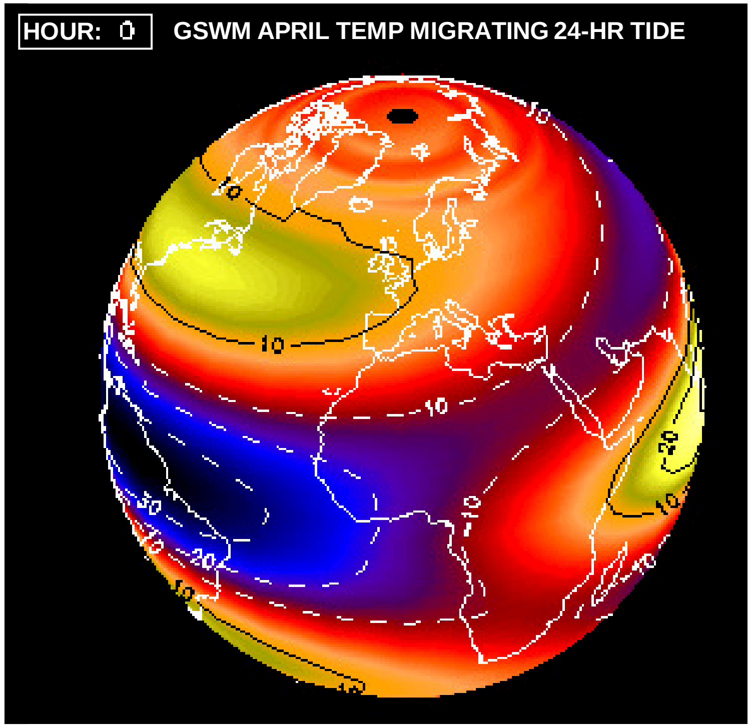
Boston University Imager
Contact: Steve Smith

Wave patterns in a meteor trail

Atmospheric solar tides over South Georgia, March 2016



Atmospheric solar tides in a model



Perturbations in atmospheric temperature from the 24-hour tide

Height ~ 111.5 km

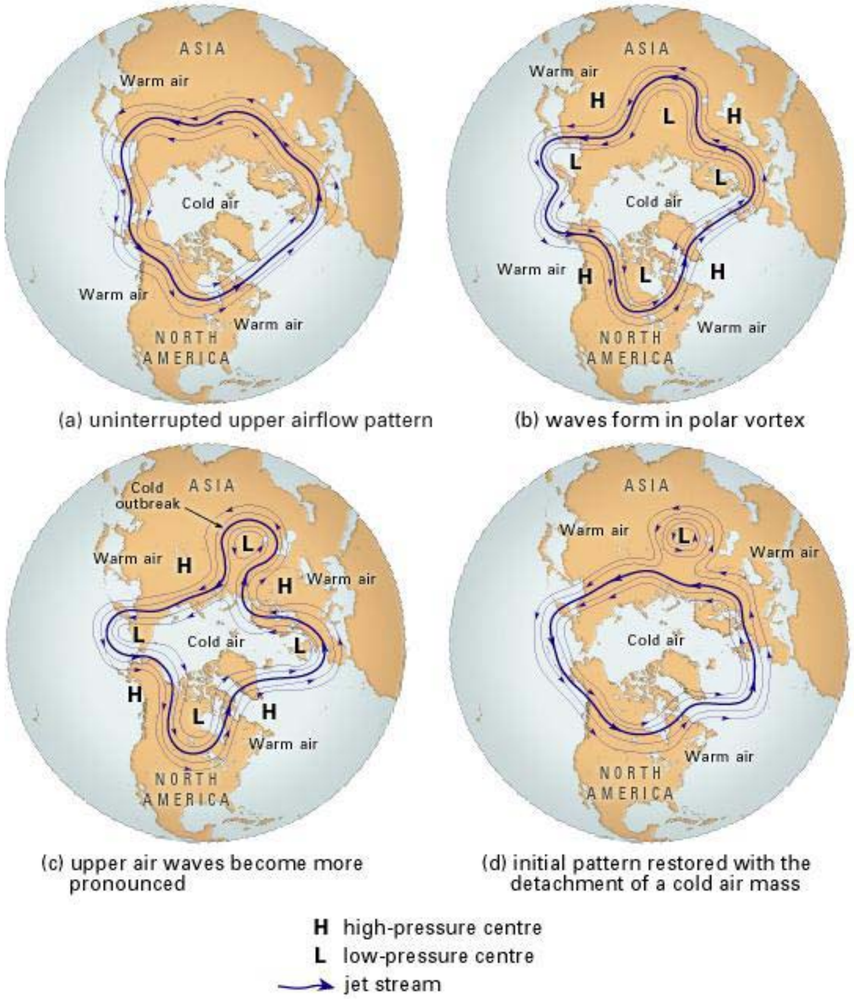
April conditions

NCAR HAO Global Scale Wave Model

Alternating "View fixed over point on Earth" and "View from Sun" frames of reference

(http://www.hao.ucar.edu/public/research/tiso/gswm/gswm.html)

Planetary Waves



(a) uninterrupted upper airflow pattern

(b) waves form in polar vortex

(c) upper air waves become more pronounced

(d) initial pattern restored with the detachment of a cold air mass

The atmosphere also supports planetary waves of many different types

Rossby waves are a common type of planetary wave

The figure shows Rossby wave perturbations in the upper tropospheric jet streams

3. The general circulation of the mesosphere – why radiative equilibrium isn't enough

The general circulation of the atmosphere

Air moves in response to forces acting on *air parcels*. There are four main forces acting on the atmosphere that produce horizontal flows:

1. **The pressure-gradient force** – *which pushes air from regions of high pressure towards regions of low pressure (NB – horizontal gradients)*
2. **The Coriolis force** – *which deflects motion to the right in the Northern Hemisphere and to the left in the Southern Hemisphere*
3. **Friction** – *which slows the flow speed when near the ground, particularly over rough terrain*
4. **Centripetal forces** – *only important in very tightly curved flows, such as tornados*

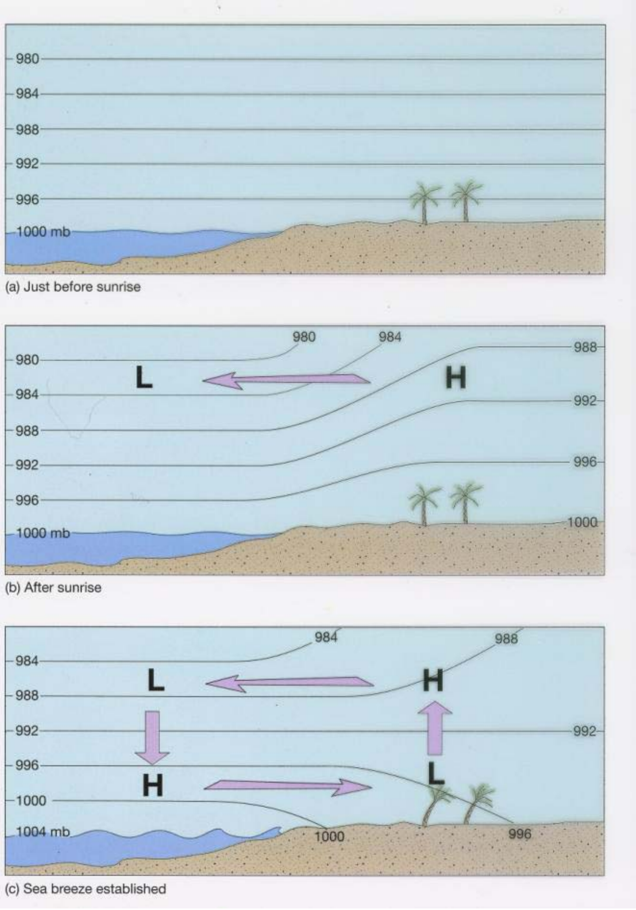
The general circulation of the troposphere is largely governed by *pressure gradient forces, Coriolis forces* and *friction*

Consider the pressure-gradient force and the Coriolis force in more detail…

1. The pressure gradient force, P_n

Variations in heating cause horizontal pressure gradients. The heating variations can be local (land/sea boundary) or global (equator/pole). In either case air attempts to flow away from regions of high pressure towards regions of low pressure in a circulatory cell.

1.
2.
3.



(a) Just before sunrise
(b) After sunrise
(c) Sea breeze established

Example of pressure gradient forces – a *sea breeze*

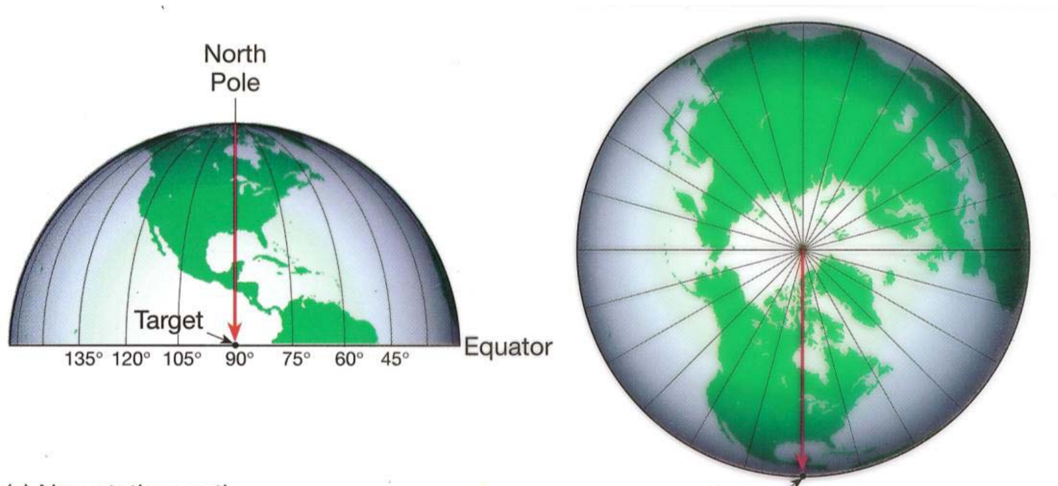
1. Before sunrise land and sea are at the same temperature. Pressure surfaces are horizontal and there are no pressure (horizontal) gradient forces

2. At sunrise, the land warms more than the ocean. Air over the land expands and pressure surfaces move *upwards* to greater heights over the land. A horizontal pressure gradient arises that pushes air from high pressure to low pressure

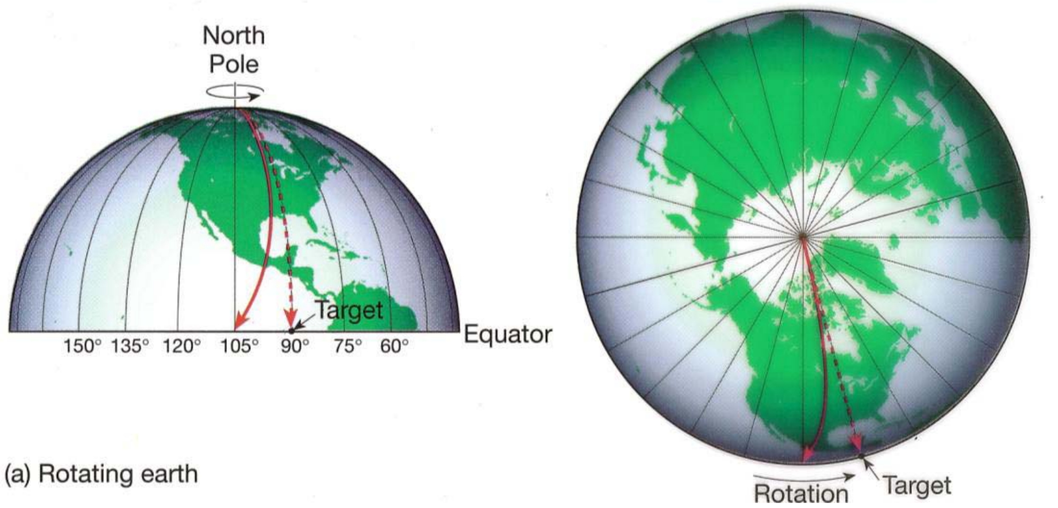
3. The accumulation of mass over the ocean results in higher pressure over the ocean surface and a circulation system is established

2. The Coriolis force

The rotation of the Earth causes an apparent “force” which acts on all moving objects on the Earth. The force is proportional to *velocity x sine(latitude).* The force acts perpendicularly to the direction of motion - to the right in the Northern hemisphere and to the left in the Southern hemisphere.



(a) Nonrotating earth



(a) Rotating earth

A conceptual explanation of the Coriolis force

Imagine a projectile fired from the North pole such that it skims the Earth’ surface and lands on the equator.

(a) Nonrotating Earth

In this case the projectile flies a straight path over the surface of the Earth.

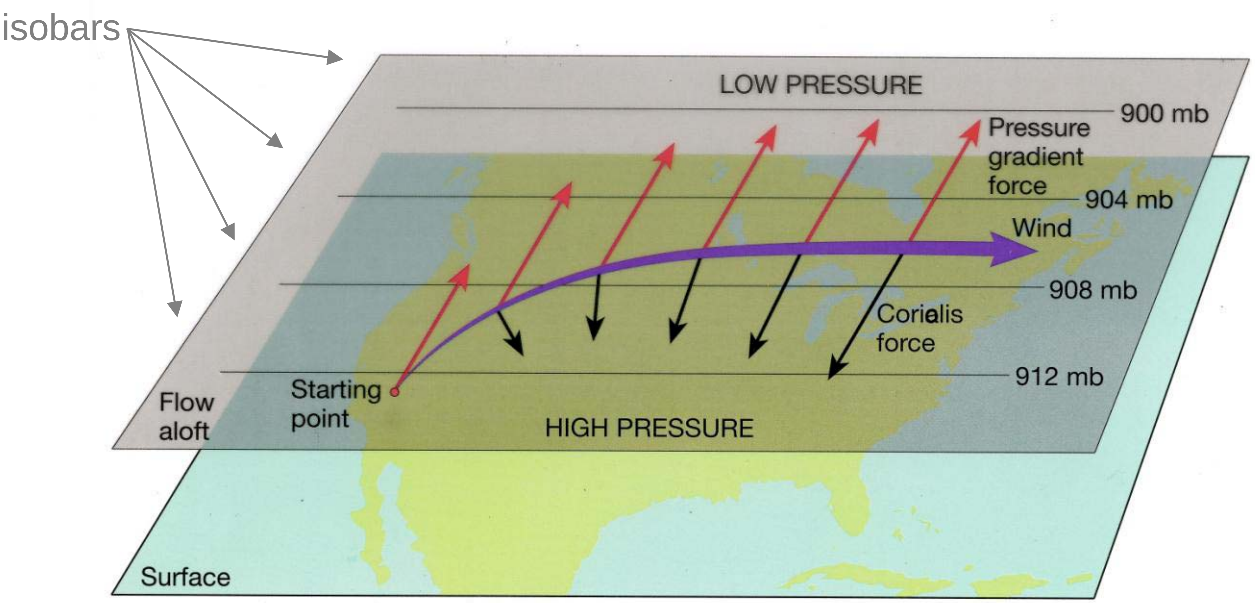
(b) Rotating Earth

In this case the rotation of the Earth means that the target has moved out of the way by the time the projectile reaches the equator. To an observer measuring the motion with respect to the Earth’s surface it appears as if a horizontal force has acted at 90^0 to the projectile’s motion and pushed it off to the right

NB/ a similar argument reveals a deflection to the left for motion in the Southern hemisphere

2. The Coriolis force & <u>geostrophic</u> flow

The effect of the Coriolis force is to deflect air flows so that they do not result in a direct high-pressure-to-low-pressure flow. Instead, the flow ends up being *parallel* to the pressure contours (isobars) at a given height.



The Coriolis force, C, is given by:

$$C = 2v\Omega\sin\phi$$

Where:

v = velocity

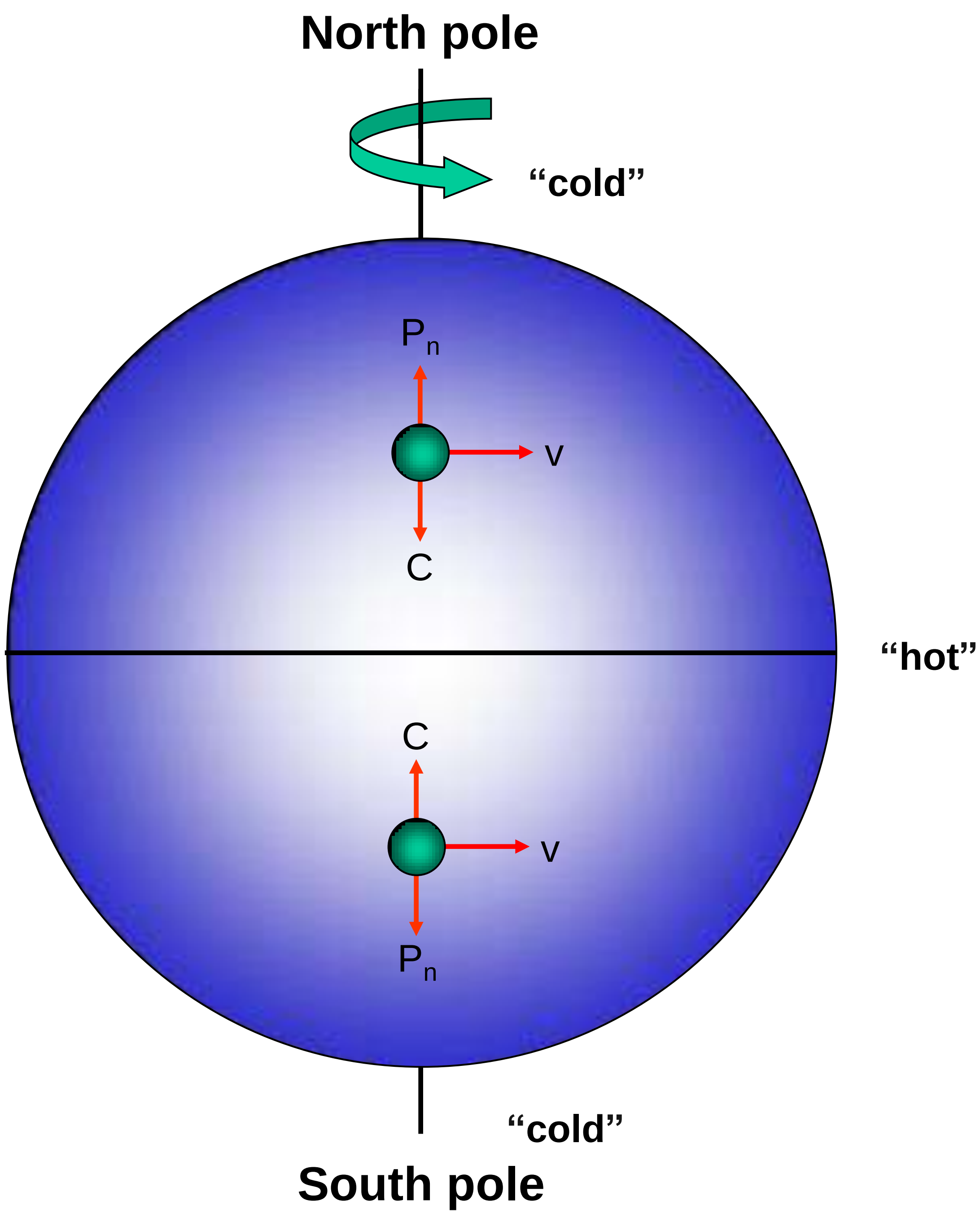
Ω = angular rotation rate of rotation of the Earth

ϕ = latitude

Geostrophic Flow

An air parcel starts to accelerate under the action of the pressure gradient force (in this case Northwards). As the air parcel accelerates, the Coriolis force starts to deflect it to the right. A steady state is eventually reached in which the pressure gradient force is equalled and opposed by the Coriolis force.

Flow where only the pressure gradient and Coriolis forces act is known as geostrophic flow



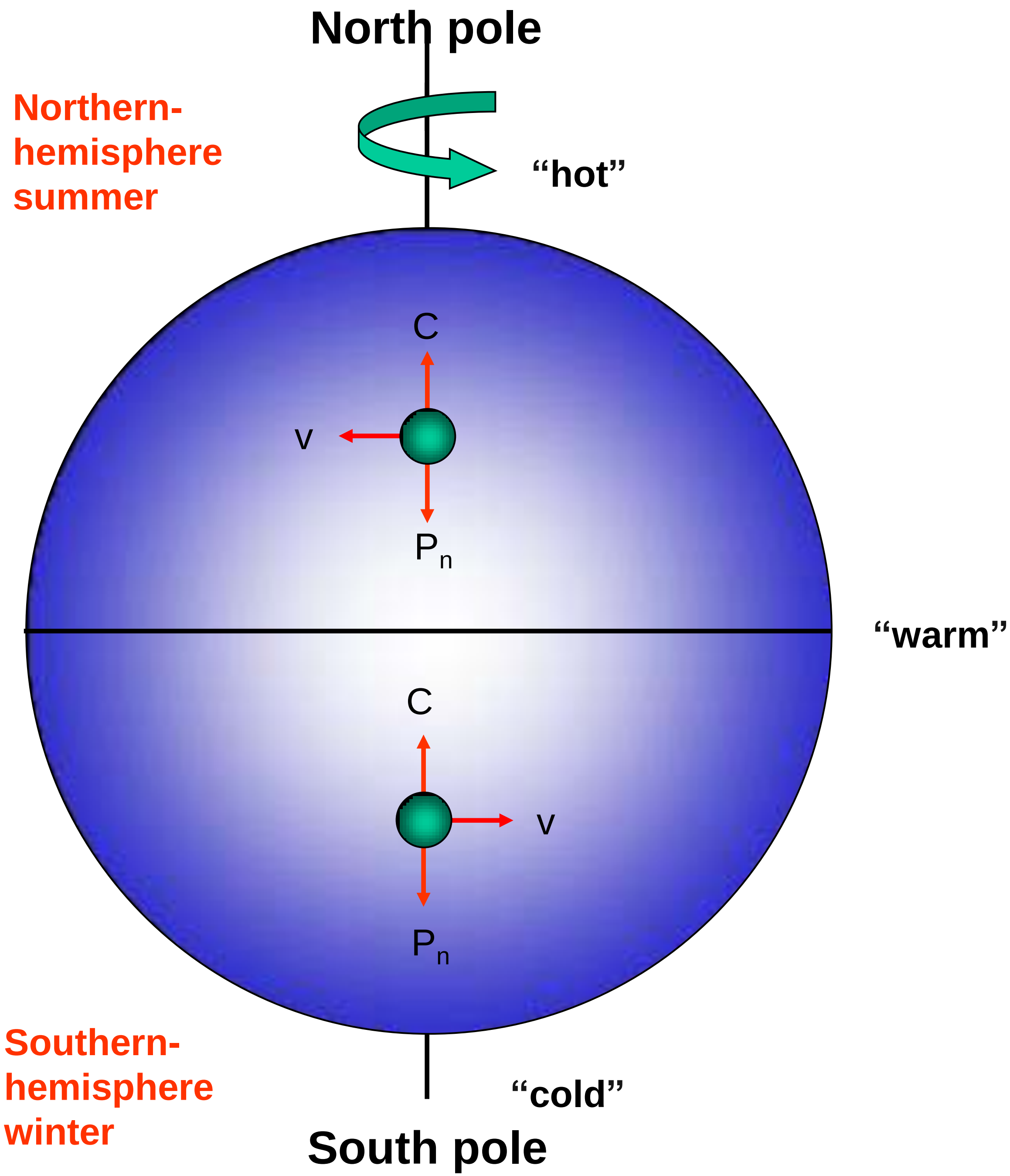
Geostrophic flow in the **upper troposphere**

The equator-to-pole temperature gradient creates a corresponding pressure gradient.

In each hemisphere, the Coriolis force, C, acts to balance the poleward pressure gradient force, P_n, and a stable East-West flow results

Because the Coriolis force acts in an opposite sense in each hemisphere, the geostrophic winds are westerly (i.e., eastwards) in both hemispheres and in all seasons.

NB – this only applies to the "winds aloft" in the upper troposphere. At the surface it's sometimes more complicated – e.g., seasonal monsoon circulations



Geostrophic flow in the **strato/mesosphere**

The summer pole is hotter than the equator because it is in 24-hour sunlight. The winter pole is cold.

The pressure gradient force is thus in the *same* direction in each hemisphere.

Because the Coriolis force acts in an *opposite* sense in each hemisphere, the geostrophic winds are easterly (i.e., westwards) in the summer hemisphere and westerly (i.e., eastwards) in the winter hemisphere.

There is thus a seasonal <u>reversal</u> of the mean winds (unlike the troposphere)

Radiative equilibrium predicted temperatures (solstice)

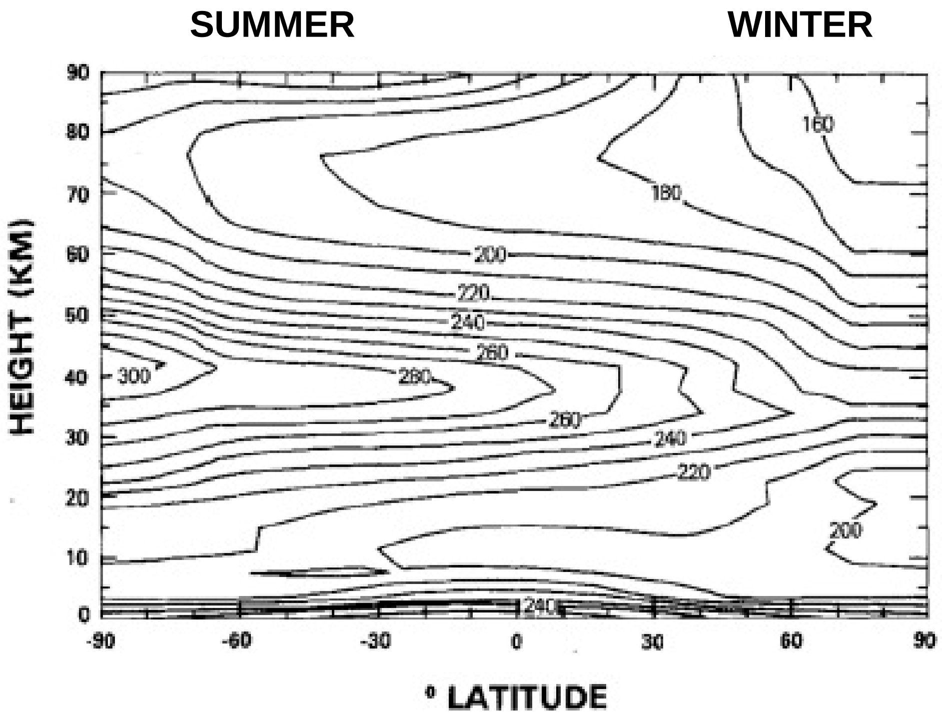


Figure 1.3: Prediction of solstitial atmospheric zonal-mean temperature as a function of height and latitude for an atmosphere , from Geller (1983).

Notice:

1. Summer pole warmer than winter pole at all heights
2. Summer polar stratosphere heated by O_3 absorption of solar UV

Radiative equilibrium predicted geostrophic winds (solstice)

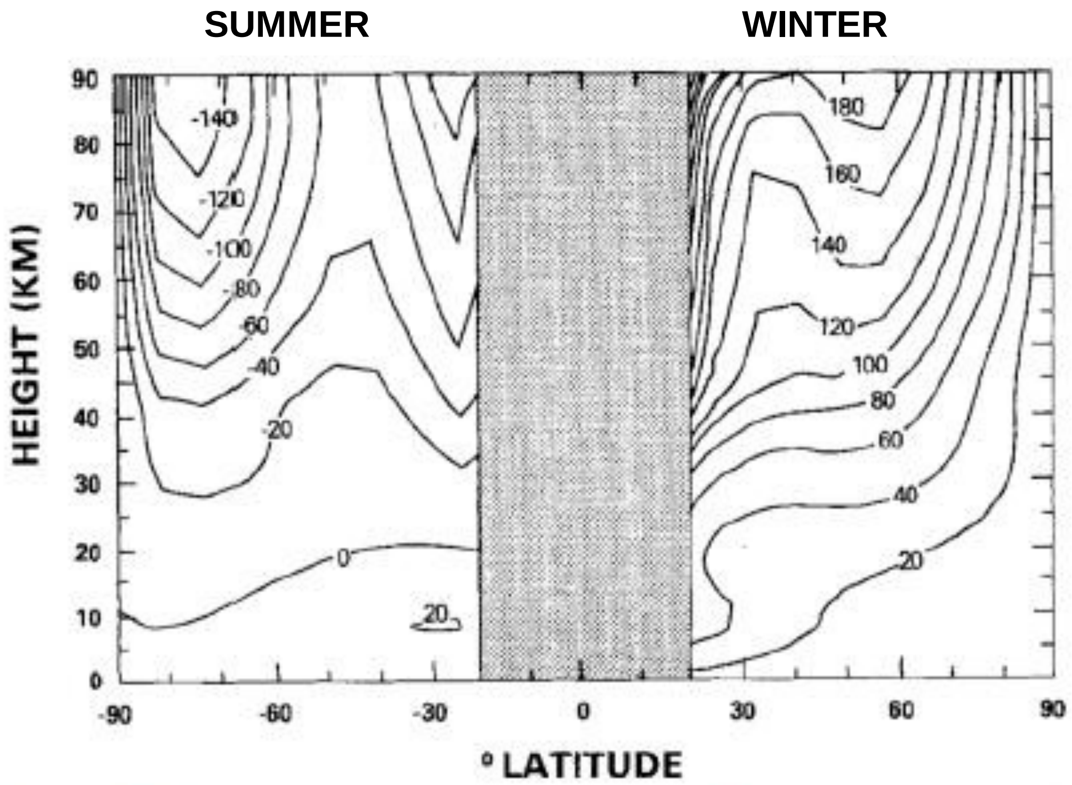


Figure 1.5: Prediction of solstitial atmospheric zonal-mean wind as a function of height and latitude in an atmosphere of radiative equilibrium, from Geller (1983).

Notice:

1. Eastward winds in summer hemisphere, westward winds in winter hemisphere
2. Winds are zonal (i.e., E-W) only, there are no meridional (N-S) winds
3. Winds increase with height
4. There are no vertical winds

Observed temperature structure (solstice)

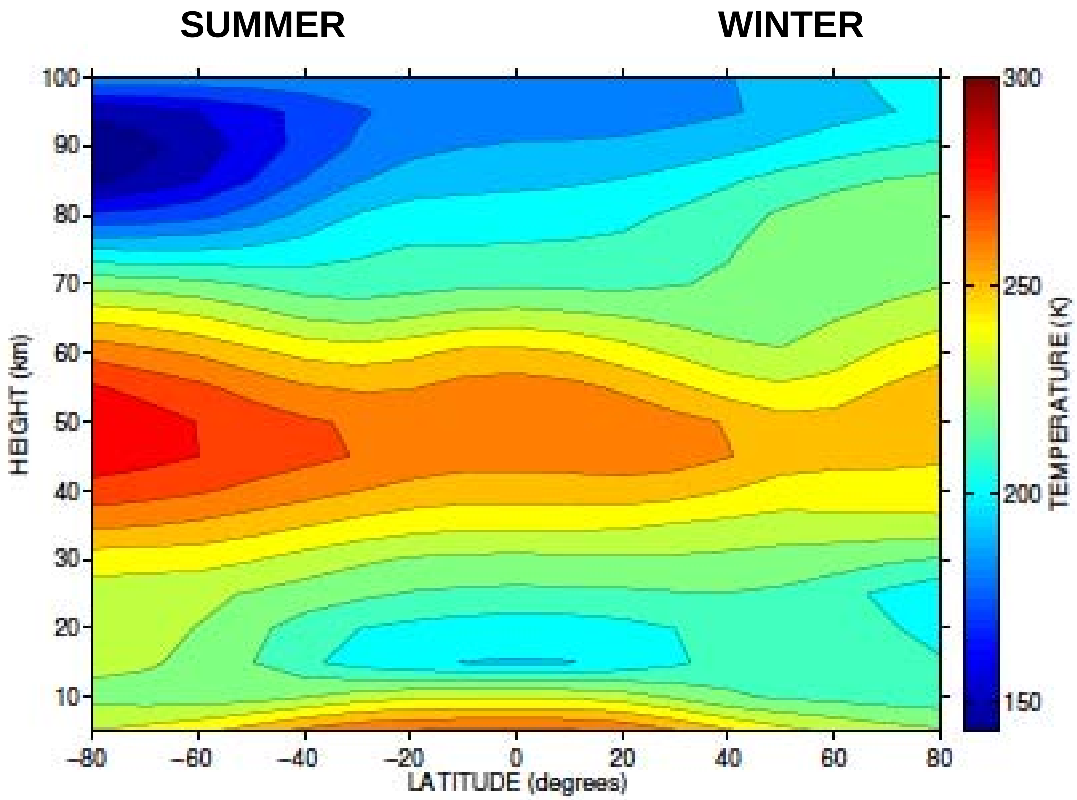


Figure 1.6: CIRA-86 zonal-mean temperatures as a function of latitude and height during the northern hemisphere winter solstice. Note that the mesopause is much colder near the summer pole than the winter.

Notice:

1. Meridional (N-S) temperature gradient is ***reversed*** in the mesosphere
2. ***Coldest*** mesopause temperatures in polar ***summer***, warmest in polar winter

Observed zonal winds (solstice)

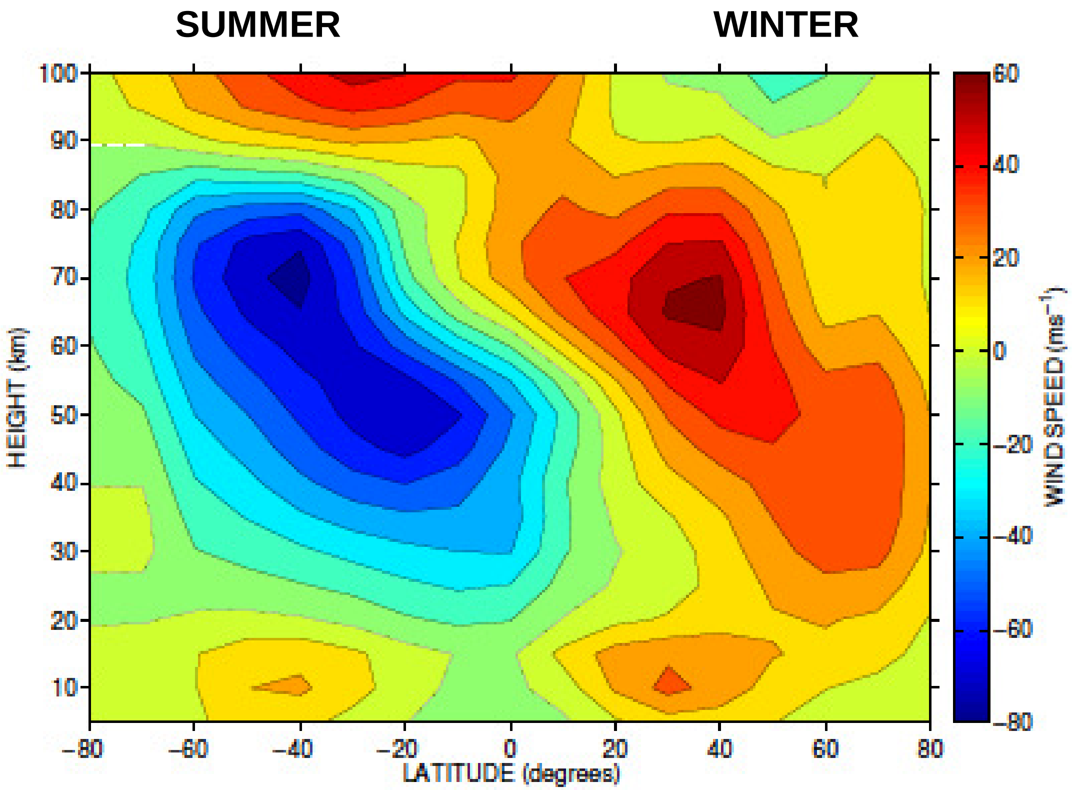
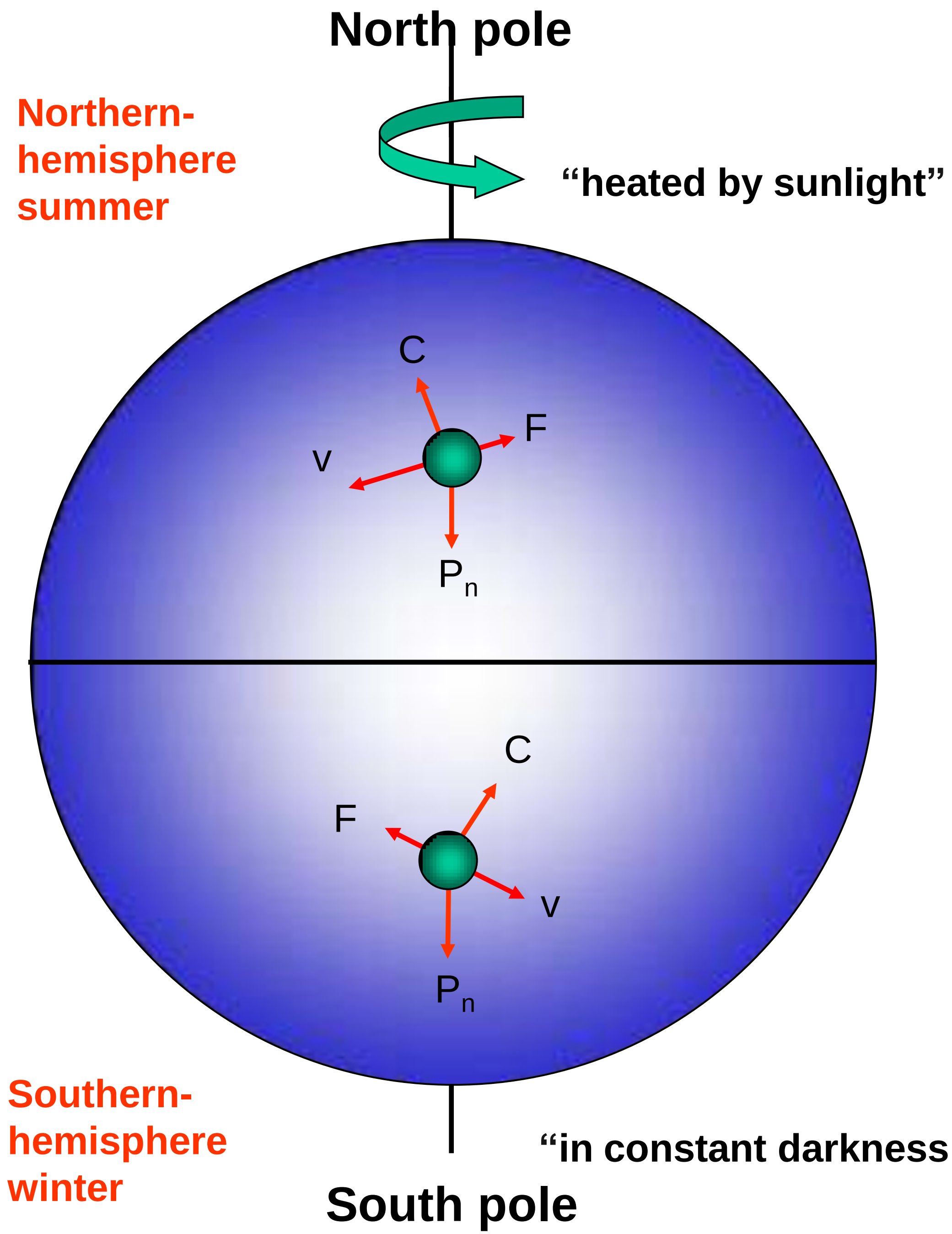


Figure 1.7: CIRA-86 zonal-mean winds as a function of latitude and height during the northern hemisphere winter solstice. The dashed line represents the zero-wind line. Note that the jets are closed, with winds reducing at heights near 70 km and reversing at heights near 90 km.

1. Eastward and westward winds still occur, but not as strong as predicted
2. But, winds ***reduce to zero*** near 90 km then actually reverse
3. There must be an **additional** force slowing then reversing the winds (“wave drag”)



Wave drag

Atmospheric waves cause a drag force, **F**, on air parcels that opposes the motion.

Steady-state flow occurs when:

$$\mathbf{P_n = C + F}$$

Note how this occurs when there is a meridional flow away from the summer pole towards the winter pole.

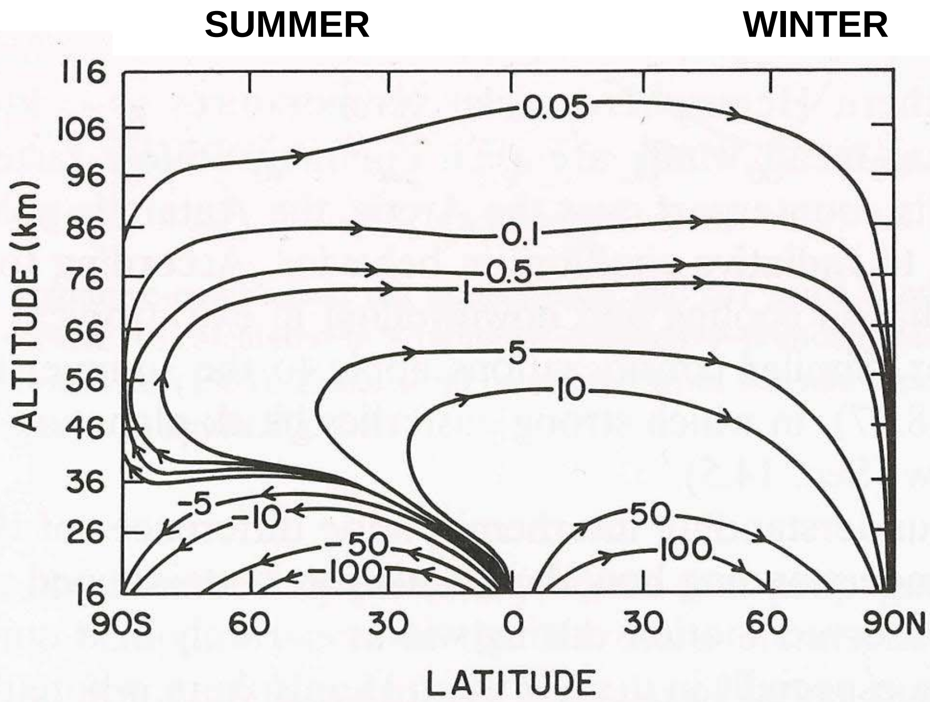
Continuity demands there be a vertical flow at high latitudes.

Observed meridional and vertical winds (solstice)

Summer Hemisphere

Upwelling flow →

Adiabatic cooling



← Winter Hemisphere

Downwelling flow

Adiabatic heating

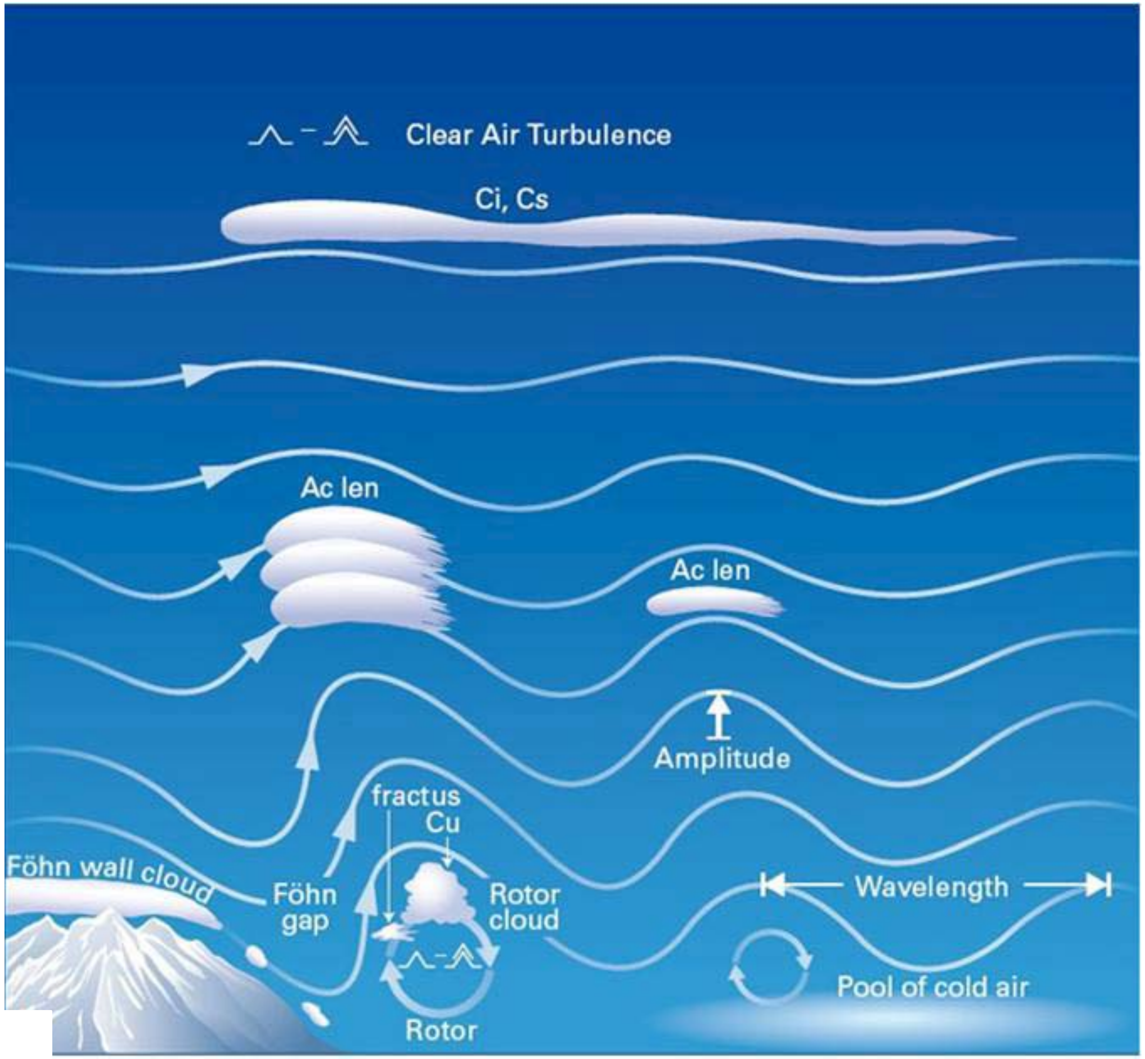
Figure 17.9 Streamlines of the mean meridional circulation of the middle atmosphere, in a quasi-Lagrangian representation. Adapted from Garcia and Solomon (1983), copyright by the American Geophysical Union.

Notice:

1. The real atmosphere has **meridional/vertical** winds (the Brewer-Dobson circulation)
2. The mesosphere has a **unique pole-to-pole** circulation
3. Vertical flow causes adiabatic heating/cooling and explains the observed temperatures
4. As with the winds, this is a consequence of ***an extra force*** acting on the atmosphere

4. Driving the circulation of the mesosphere by gravity waves

A gravity wave caused by flow over a mountain

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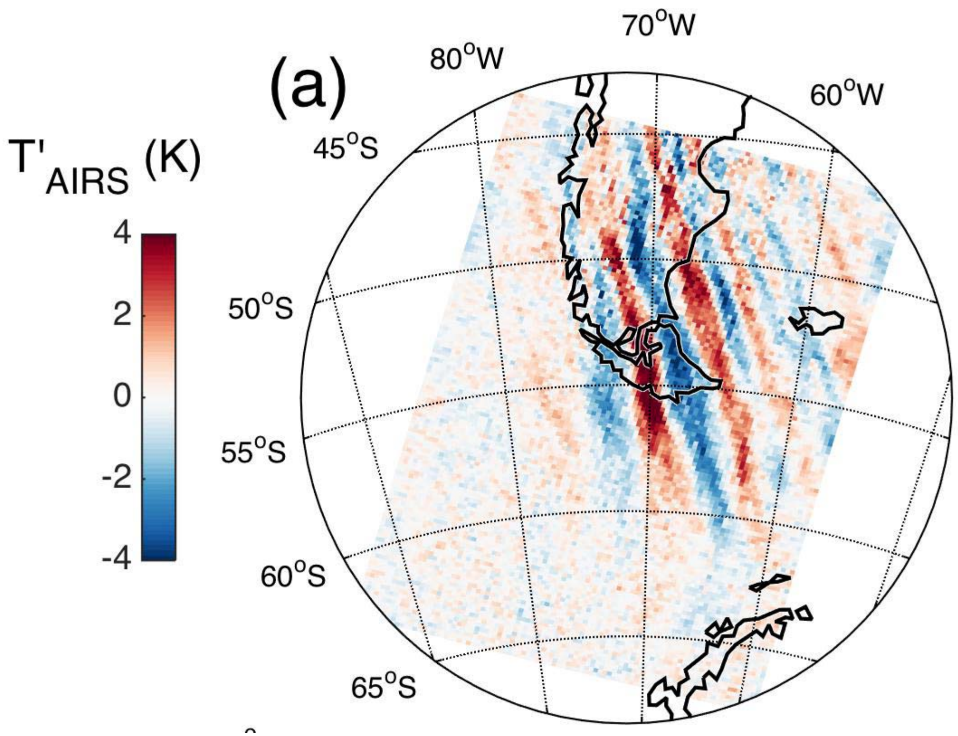
Gravity waves in the middle atmosphere

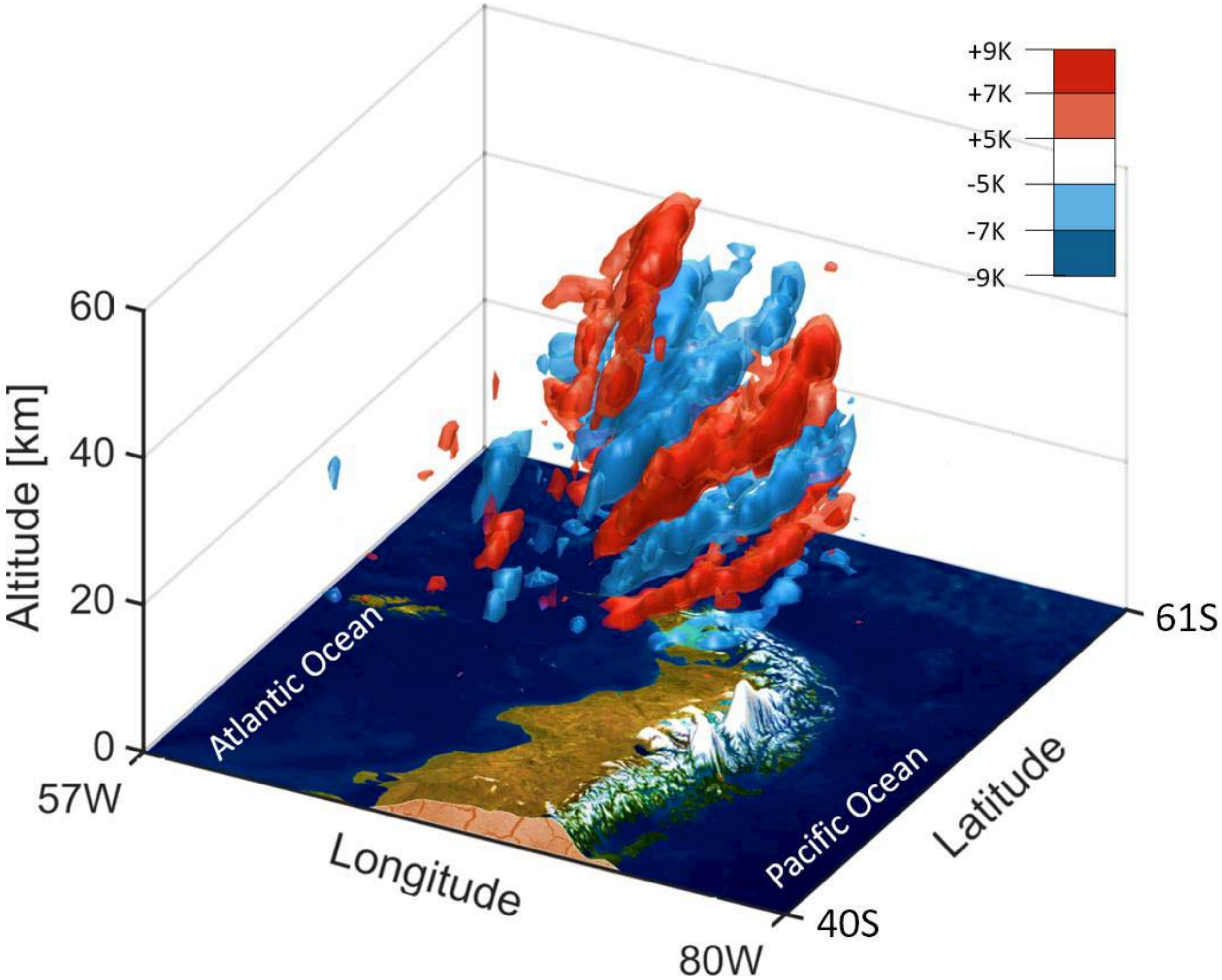
A gravity wave over the Southern Andes



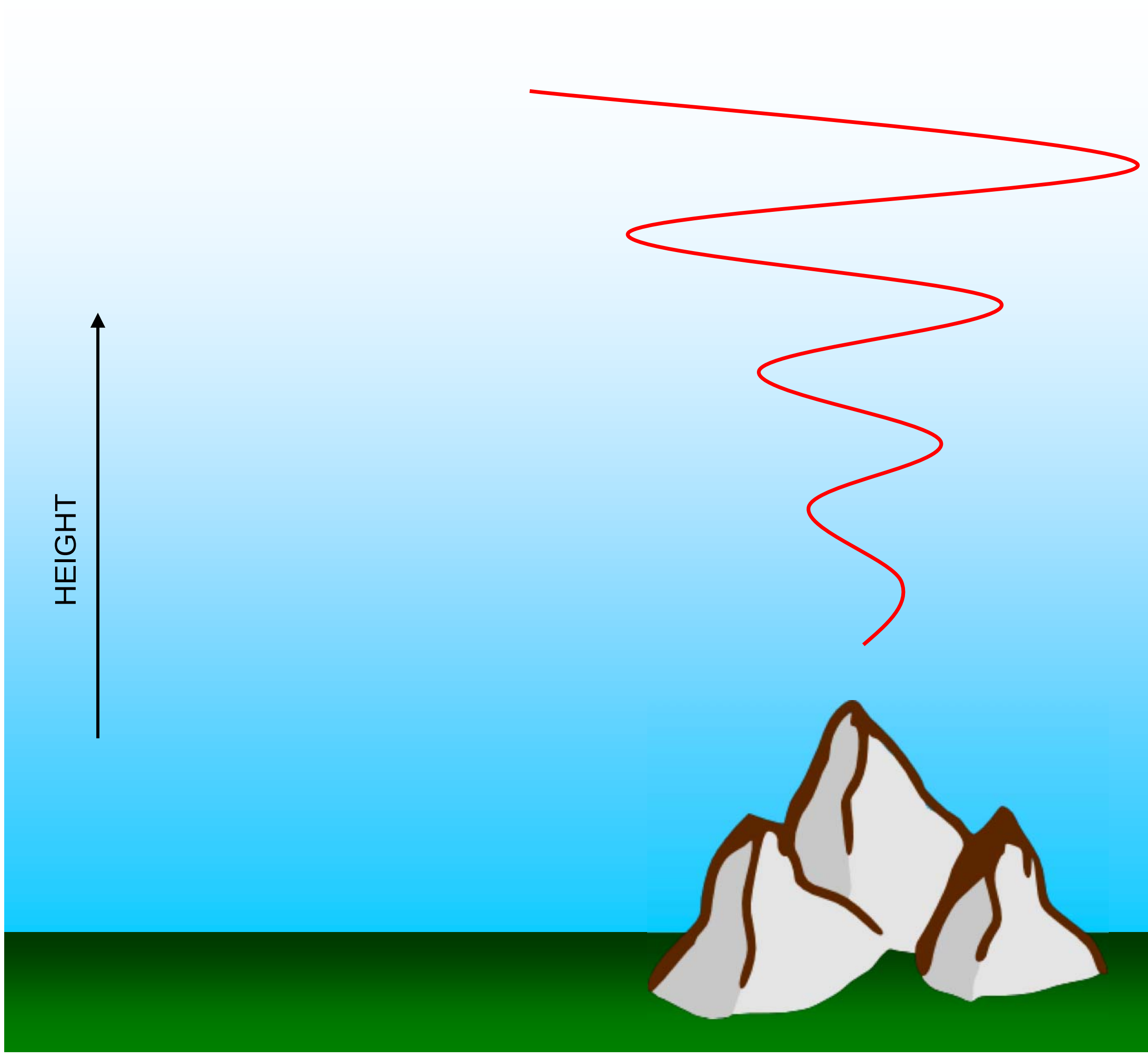
Data from the NASA AIRS instrument on the Aqua satellite

Temperature perturbations at a height of ~ 40 km in the stratosphere

Mountain waves in a 3D analysis using NASA/AIRS data



Why are gravity waves important in the mesosphere?

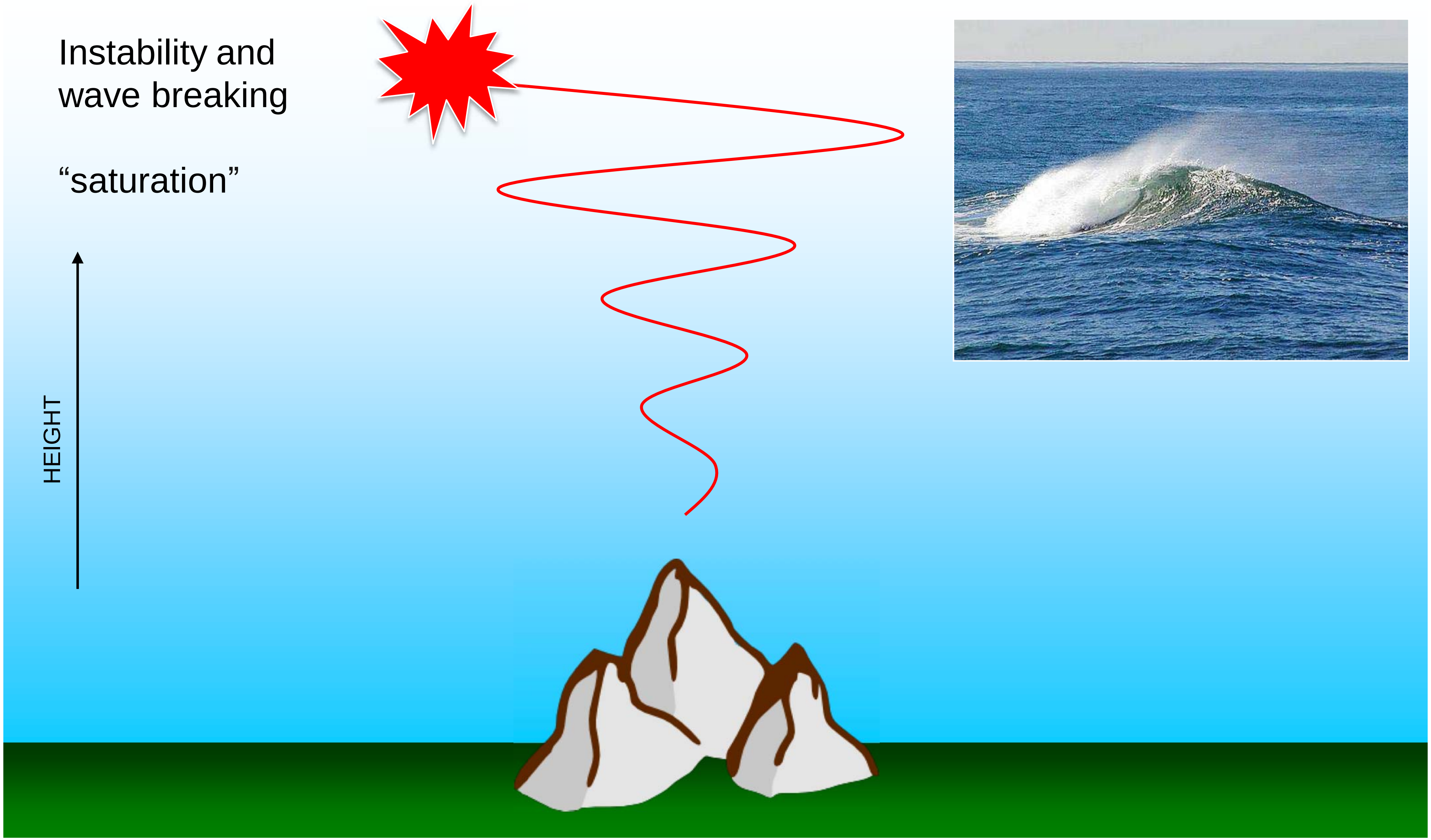


A wave of amplitude V ms^{-1} has energy per unit volume, E, Joules per m^3, where:

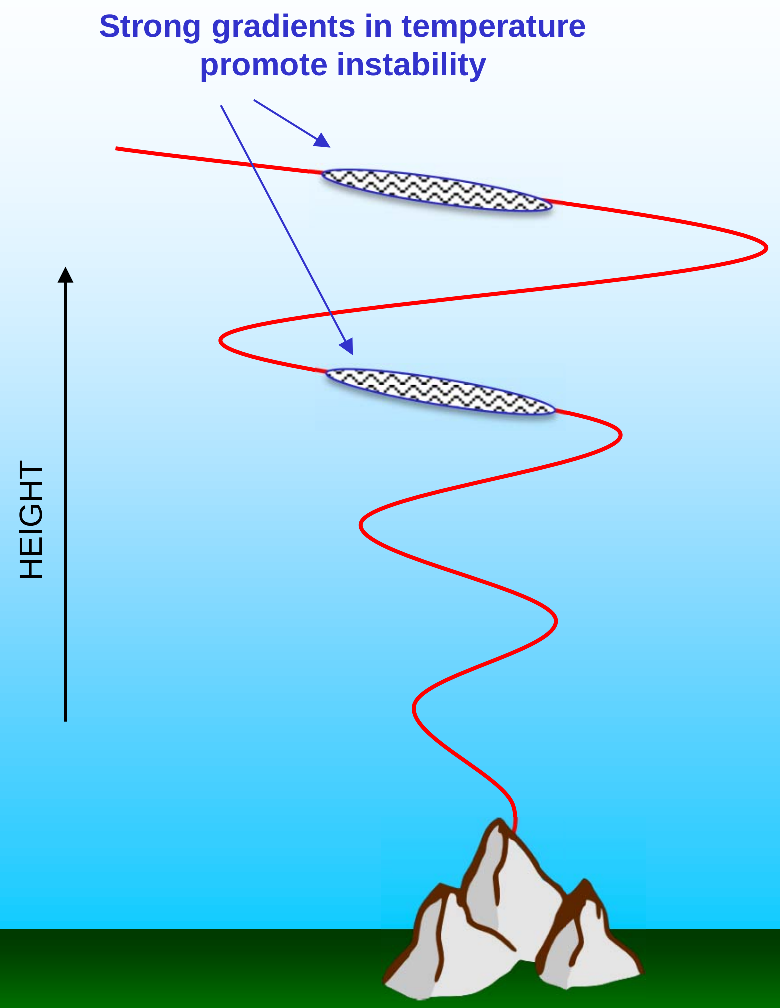
E = ½ (atmospheric density)V^2

Thus, as the wave ascends, if energy is conserved, the amplitude, V, must rise to balance the decrease in gas density, ρ.

Why are gravity waves important in the mesosphere?



Why are gravity waves important in the mesosphere?



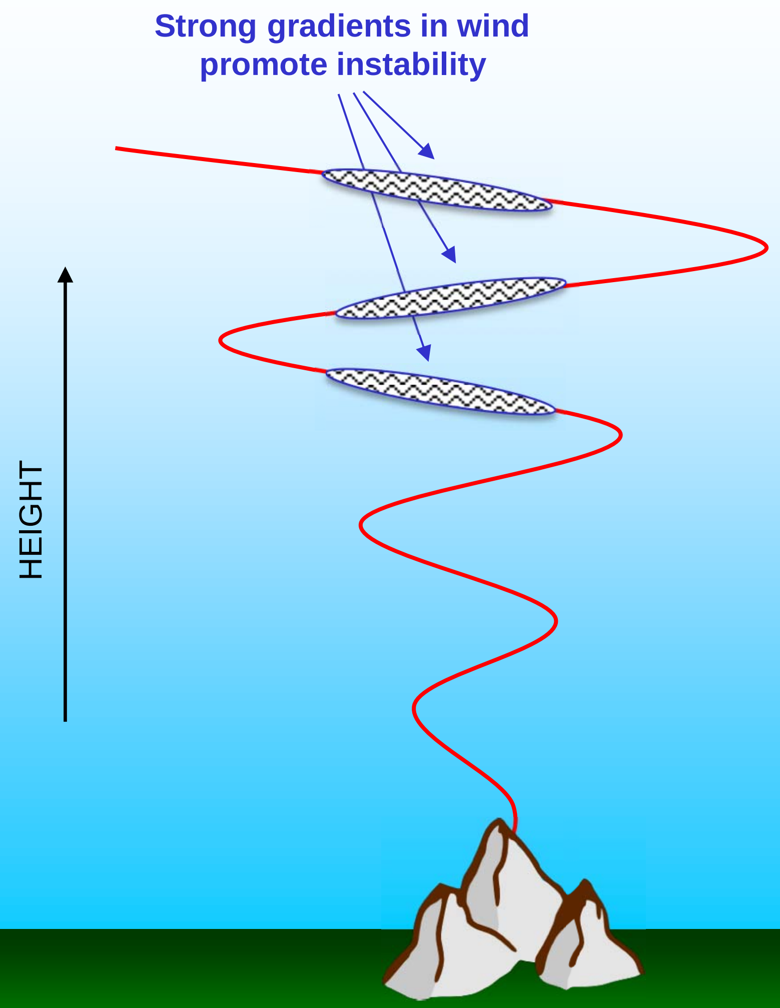
Breaking waves

1. Convective Instability

In which the wave produces *superadiabatic temperature gradients*, i.e.,

$$dT/dz < 9.8 \text{ K/km}$$

Why are gravity waves important in the mesosphere?



Breaking waves

2. Shear Instability

In which the wave produces unstable shears in the fluid flow (i.e., Richardson numbers, $R_i < 0.25$).

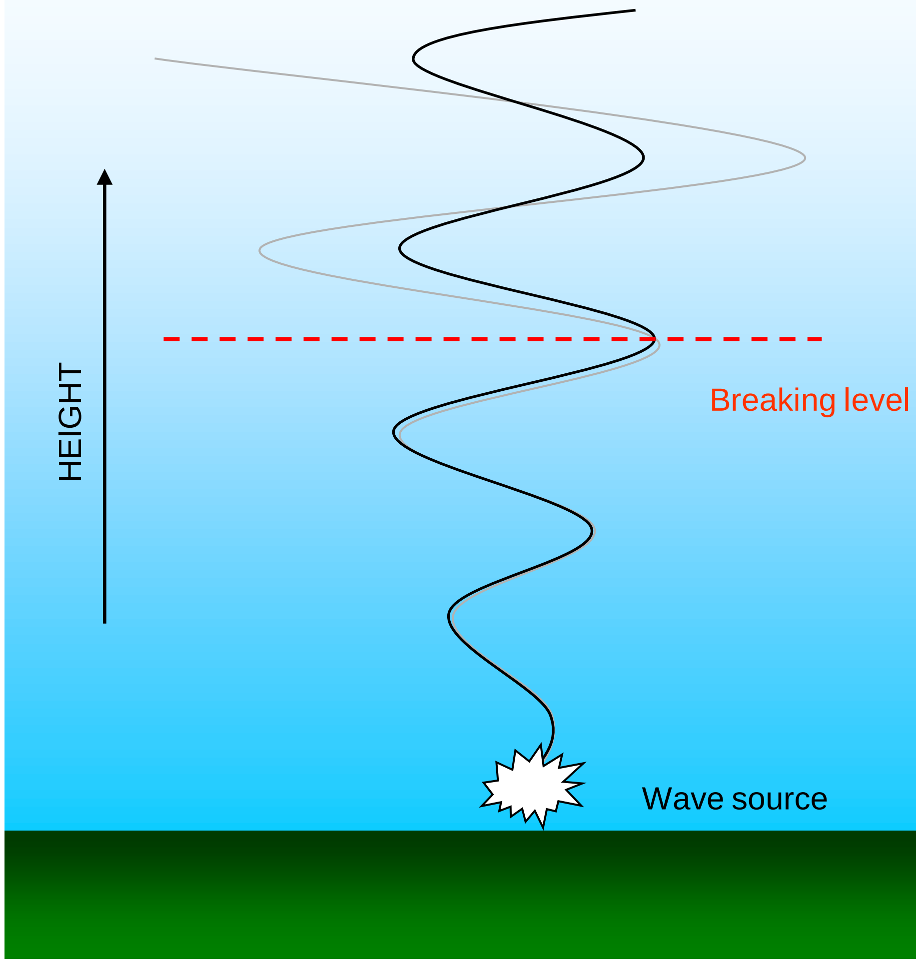
$$Ri = N^2 / (du / dz)^2$$

NB, Both processes cause the wave to “break” into turbulence – energy is lost from the wave and its amplitude growth is limited.

Why are gravity waves important in the mesosphere?

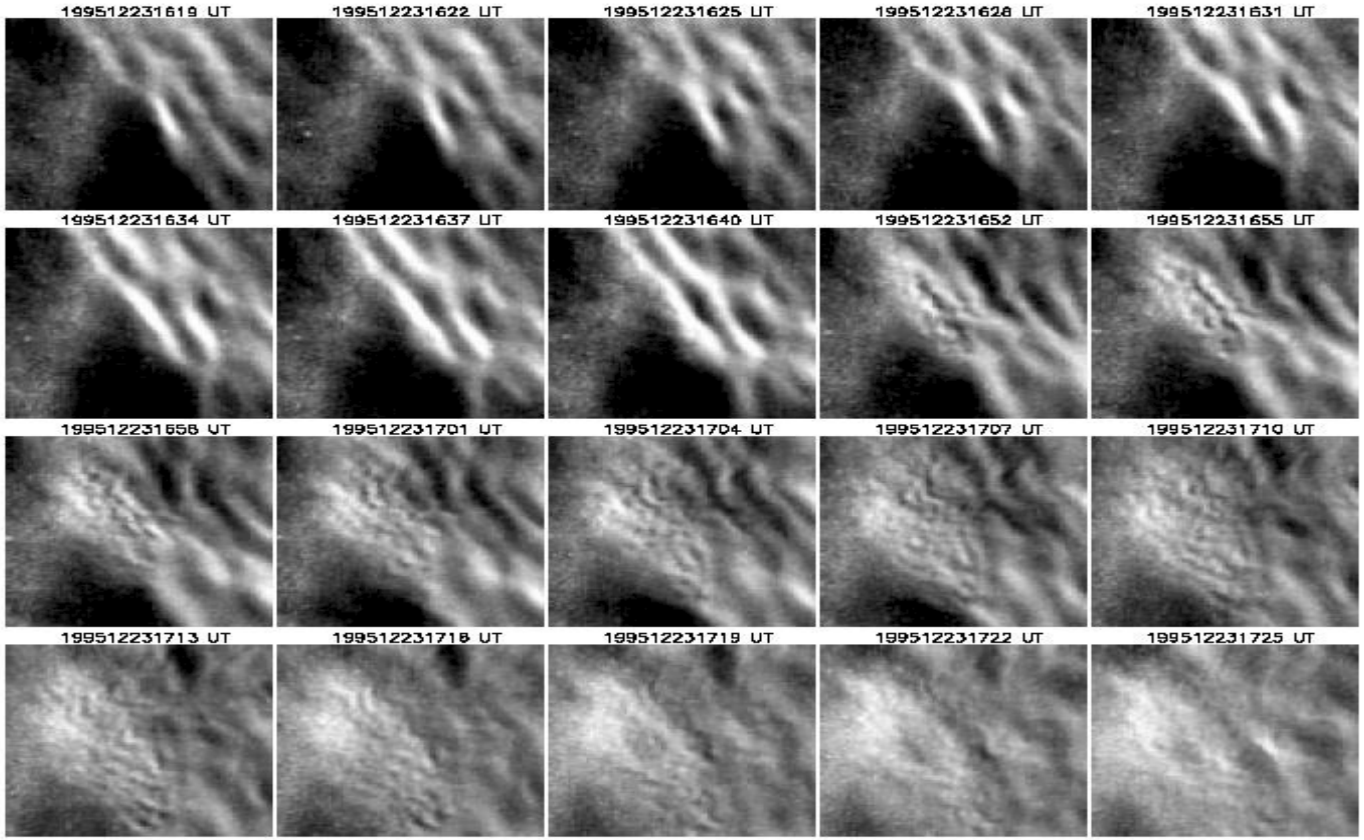
Wave amplitudes thus grow until a “breaking level” is reached. Above that level, wave amplitudes are constrained and held approx. constant.

Wave energy and momentum flux are no longer conserved.



- Wave energy → turbulent energy
- **Momentum carried by the wave is deposited into the mean flow and imposes a force on the flow of the background atmosphere – “wave drag”.**
- Momentum deposited by waves provides up to ~ 70% of the momentum of the flow in the MLT.
- **The MLT has a wave-driven large-scale circulation.**

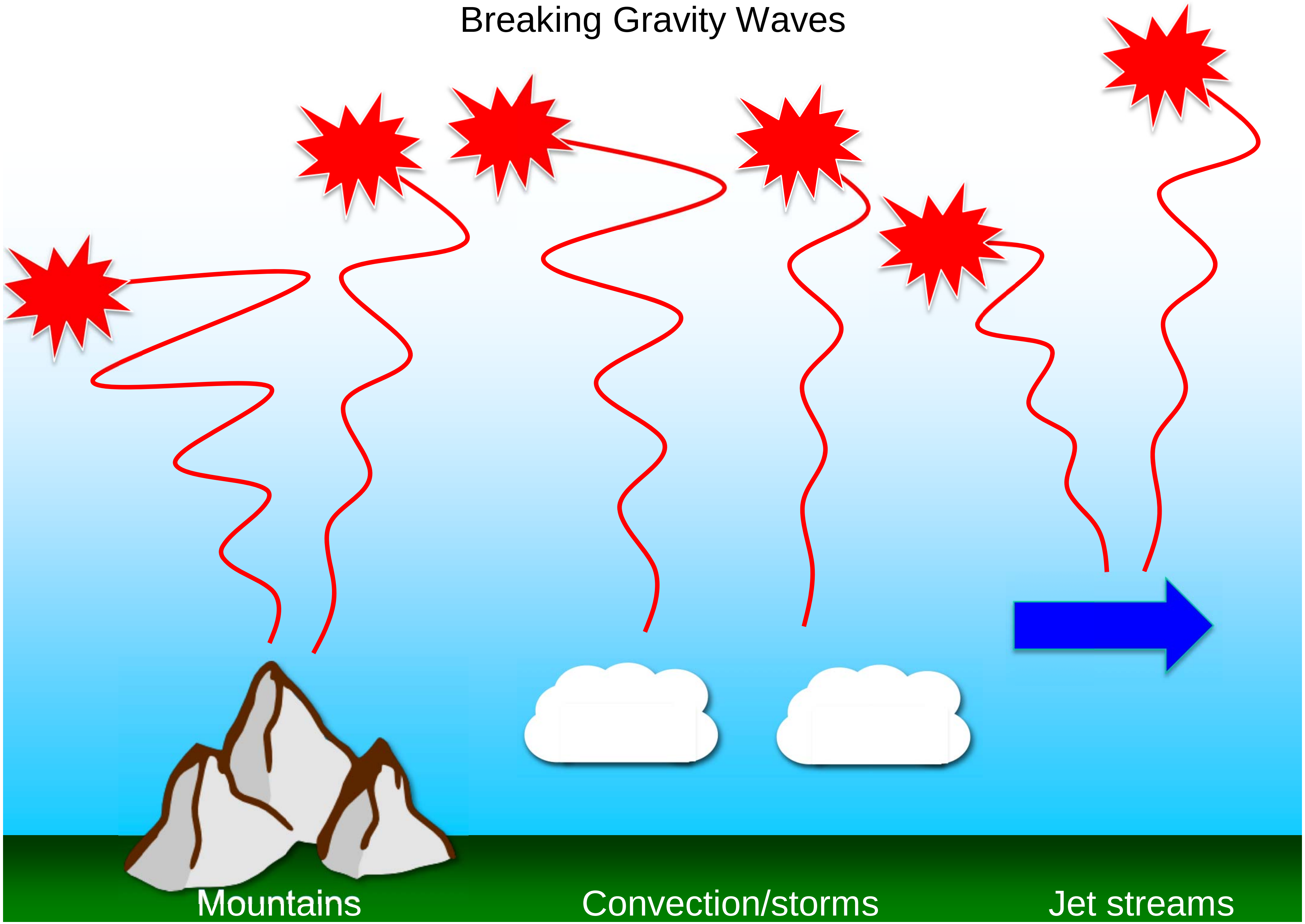
An example of a breaking wave in the mesosphere



A sequence of OH airglow images from an interval of ~ 1 hr 6 min reveal a gravity wave breaking rapidly into turbulence.

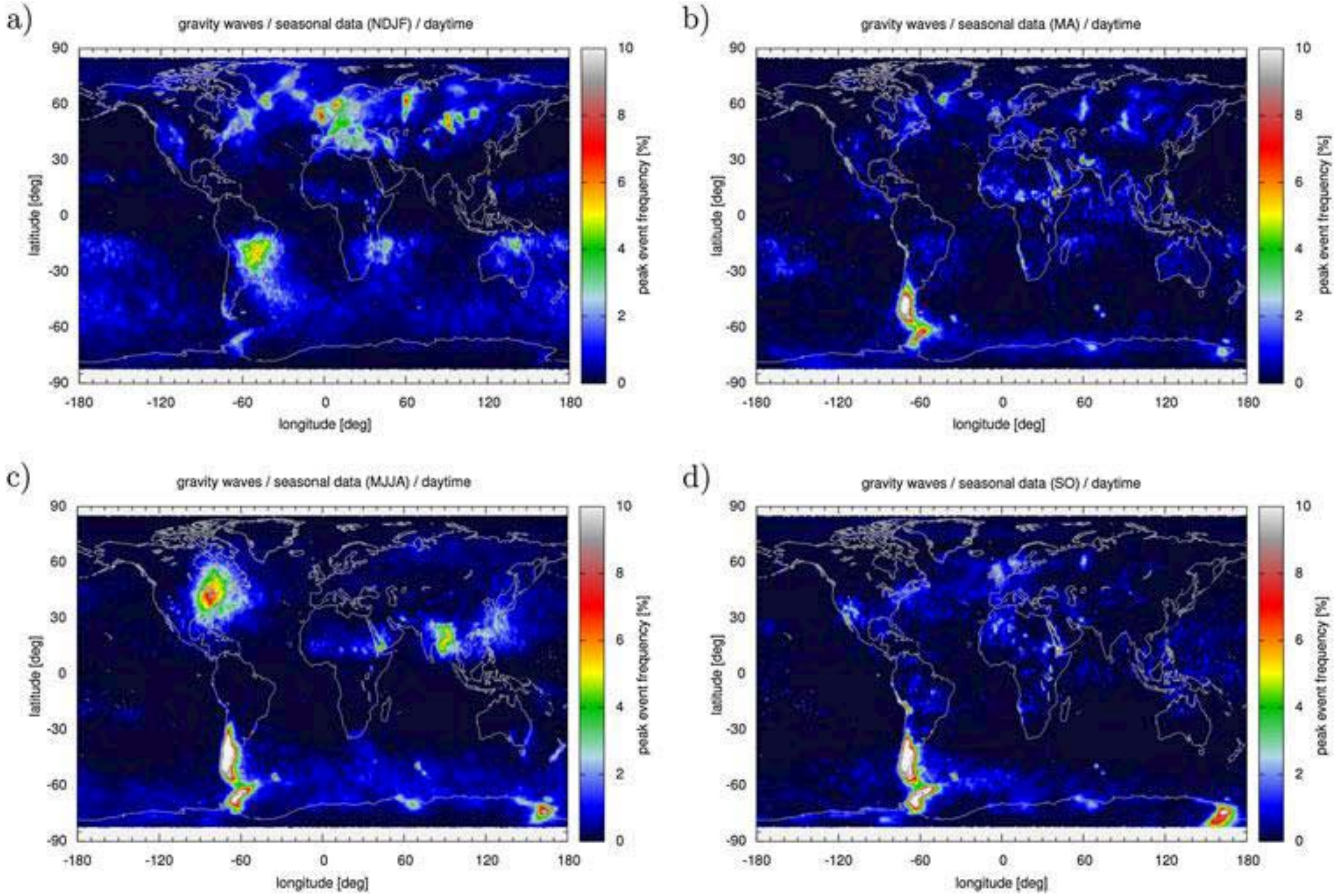
It is likely that ***convective instability*** is breaking the wave in this particular instance.

OH airglow images 16:19 – 17:25 UT, at a height of ~ 87 km, over Japan, 23/12/95. The images are spaced by ~ 3 minutes. The centre of each image is the zenith. The horizontal wavelength of the original waves is ~ 27 km and the period was deduced to be ~ 6 minutes (Yamada *et al*., GRL, 2001)

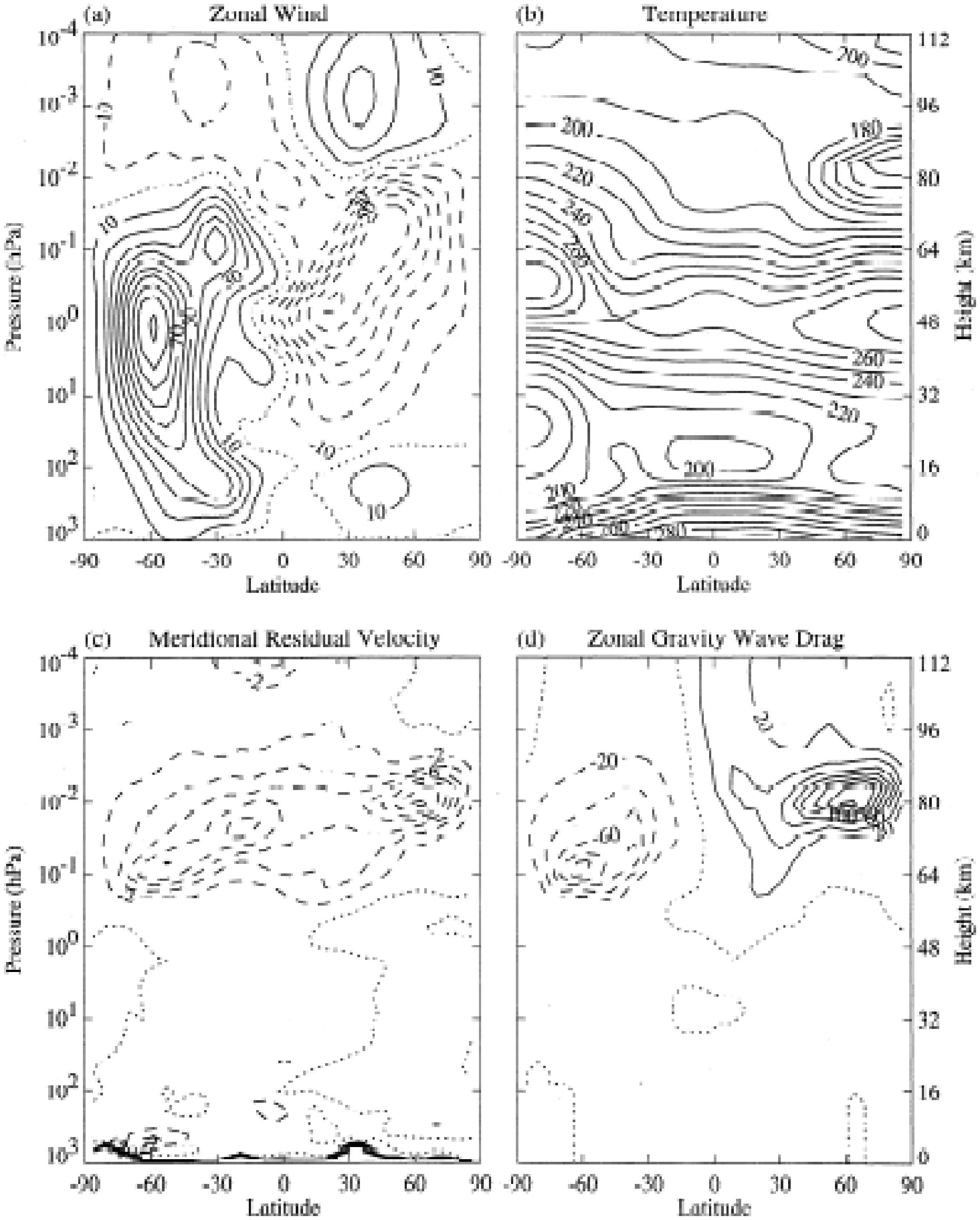


Breaking Gravity Waves
Mountains
Convection/storms
Jet streams

Where and what are the sources of gravity waves?



Hoffmann, L., X. Xue, and M. J. Alexander (2013), J. Geophys. Res. Atmos., 118, 416–434, doi:10.1029/2012JD018658.



Gravity-Wave Drag Maximises in the Mesosphere

Global Circulation Model, Norton & Thuburn, JGR, 1999

4. Driving the circulation of the mesosphere by gravity waves

Science questions for the next decade

What are the relative contributions of mountains, storms, small islands and jet streams to the fluxes and variability of gravity waves?

How do gravity waves interact with planetary waves and with tides?

Why were noctilucent clouds not observed before the 1880s?

Is there climate change in the mesosphere?

What are the physical processes that control the propagation and dissipation of waves and tides?

How can we include the effects of gravity waves in GCMs?

What effect do lower atmosphere phenomena like ENSO and the tropical Madden-Julian Oscillation have on the middle and upper atmosphere?