Title: The impact of the Atmosphere on space-bound Vehicles

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Abstract: When rockets and space-bound vehicles are fired into space, they have to deal with turbulence, winds and waves in the Earth's atmosphere. Different height regimes cause different problems. In the lower regions (0 to 20 km altitude), winds and turbulence are major issues, whereas above 50 km altitude, large atmospheric waves have serious importance on safe passage. Similar issues arise on re-entry. In this talk, I will discuss the ways in which these atmospheric phenomena manifest themselves, and how they are best mitigated. One example of particular significance will be the Space Shuttle Columbia disaster, for which I consulted with NASA in respect to possible atmospheric influences. I will also describe some of the instrumentation used to measure these phenomena.

The impact of the Atmosphere on space-bound Vehicles

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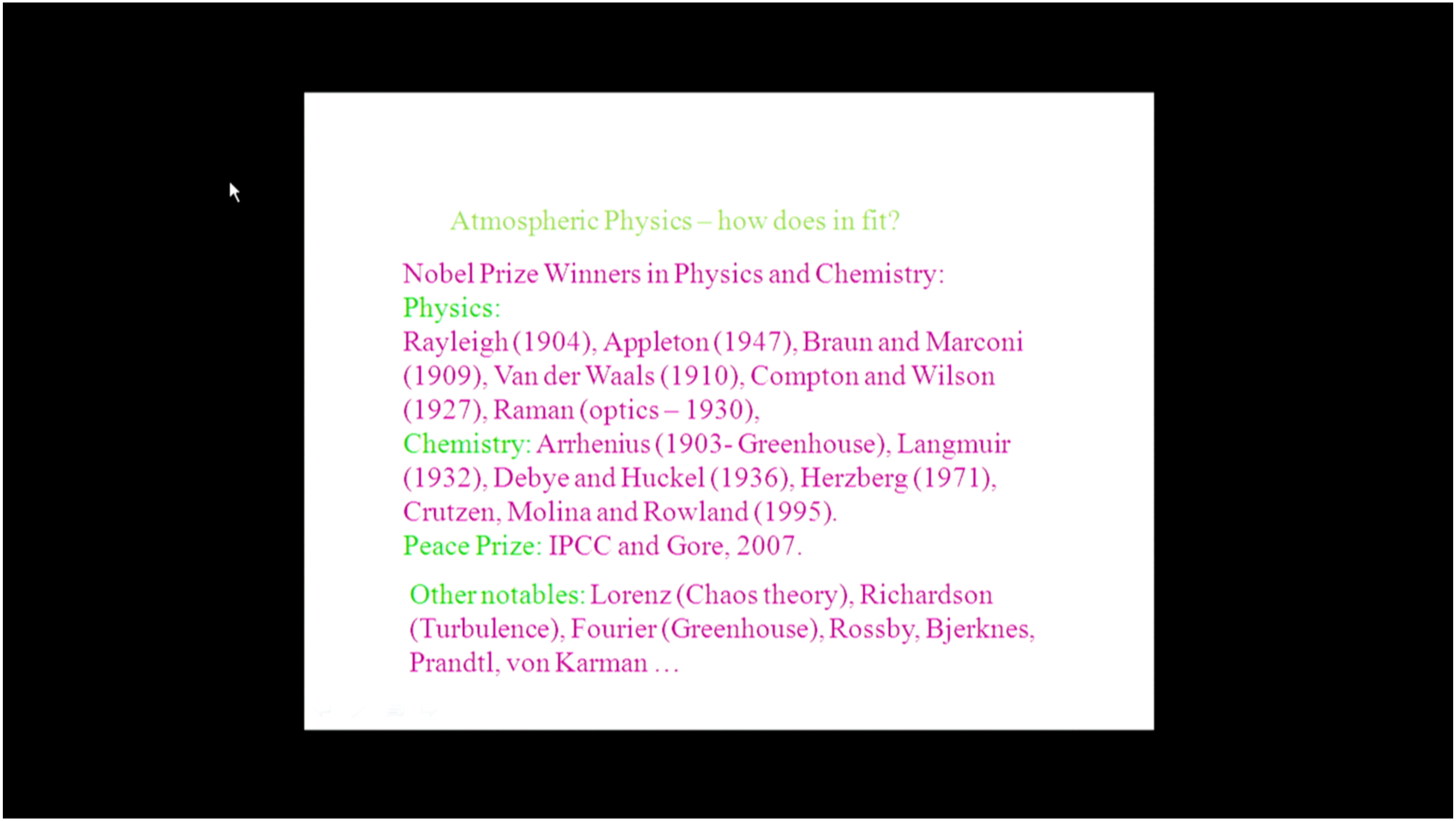
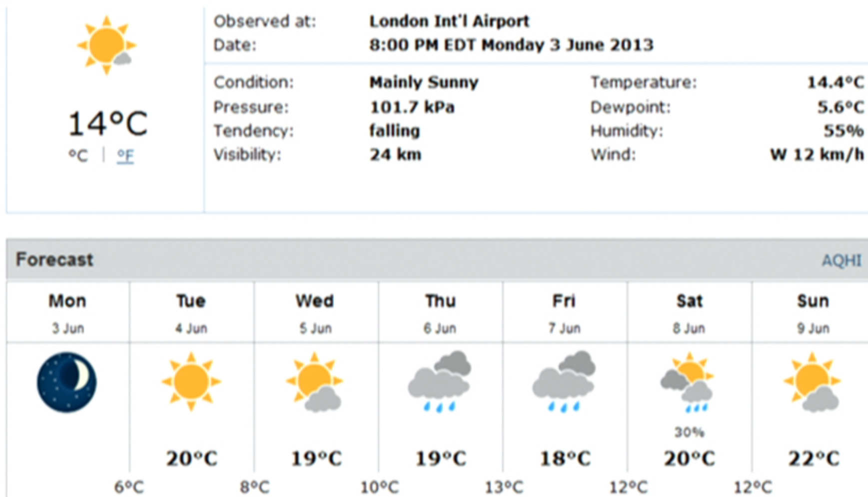
CAM, Waterloo, 2013


Atmospheric Physics – how does in fit?
Nobel Prize Winners in Physics and Chemistry:
Physics:
Rayleigh (1904), Appleton (1947), Braun and Marconi (1909), Van der Waals (1910), Compton and Wilson (1927), Raman (optics – 1930),
Chemistry: Arrhenius (1903- Greenhouse), Langmuir (1932), Debye and Huckel (1936), Herzberg (1971), Crutzen, Molina and Rowland (1995).
Peace Prize: IPCC and Gore, 2007.
Other notables: Lorenz (Chaos theory), Richardson (Turbulence), Fourier (Greenhouse), Rossby, Bjerknes, Prandtl, von Karman …

Studies in Atmospheric Physics requires background in..

Electromagnetism, Thermodynamics, Optics, Fluids, Non-linear processes, gas kinetics, radar, signal-processing, Quantum Mechanics, scattering theory, computer modeling, chemistry…

A typical weather forecast nowadays…



14°C	Observed at:	London Int'l Airport		
°C | °F	Date:	8:00 PM EDT Monday 3 June 2013		
	Condition:	Mainly Sunny	Temperature:	14.4°C
	Pressure:	101.7 kPa	Dewpoint:	5.6°C
	Tendency:	falling	Humidity:	55%
	Visibility:	24 km	Wind:	W 12 km/h

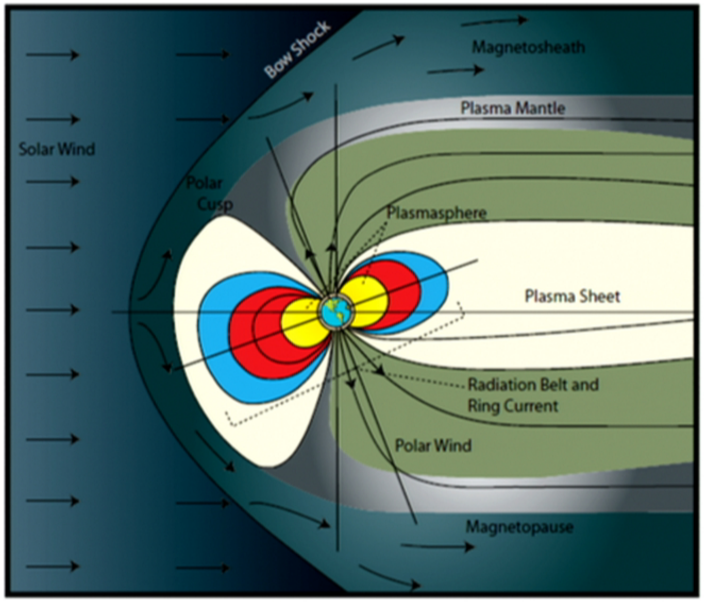
Forecast AQHI

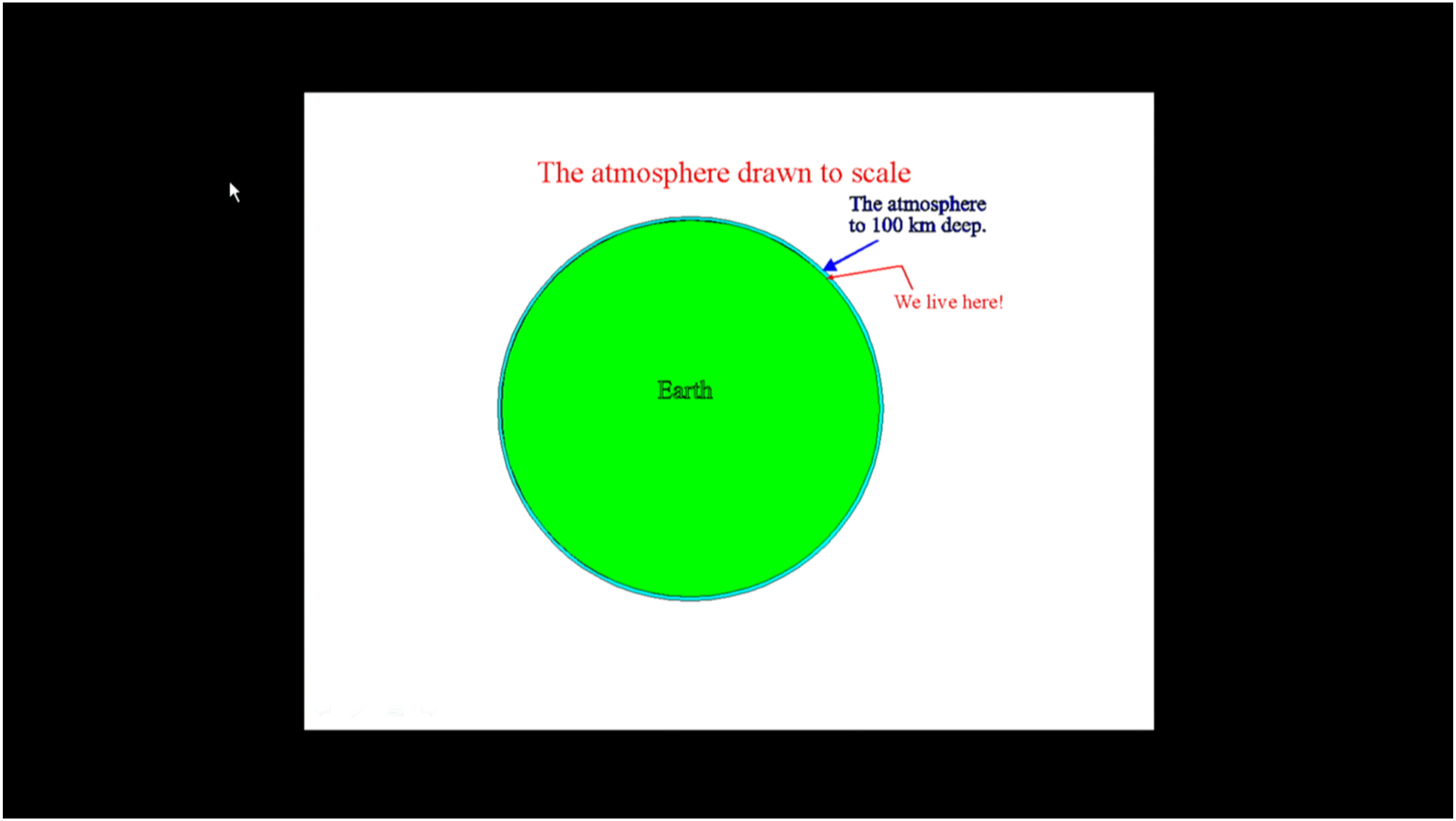
Mon 3 Jun	Tue 4 Jun	Wed 5 Jun	Thu 6 Jun	Fri 7 Jun	Sat 8 Jun	Sun 9 Jun
					30%	
	20°C	19°C	19°C	18°C	20°C	22°C
6°C	8°C	10°C	13°C	12°C	12°C	

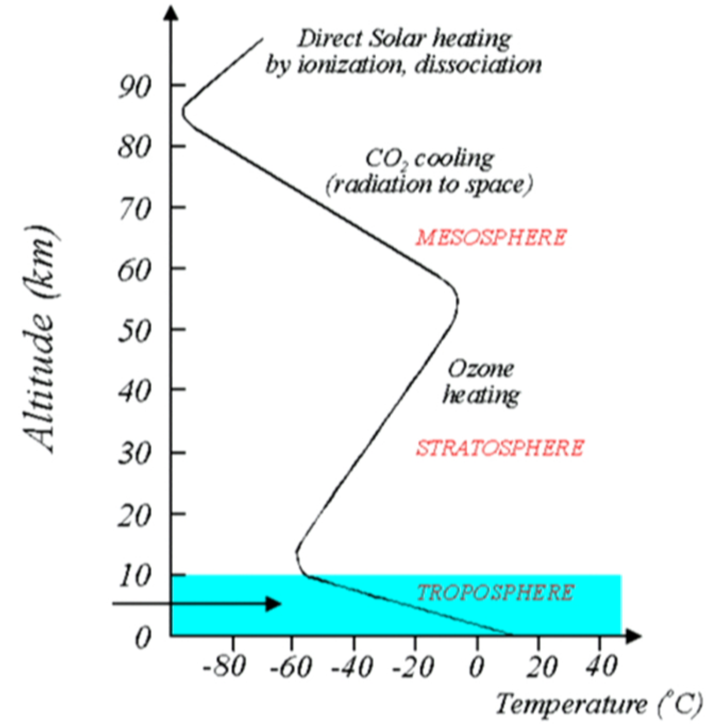
An aviation weather forecast is not too much different, but might include wind maps, turbulence map.

But what about in the future – what will a "weather forecast" look like in the days of space travel?

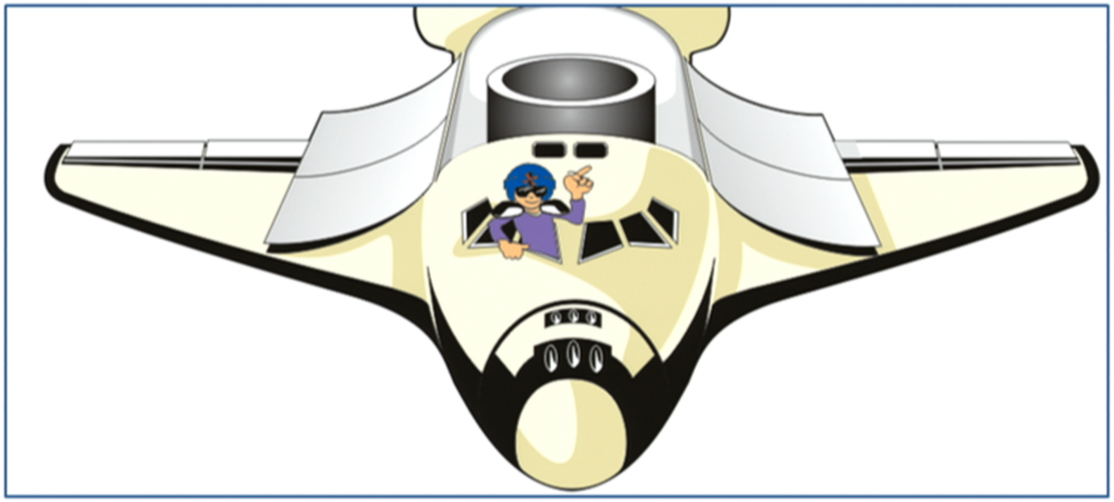
So where is the future of flight? Certainly into the upper atmosphere and beyond – so let us prepare for that eventuality…


Bow Shock
Magnetosheath
Plasma Mantle
Solar Wind
Polar
Cusp
Plasmasphere
Plasma Sheet
Radiation Belt and
Ring Current
Polar Wind
Magnetopause


The atmosphere drawn to scale
The atmosphere
to 100 km deep.
We live here!
Earth


Direct Solar heating
by ionization, dissociation
CO_2 cooling
(radiation to space)
MESOSPHERE
Ozone
heating
STRATOSPHERE
TROPOSPHERE
Altitude (km)
90
80
70
60
50
40
30
20
10
0
-80
-60
-40
-20
0
20
40
Temperature (°C)

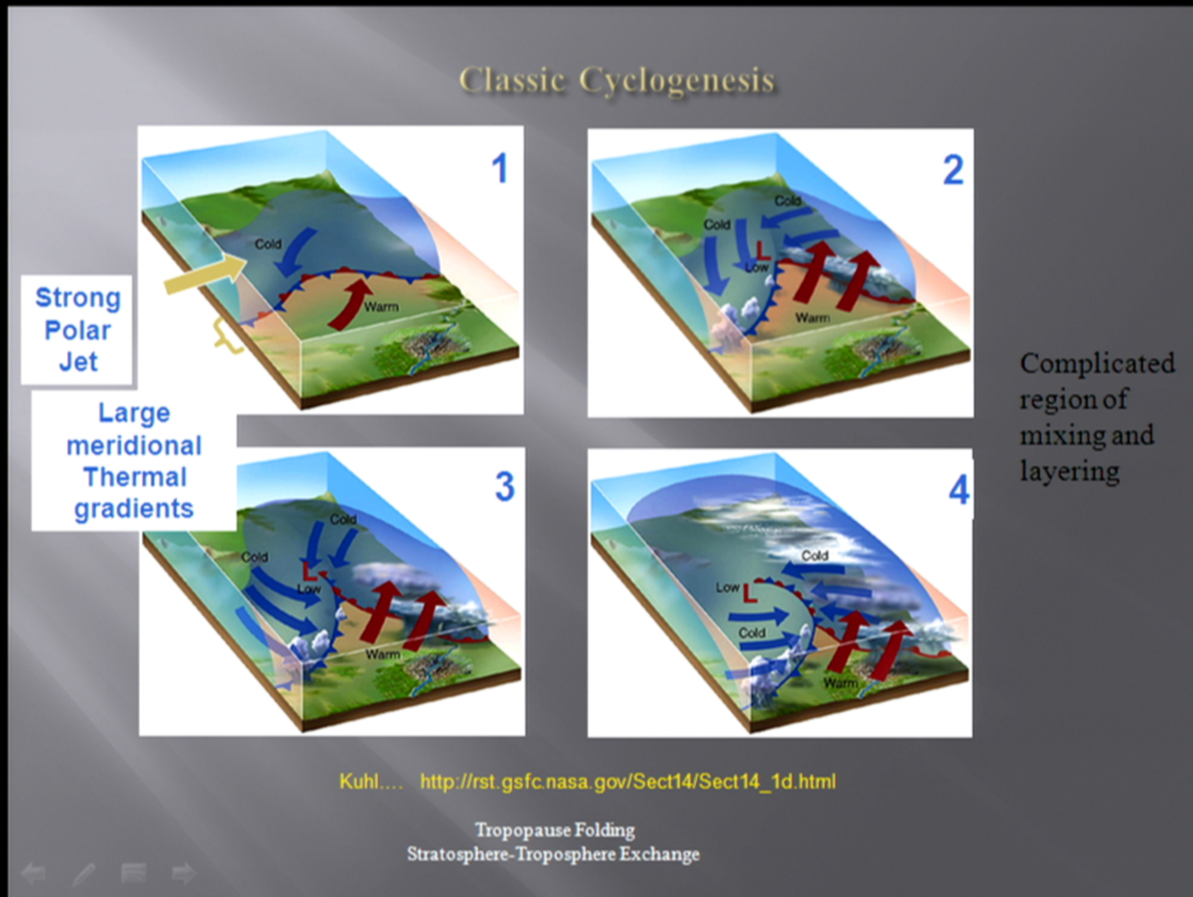
V2

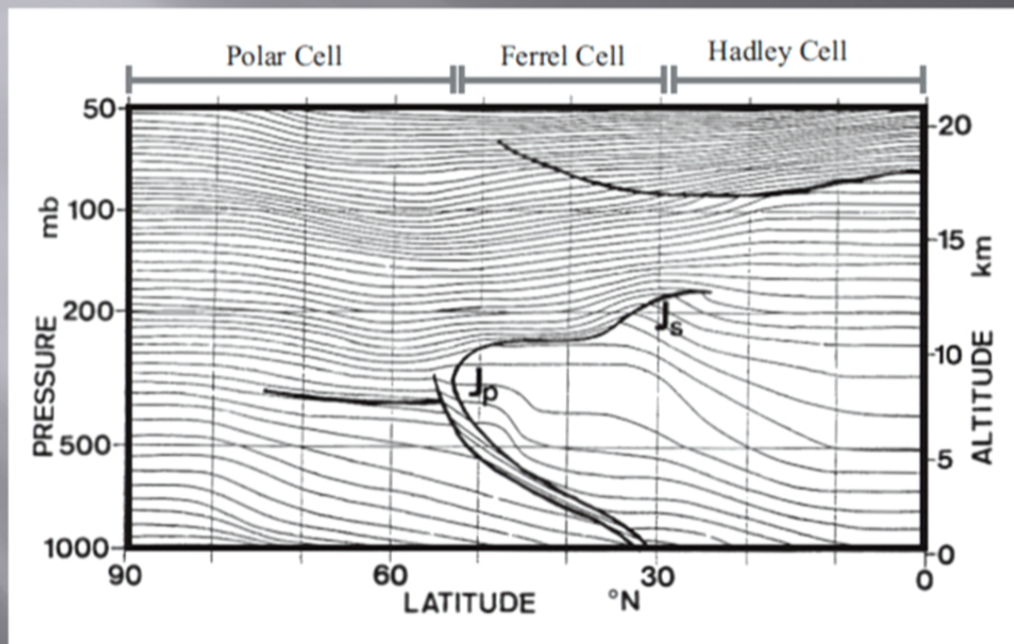


To infinity … and beyond!

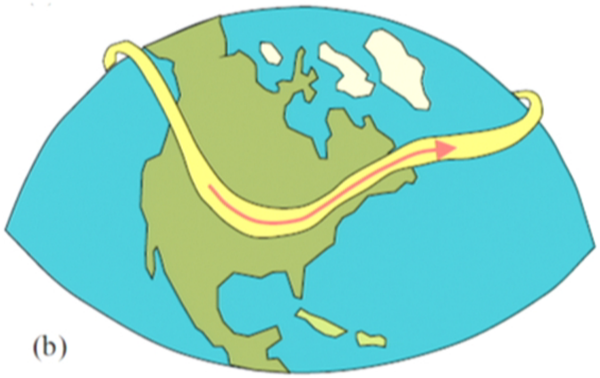
The Tropopause

NOT a simple transition region – a complex region of physical and chemical processes involving multiple dynamical processes..


Classic Cyclogenesis
1
2
3
4
Strong Polar Jet
Large meridional Thermal gradients
Cold
Warm
Low
Complicated region of mixing and layering
Kuhl.... http://rst.gsfc.nasa.gov/Sect14/Sect14_1d.html
Tropopause Folding
Stratosphere-Troposphere Exchange

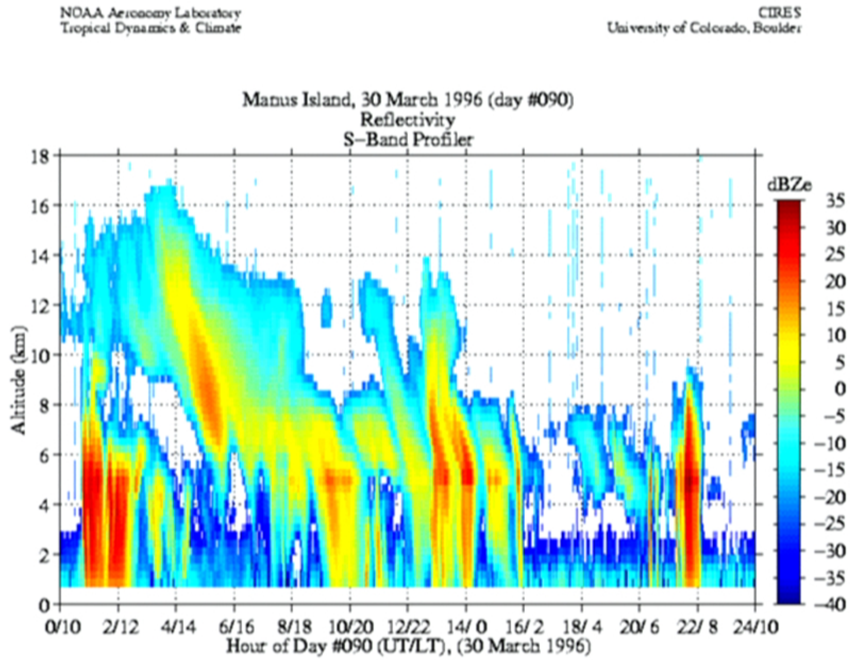


Complicated latitudinal structure



Jet-stream

Jet-stream flow over the Rockies is a major generator of low-pressure systems and ultimately severe weather.



Giant plumes of hot air rising into the stratosphere..

What does this picture tell us about the upper atmosphere?

Credit: Mel Wright

So… cold temperatures …Triple point, sublimation curve..

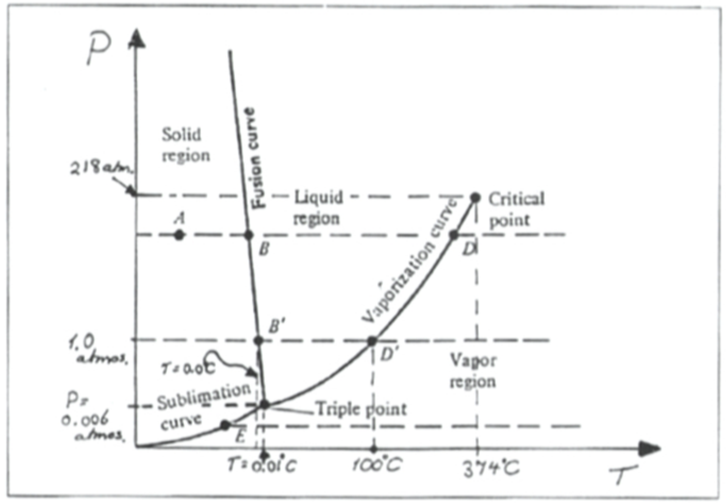


Figure 3.6: More realisitic phase diagram for water. Remember that for most substances the fusion curve points up and to the right - it only points to the left as water expands on freezing.

So… cold temperatures, no water..just ice and vapour

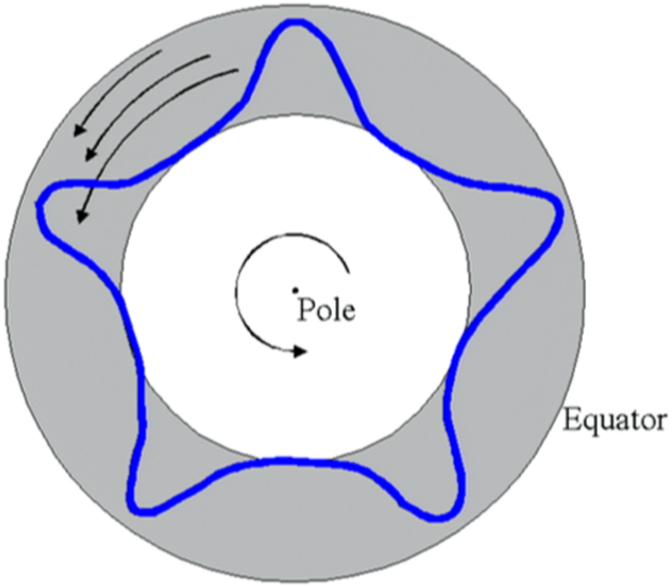
Stable temperature profile, (heating due to Ozone chemistry) – pretty boring, right?

But something else enters the picture…

… WAVES….

PLANETARY WAVES

Development of large-scale waves
by differential heating and velocity shear.



Buoyancy (Gravity) Waves

Waves – generated either in-situ or in the troposphere, and propagate upward.

Navier-Stokes

$$\frac{D\vec{u}}{Dt} = -\frac{1}{\rho}\vec{\nabla}P - 2\vec{\Omega}\times\vec{u} + \vec{g} + \nu\nabla^2\vec{u}, \tag{2.1}$$

$$\frac{D\rho}{Dt} = \frac{1}{c_s^2}\frac{DP}{Dt} \tag{2.2}$$

$$\frac{D\rho}{Dt} + \rho\vec{\nabla}\cdot\vec{u} = 0 \tag{2.3}$$

$$\frac{D\Theta}{Dt} = \frac{\kappa}{\rho}\nabla^2\Theta \tag{2.4}$$

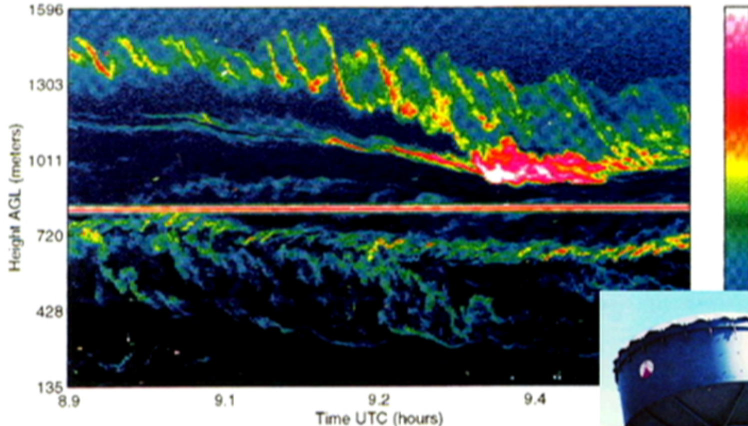
Impact:

Waves carry energy, momentum long distances

They also break, and are THE major source of turbulence above the atmospheric boundary layer..

Abitibi breaking wave

Kelvin Helmholtz (credit: Mel Wright)


1596
1303
1011
720
428
135
Height AGL (meters)
8.9
9.1
9.2
9.4
Time UTC (hours)

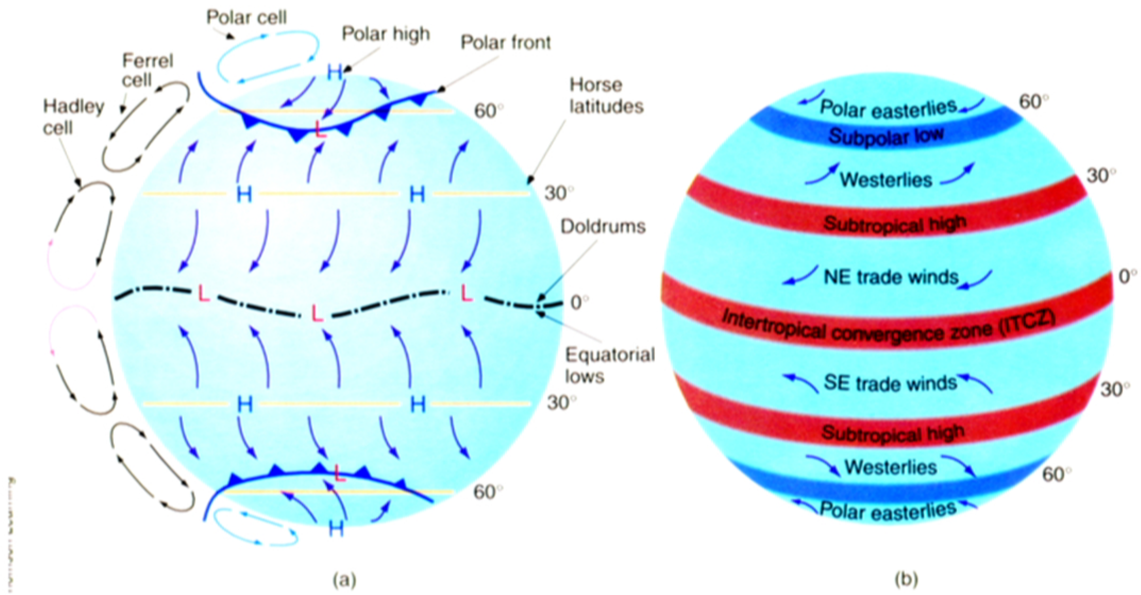
In the stratosphere, two main impacts for aircraft:

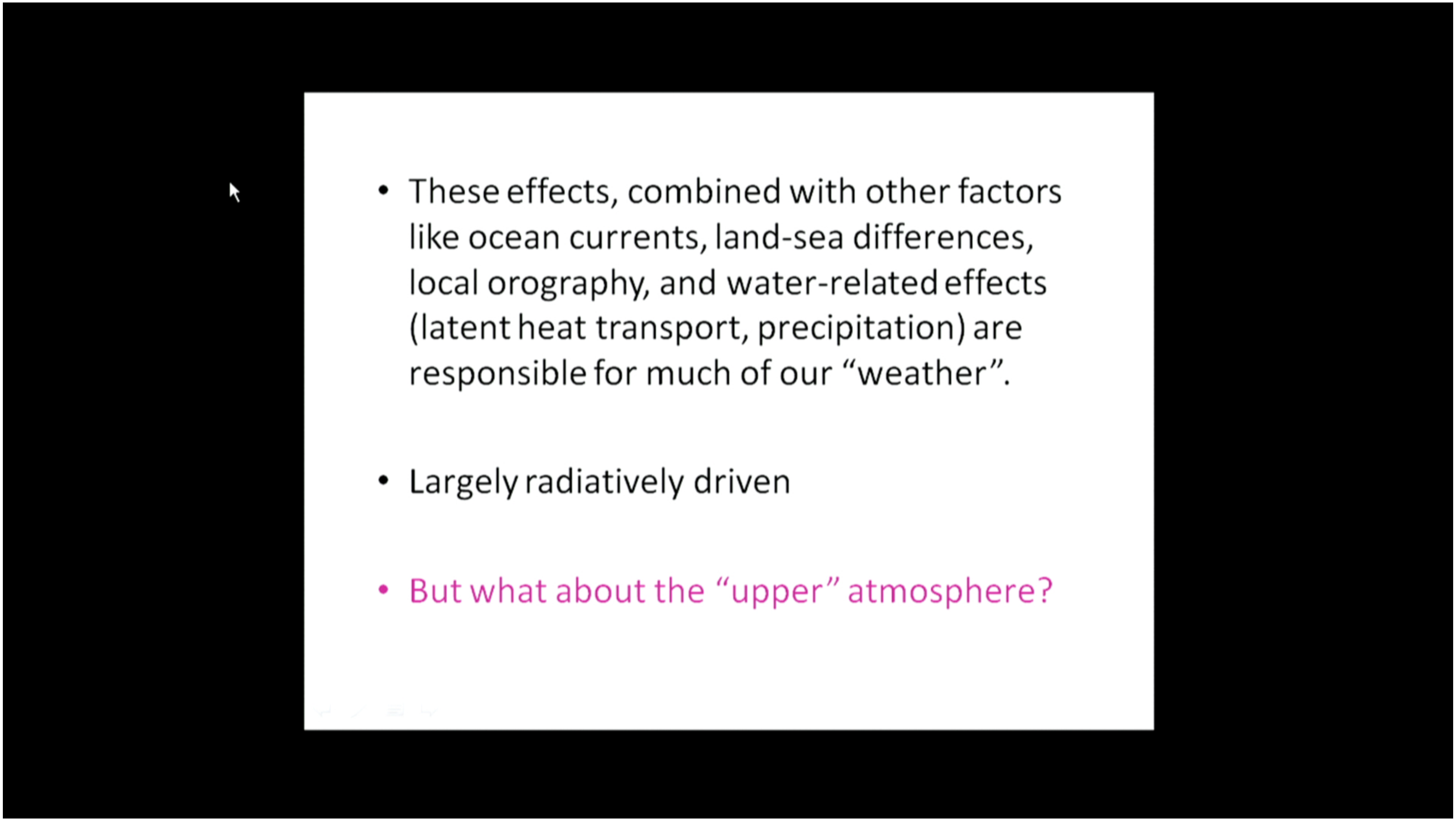
1. Highly developed non-linearities in planetary-waves lead to development of subsequent radiated waves and turbulence

Breakdown of gravity waves leads to development of clear-air-turbulence, which can be quite severe.

Dynamically, even more important, since they impact the general circulation of the atmosphere.

First, remind ourselves of the causes of the tropospheric circulation


Polar cell
Polar high
Polar front
Ferrel cell
Hadley cell
Horse latitudes
60°
30°
Doldrums
0°
Equatorial lows
30°
60°
H
L
(a)
Polar easterlies
Subpolar low
60°
Westerlies
30°
Subtropical high
NE trade winds
0°
Intertropical convergence zone (ITCZ)
SE trade winds
30°
Subtropical high
Westerlies
60°
Polar easterlies
(b)


These effects, combined with other factors like ocean currents, land-sea differences, local orography, and water-related effects (latent heat transport, precipitation) are responsible for much of our "weather".
Largely radiatively driven
But what about the "upper" atmosphere?

Stratosphere:

Driven by pole-to-pole pressure gradient above 40 km altitude (no clouds mean heating is dominant at the summer pole)

Surf-zone… breaking planetary waves – ozone bubbles…

Planetary waves DRIVE the stratospheric circulation (Brewer-Dobson)

Breaking gravity waves produce additional; dynamical driving of the atmosphere.. a very different circulation to that of the troposphere.

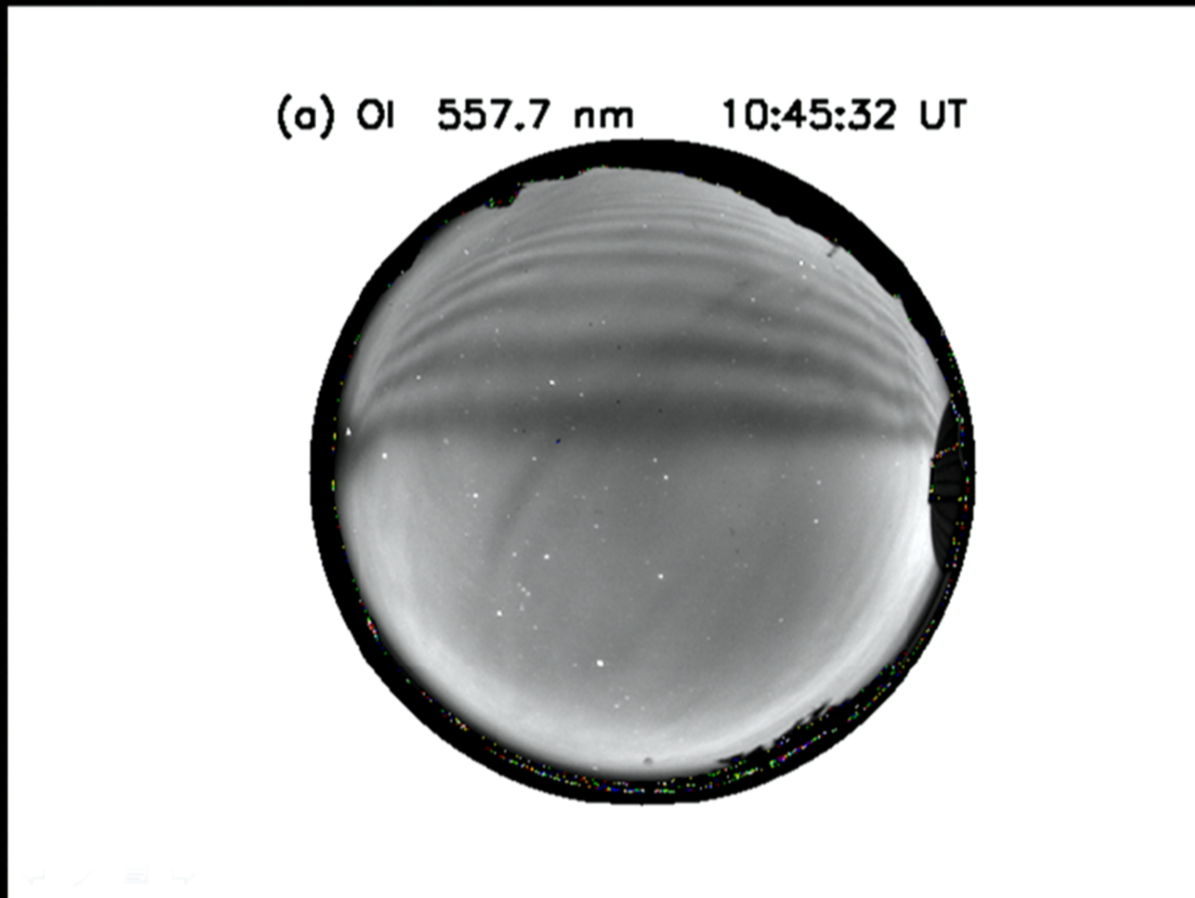
Breaking planetary waves and gravity waves produce hazards for transport.

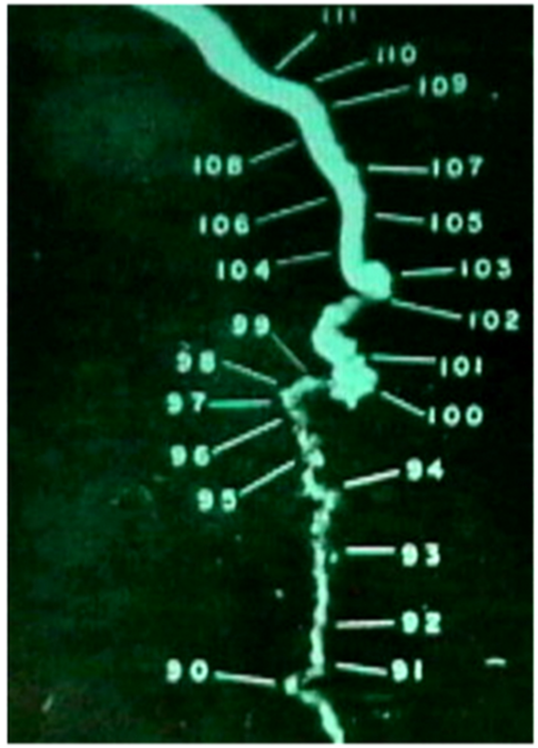
Ozone heating produces TIDES…

Mesospheric Circulation

- Little to no water vapour
- Heating distribution differs
- Ozone heating, particle heating, IR radiation
- Dynamical and wave processes much more important
- **Waves** ***
- No direct frictional drag due to ground
- coupling with troposphere and ionosphere

In the mesosphere, Buoyancy waves (gravity waves) and TIDES become areas of major concern to our space-travellers, being even more important than planetary waves.


(a) OI 557.7 nm 10:45:32 UT


111
110
109
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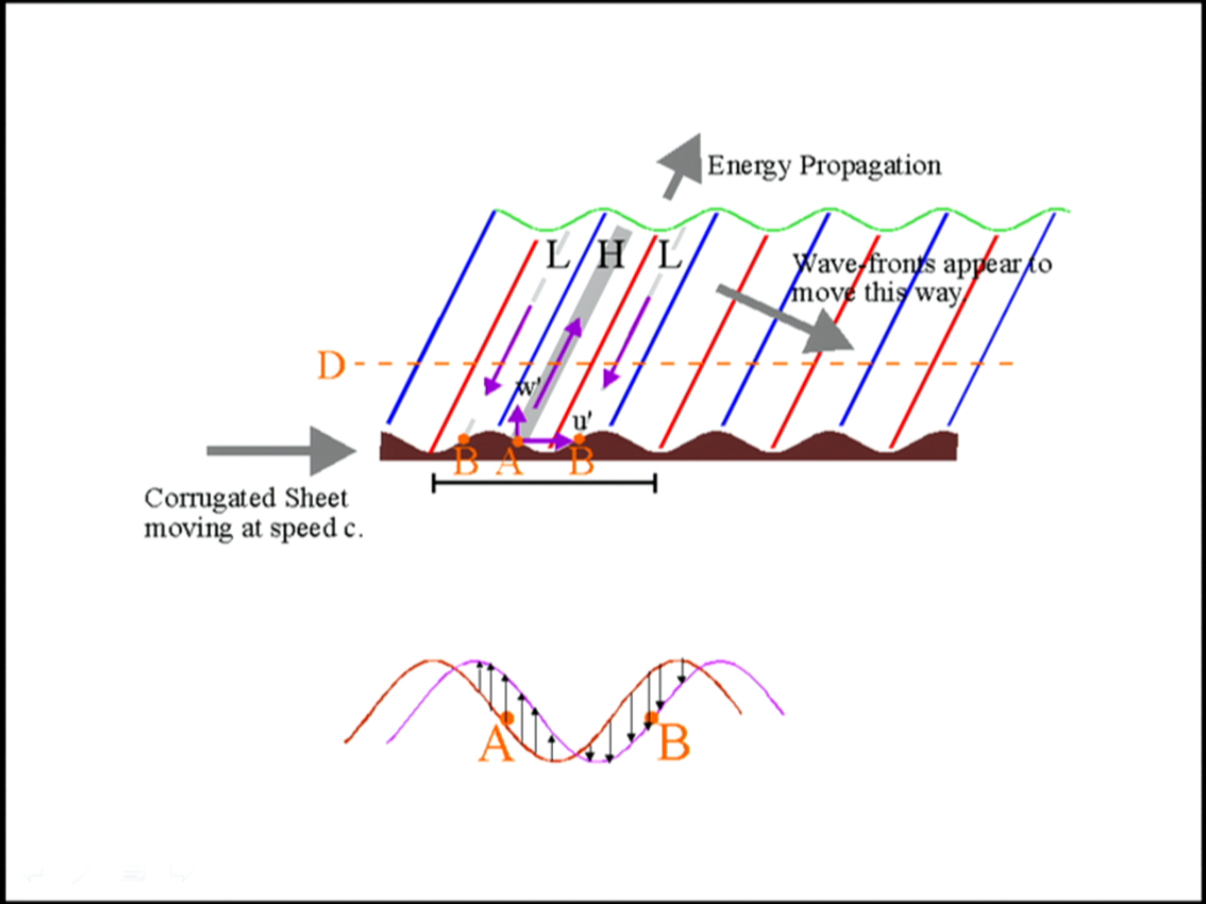
90
91


Energy Propagation
L
H
L
Wave-fronts appear to move this way
D
w'
u'
B A B
Corrugated Sheet moving at speed c.
A
B

Gravity Waves....

1. Grow exponentially with height in order to conserve kinetic energy per unit volume

2. Can achieve velocity amplitudes of the order of tens of metres per second.

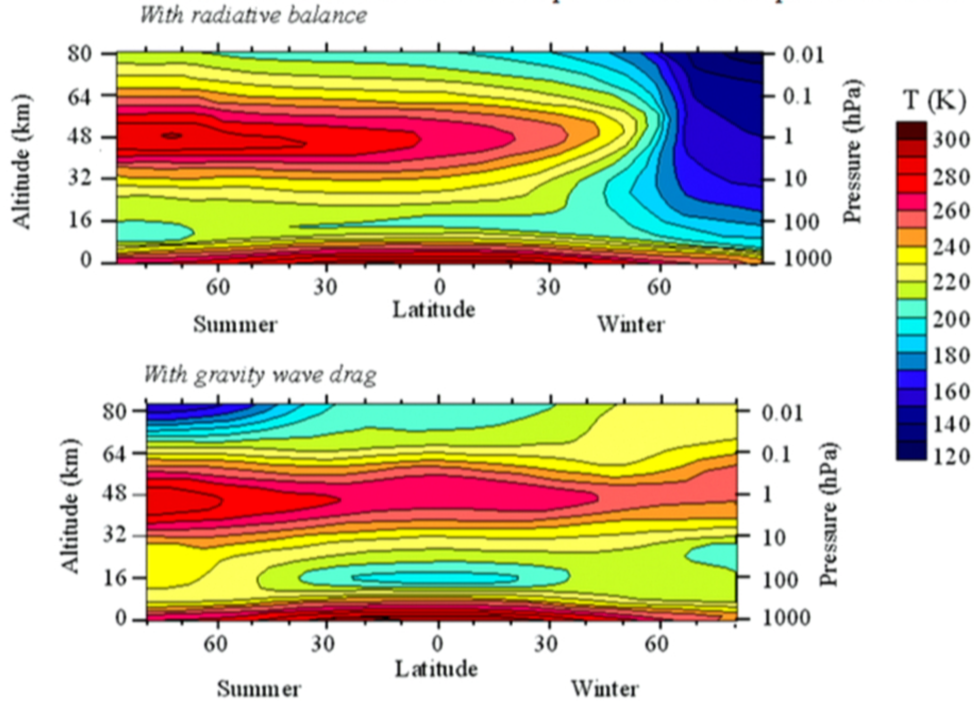
3. Dissipate when they encounter a critical level (phase speed equals mean wind)

4. Convectively break down when their amplitude u' exceeds |u-c|.

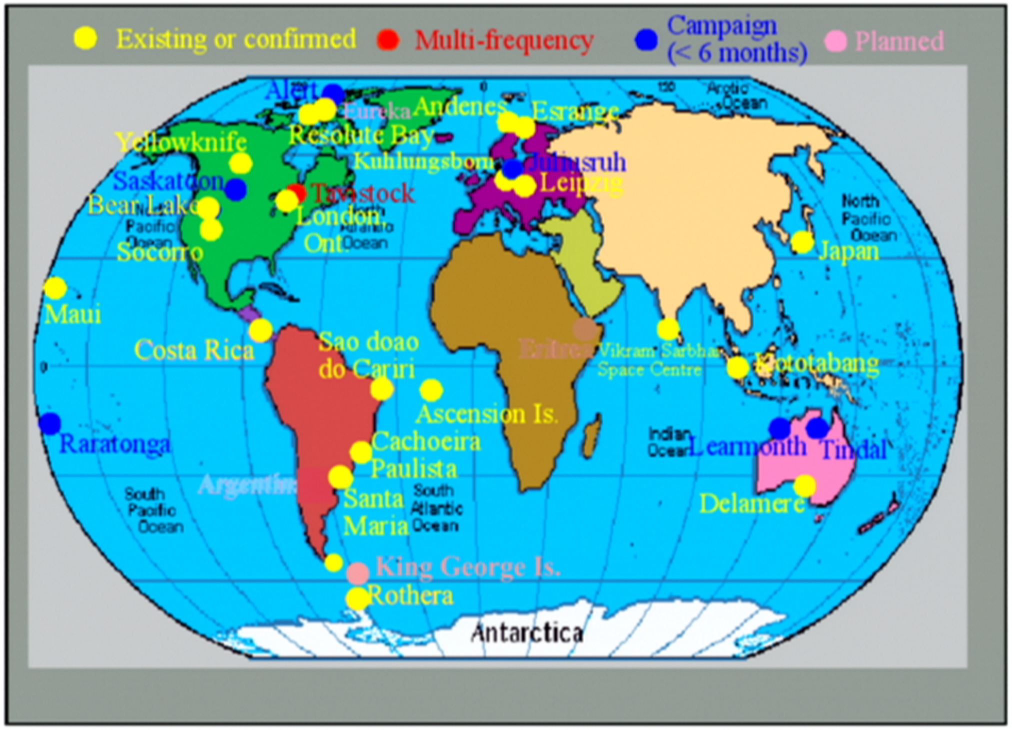
5. Can also break down by other processes (slant-wise instability, K-H instability etc.)

Asymmetric filtering of gravity waves produces nett forcing on the upper atmosphere, completely altering the large-scale dynamical flow.

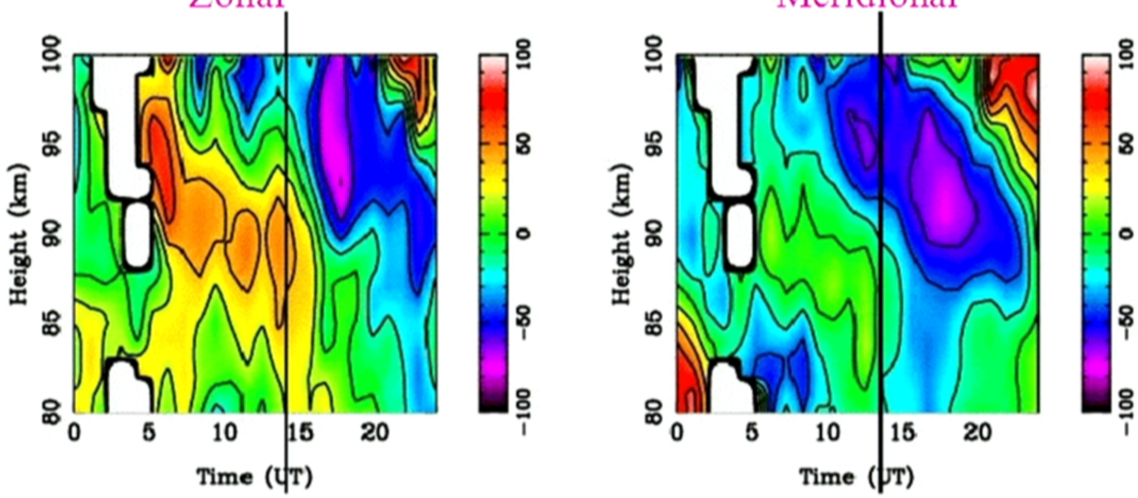
What a difference- and the summer pole is the coldest place on Earth!



SKiYMET Meteor Radars.

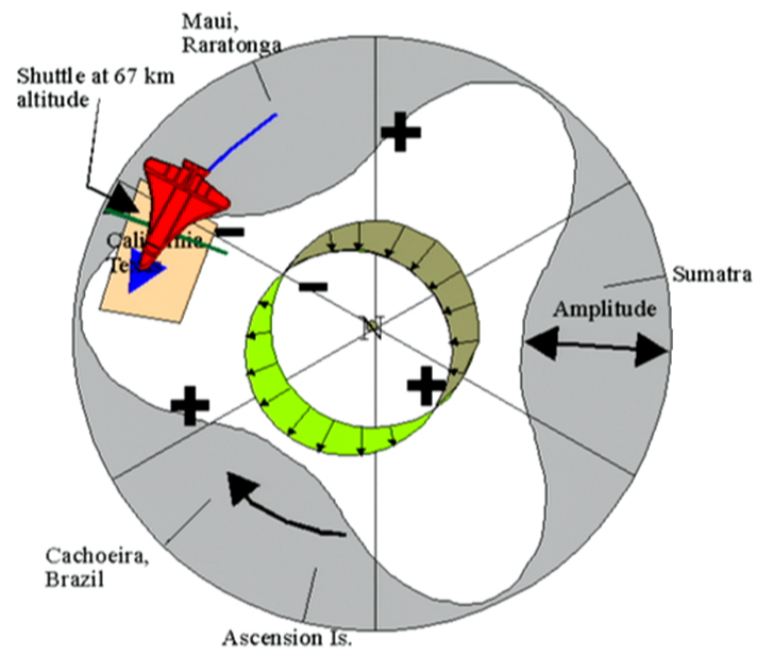


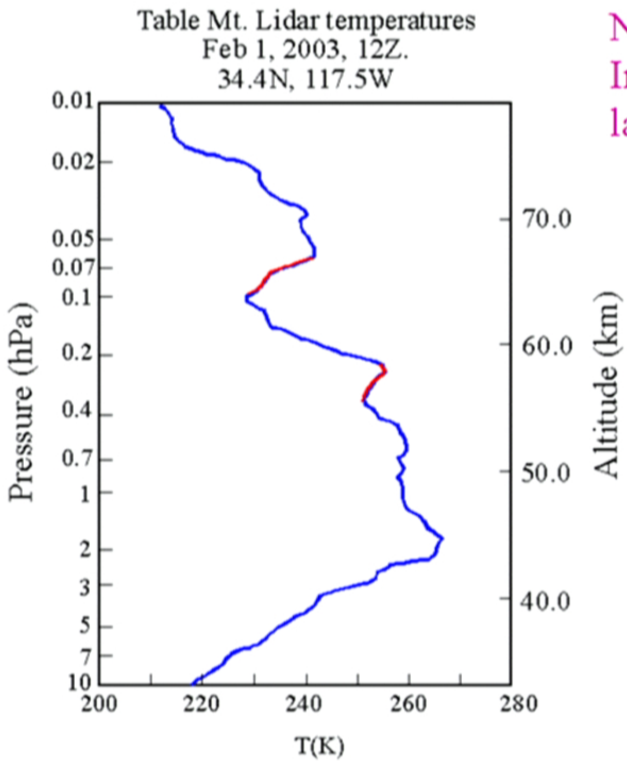
Maui, 1 Feb 2003.



Shuttle re-entry

Shuttle re-rentry


Maui,
Raratonga
Shuttle at 67 km
altitude
Sumatra
Amplitude
N
Cachoeira,
Brazil
Ascension Is.



No turbulent layer –
In fact 2 very stable layers!!

We need to recognize that

- Total density $\rho = <\rho> + \rho'$
- Total velocity $v = <v> + v'$

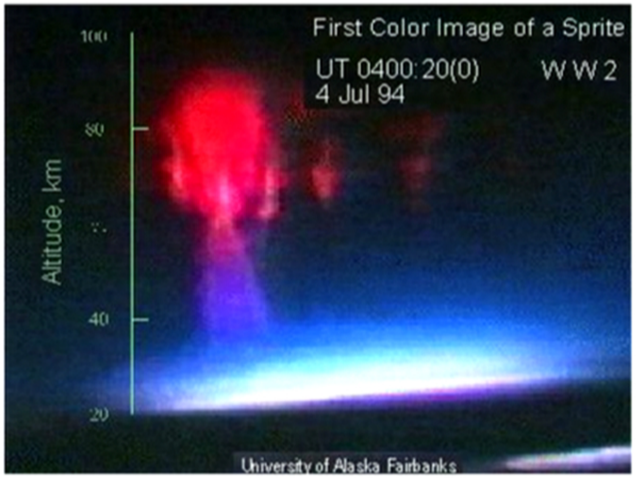
The degree of bufetting experienced by the space-craft is

$$\sigma_F = 0.5 \; C_D A \rho_0 u_0 . v_{RMS}(2+\beta u_0)$$

where v_{RMS} is the RMS along-track velocity, u_0 is the shuttle speed,

and $\beta \propto 1/\sqrt{(gT)} \; \sqrt{(dT/dz + \Gamma_a)}/$

The nett result is that at low speeds, (< Mach 1), buffeting is due to standard turbulence, BUT… at high speeds (~ Mach 18) the dominant source of buffeting is the spacecraft bouncing off gravity-wave density perturbations as it hurtles through the air!



Sprites and Elves – 30-95 km
"lightning" and electromagnetic
pulses (durations a few milliseconds)

Aurora Borealis

So… lots of reasons for “flight cancelled” announcements!

SPACE TRAVEL…???