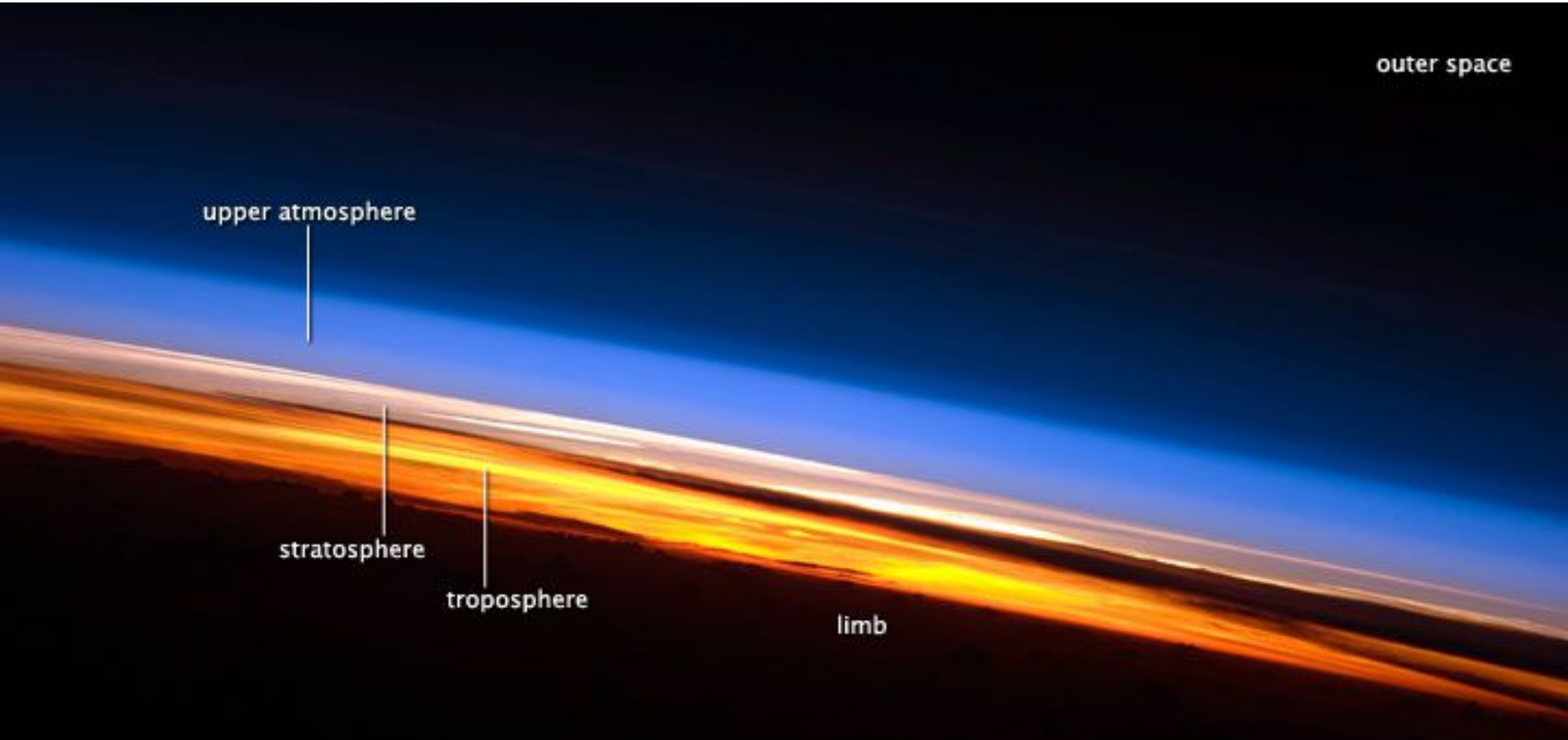
Exploring the Ripples of Earth's Upper Atmosphere: Waves & Tides

Dr. Katelynn R. Greer, University of Colorado – Boulder



*Special Thanks to Dr. Federico Gasperini

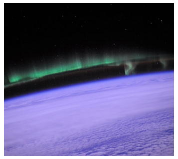
GOLD
Global-scale Observations of the Limb and Disk

Ask questions!

LASP
Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

Exploring the Ripples of Earth's Upper Atmosphere: Waves & Tides

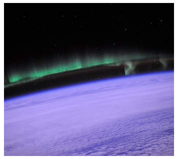
Dr. Katelynn R. Greer, University of Colorado – Boulder



Variability in the Thermosphere

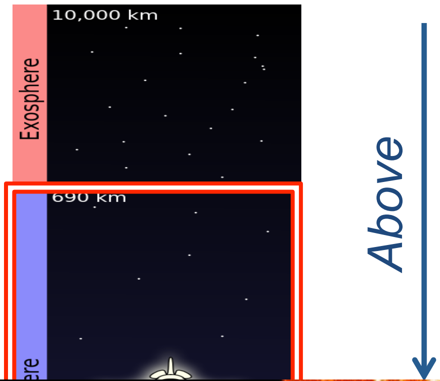
Atmospheric Waves

Observation of Wave Field

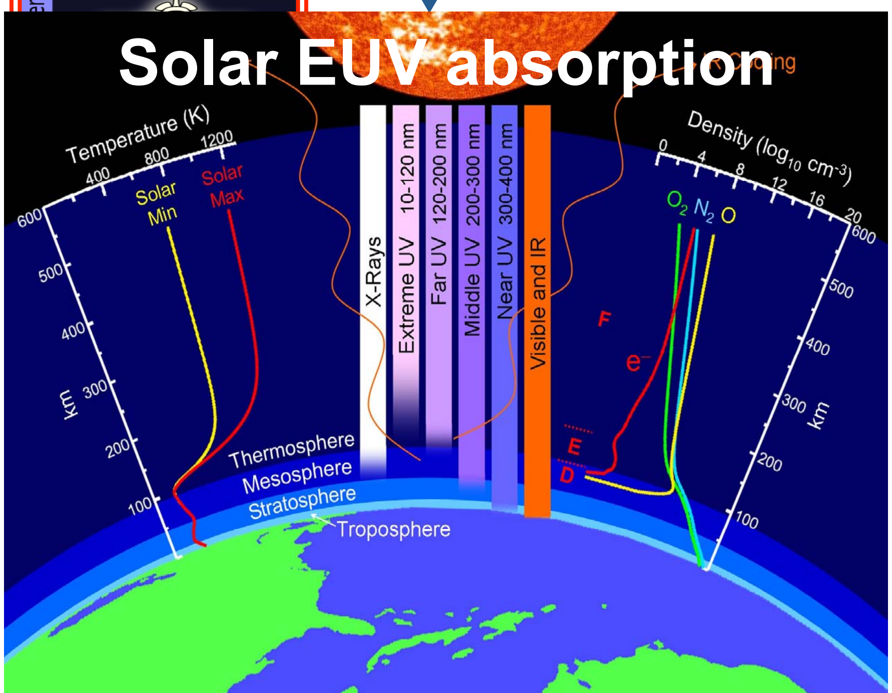


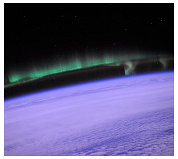
Variability in the Thermosphere

SOURCES



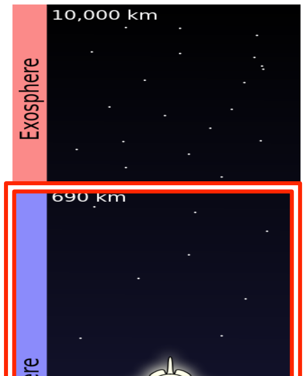
- Absorption of Solar EUV Radiation





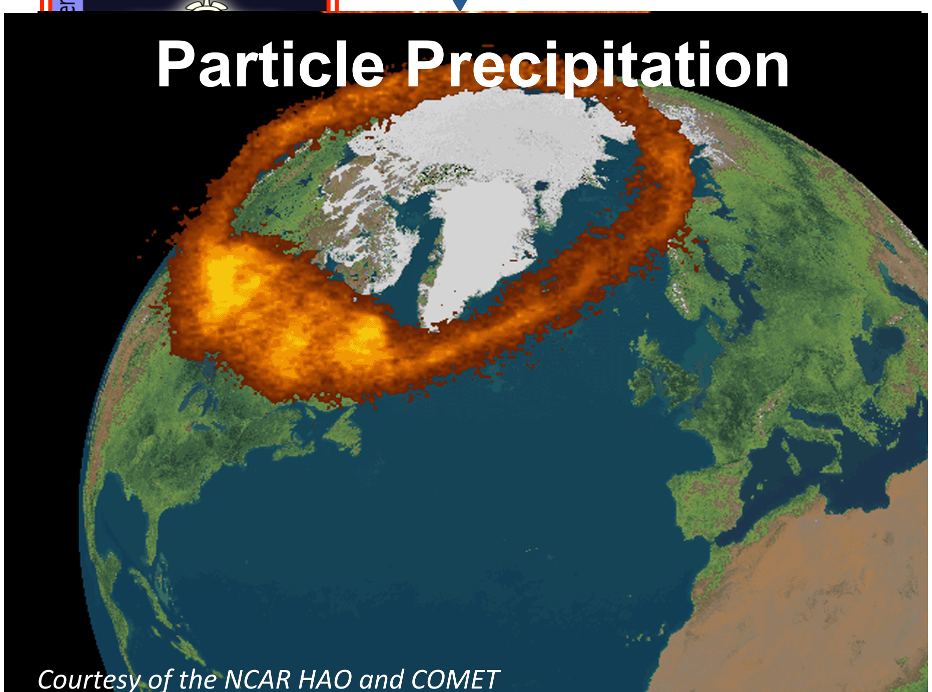
Variability in the Thermosphere

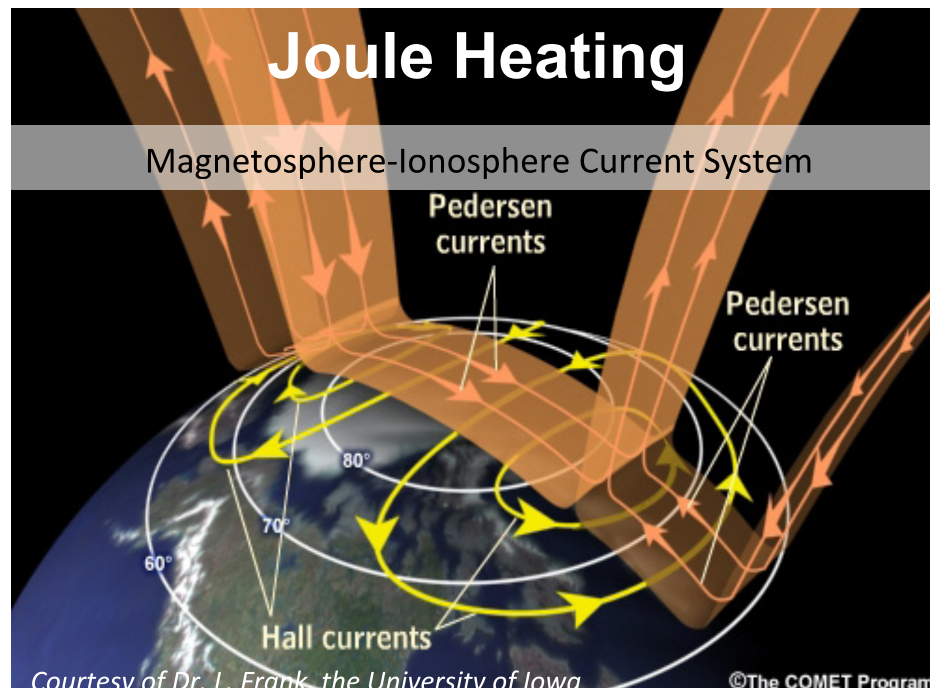
SOURCES

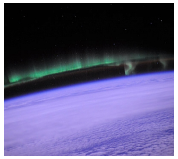


Above

- Absorption of Solar EUV Radiation
- Particle Precipitation
- Joule Heating

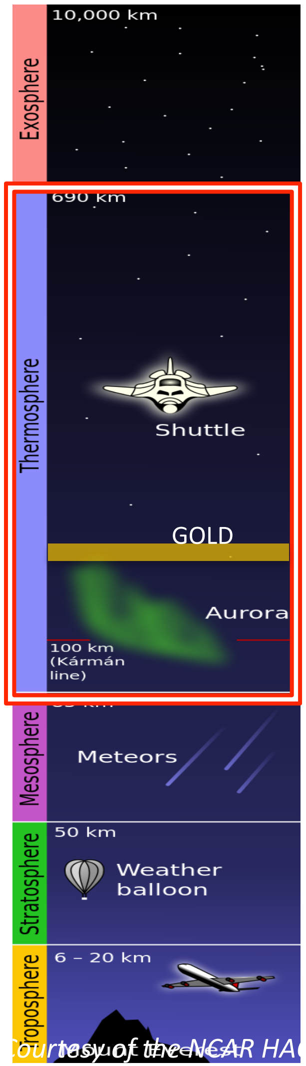






Variability in the Thermosphere

SOURCES



Above

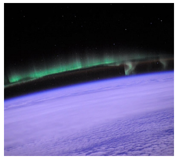
- Absorption of Solar EUV Radiation
- Particle Precipitation
- Joule Heating

In the last decade evidence has shown that terrestrial weather significantly influences the ionosphere-thermosphere system

Below

- Dissipation of Upward Propagating Waves

Courtesy of the NCAR HA



Variability in the Thermosphere

SOURCES

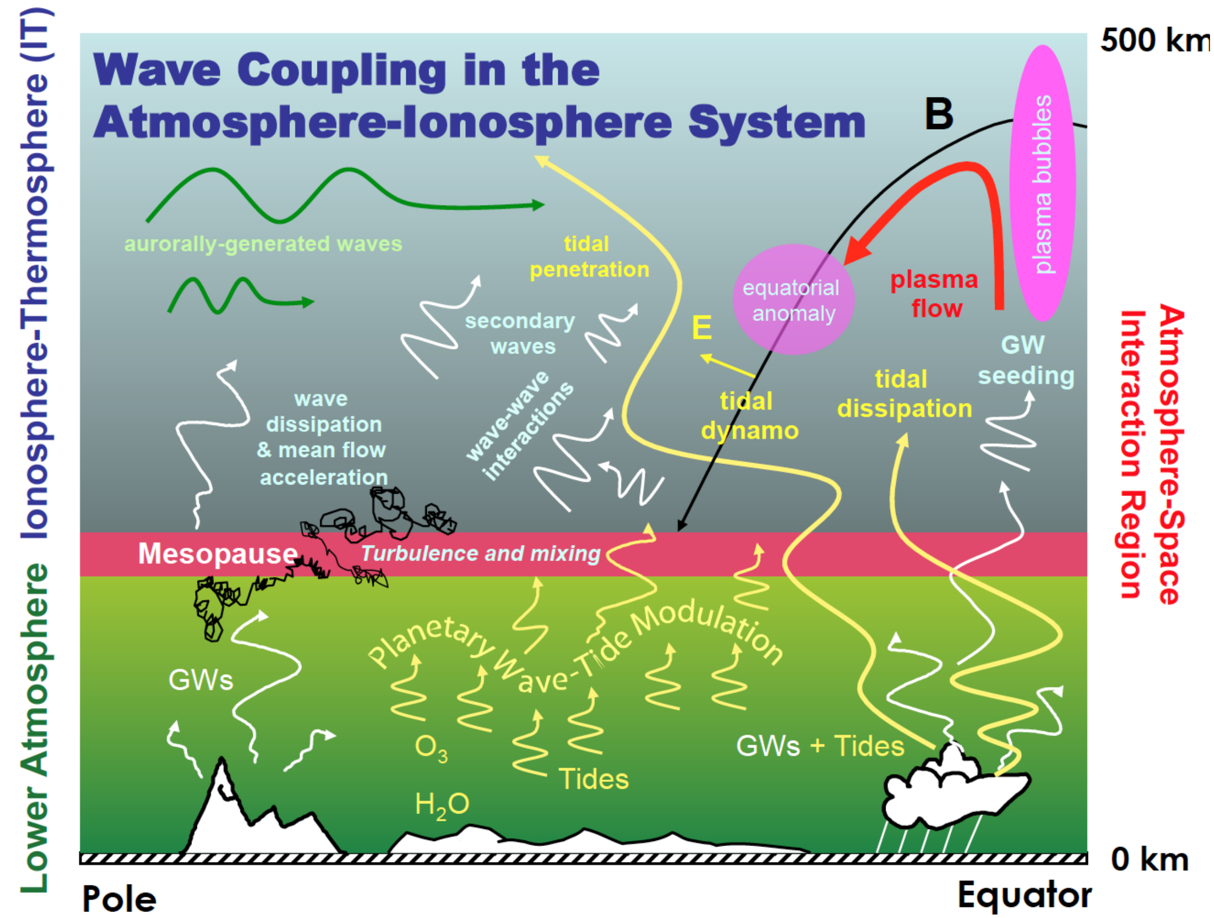
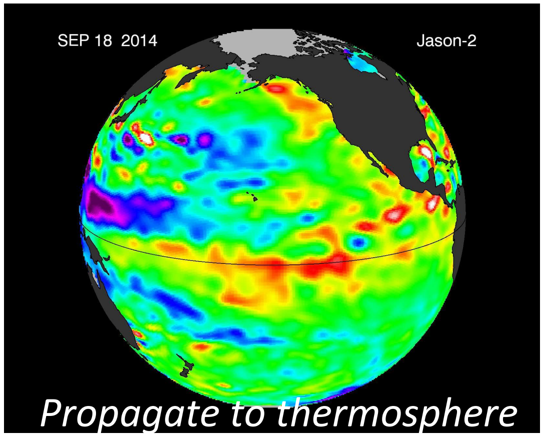


Illustration from the Solar and Space Physics Decadal Survey

- The primary mechanism through which energy and momentum are transferred from the lower atmosphere to the upper atmosphere and ionosphere is through the propagation of waves

Atmospheric Waves

Kelvin Waves



Propagate to thermosphere

time scale: 2-20 days

$\lambda_x \cong$ Earth's circumference

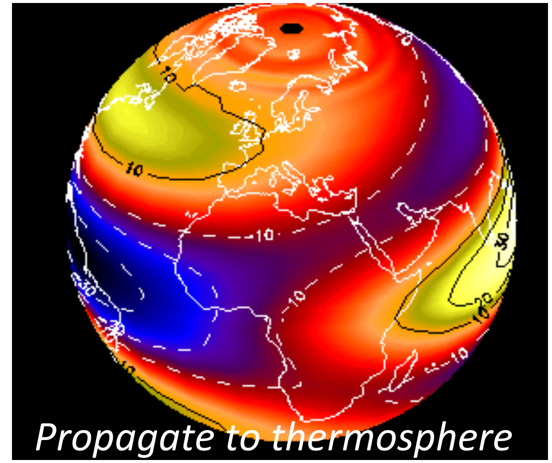
Rossby (Planetary) Waves

Do not easily propagate to thermosphere

time scale: 2 to >30 days

$\lambda_x \cong$ 1-1000 km

Thermal Tides

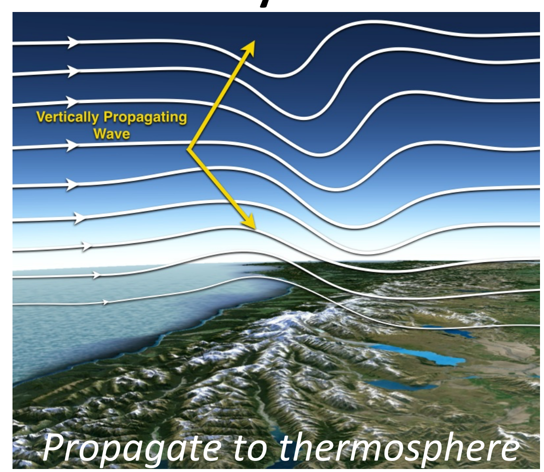


Propagate to thermosphere

time scale: 1/3 to 1 solar day

$\lambda_x \cong$ Earth's circumference

Gravity Waves



Propagate to thermosphere

time scale: min-hrs

$\lambda_x \cong$ 1 to >100 km

Atmospheric Waves

Kelvin Waves

The focus is on Thermal Tides and Gravity Waves, waves responsible for coupling the lower atmosphere to the upper atmosphere and ionosphere

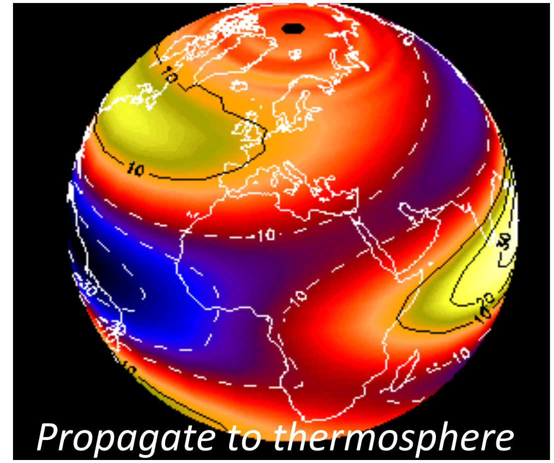
λ_x ≅ Earth's circumference

Rossby (Planetary) Waves

time scale: 2 to >30 days

λ_x ≅ 1-1000 km

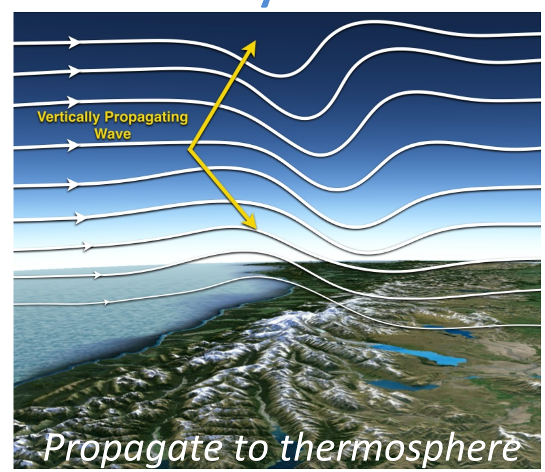
Thermal Tides



time scale: 1/3 to 1 solar day

λ_x ≅ Earth's circumference

Gravity Waves

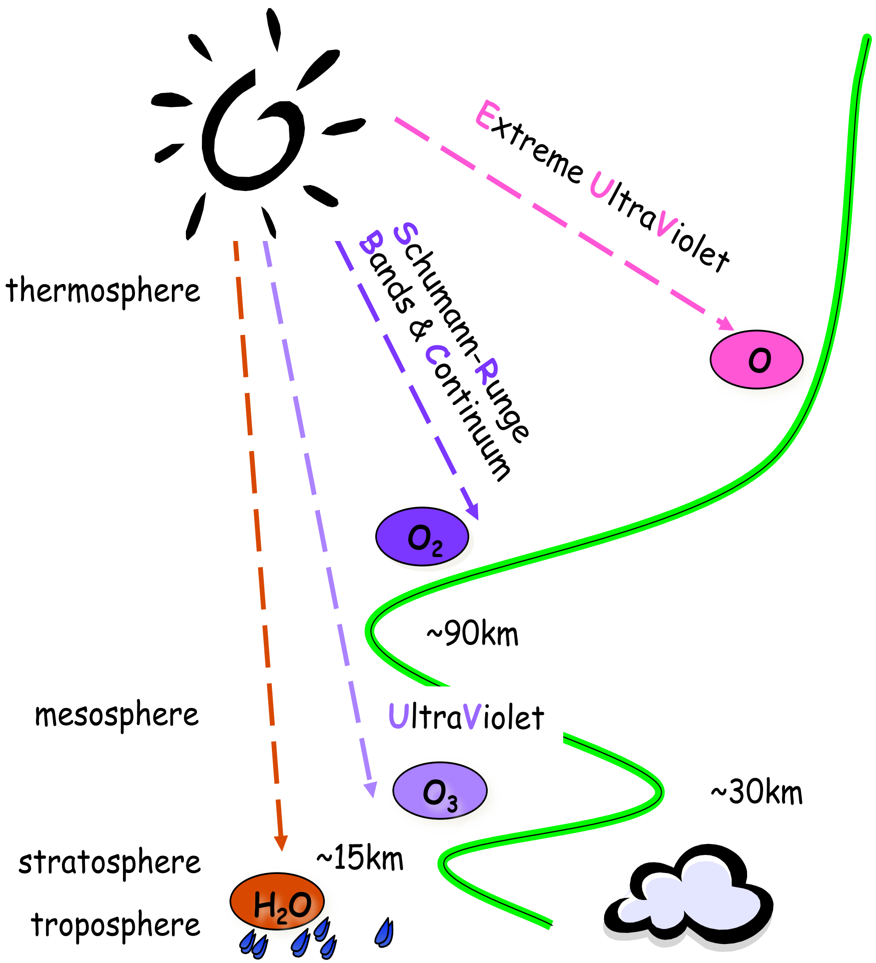


time scale: min-hrs

λ_x ≅ 1 to >100 km

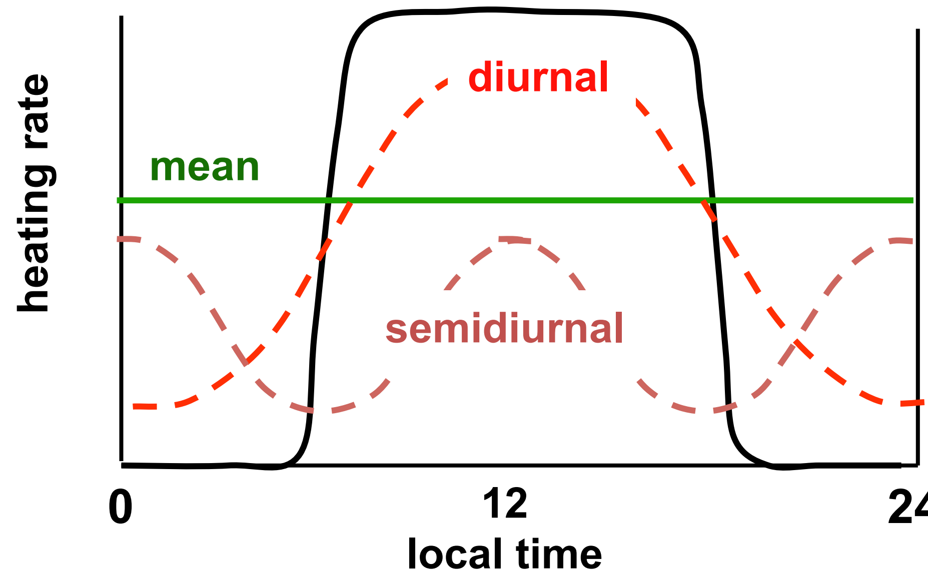
Atmospheric Waves
Thermal Tides

- The primary mechanism of excitation: periodic heating of the atmosphere by the Sun



$$\sum_{s=-k}^{s=+k}\sum_{n=1}^{N} A_{n,s}(z,\theta)\cos\left(n\Omega t + s\lambda - \phi_{n,s}(z,\theta)\right)$$

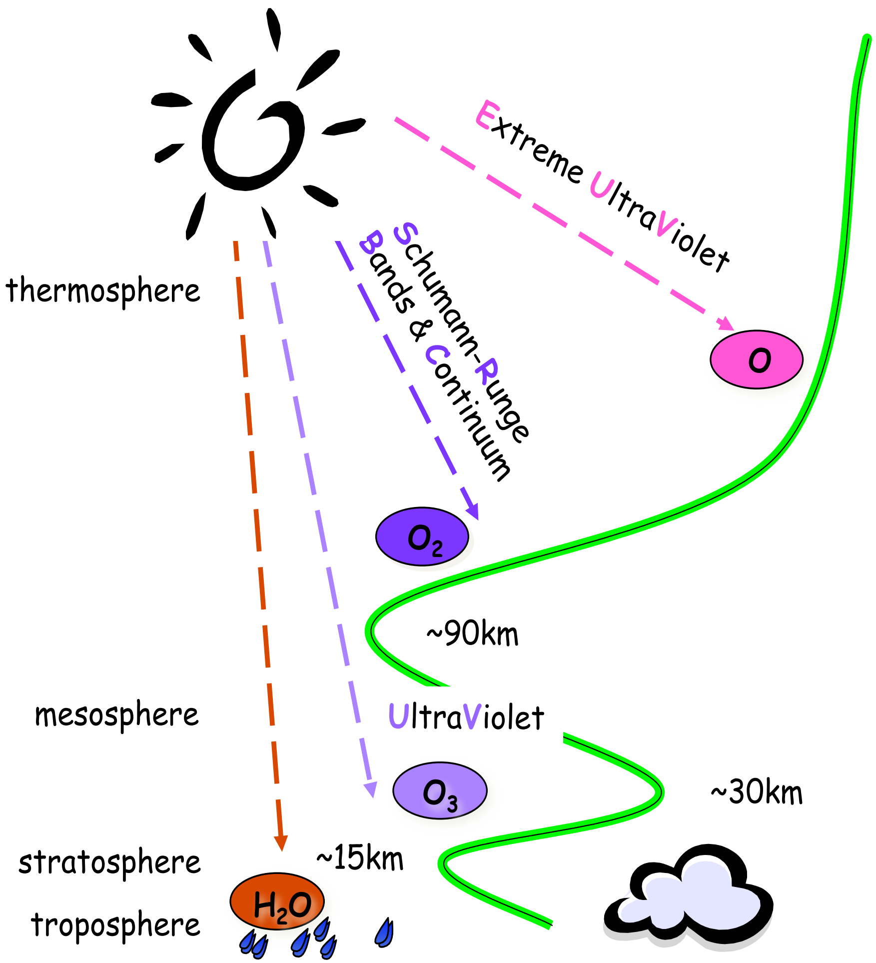
z = height
θ = latitude
Ωn = frequency
Ω = 2π/24
t = UT time
s = zonal wavenumber (s>0 to west)
λ = longitude
Φ = phase



Atmospheric Waves

Thermal Tides

- The primary mechanism of excitation: periodic heating of the atmosphere by the Sun



$$\sum_{s=-k}^{s=+k} \sum_{n=1}^{N} A_{n,s}(z,\theta)\cos\left(n\Omega t + s\lambda - \phi_{n,s}(z,\theta)\right)$$

z = height
θ = latitude
Ωn = frequency
Ω = 2π/24
t = UT time
s = zonal wavenumber (s>0 to west)
λ = longitude
Φ = phase

- Global waves observed in measurements like **Temperature** and **Wind**
- Waves with s = n are referred to as migrating tides, follow the apparent motion of the Sun
- Waves with s ≠ n are referred to as non-migrating tides

Atmospheric Waves

Thermal Tides

$$\sum_{s=-k}^{s=+k} \sum_{n=1}^{N} A_{n,s}(z,\theta)\cos\left(n\Omega t + s\lambda - \phi_{n,s}(z,\theta)\right)$$

Standard Nomenclature

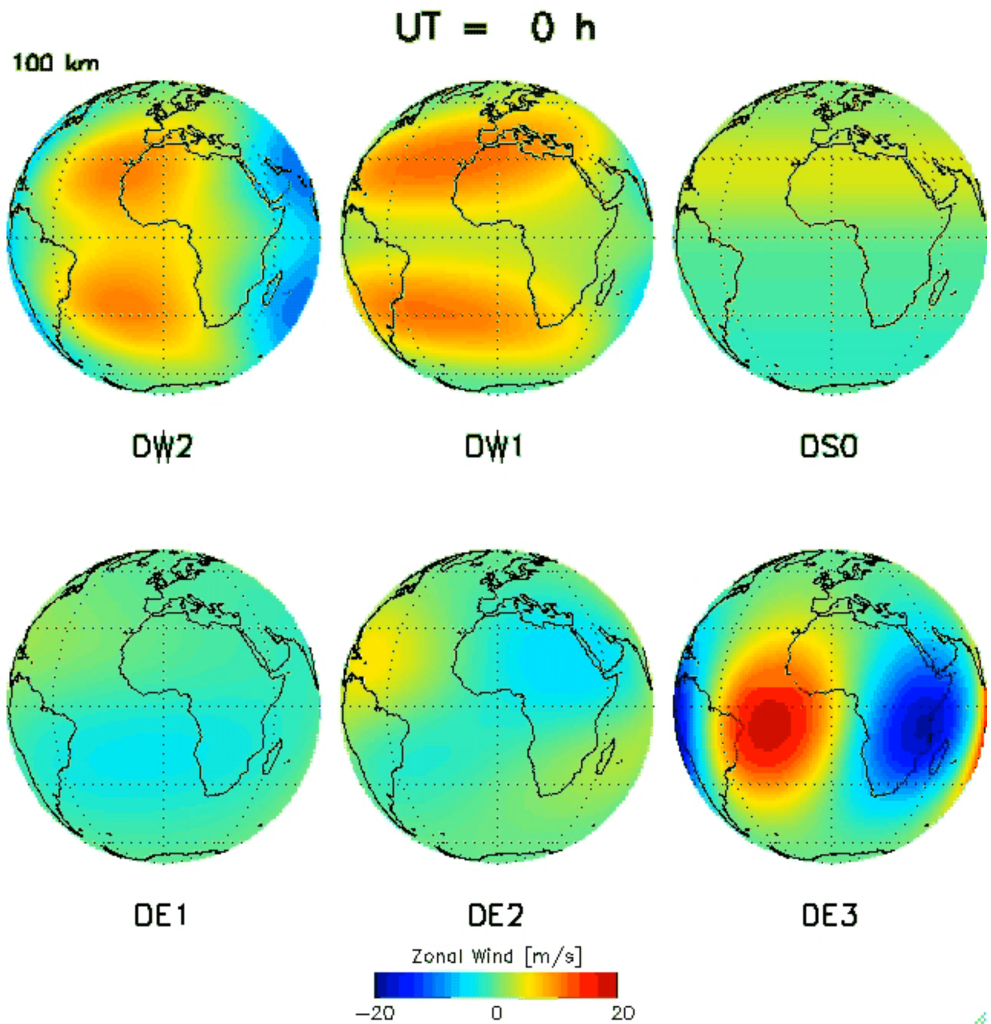
- *DWx* (*DEx)* to denote a westward- (eastward-) propagating diurnal tide with zonal wavenumber *x = s*
- For semidiurnal and terdiurnal tides *S* and *T* replaces *D*

Diurnal Eastward-propagating Tide with s=3, *or* **DE3**

- Major driver of the wave-4 structure in the ionosphere/thermosphere
- Excited in the tropical troposphere by latent heat release in deep convective clouds
- Large source of variability in the MLT (up to 30 K, or 20 m/s)

Atmospheric Waves
Thermal Tides

➢ The primary mechanism of excitation: periodic heating of the atmosphere by the Sun

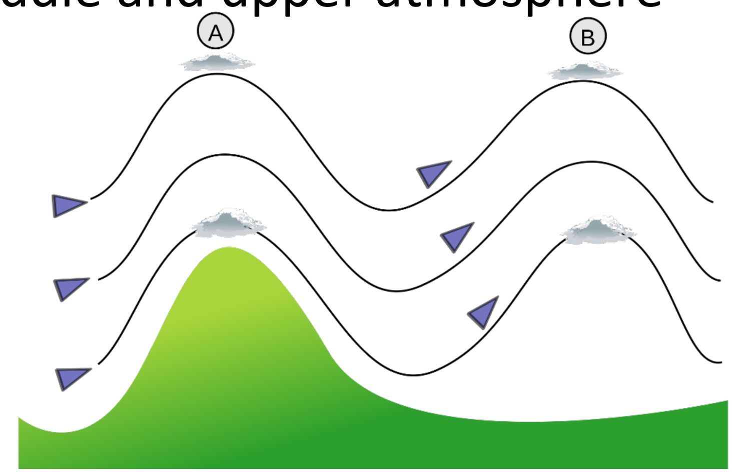


Curtesy of J. Oberheide

Atmospheric Waves
Gravity Waves (GWs)

✧ Not to be confused with Gravitational Waves

- Gravity and Buoyancy are the restoring force for air parcels
- Local Waves
- Play an important role in coupling the lower atmosphere with the middle and upper atmosphere

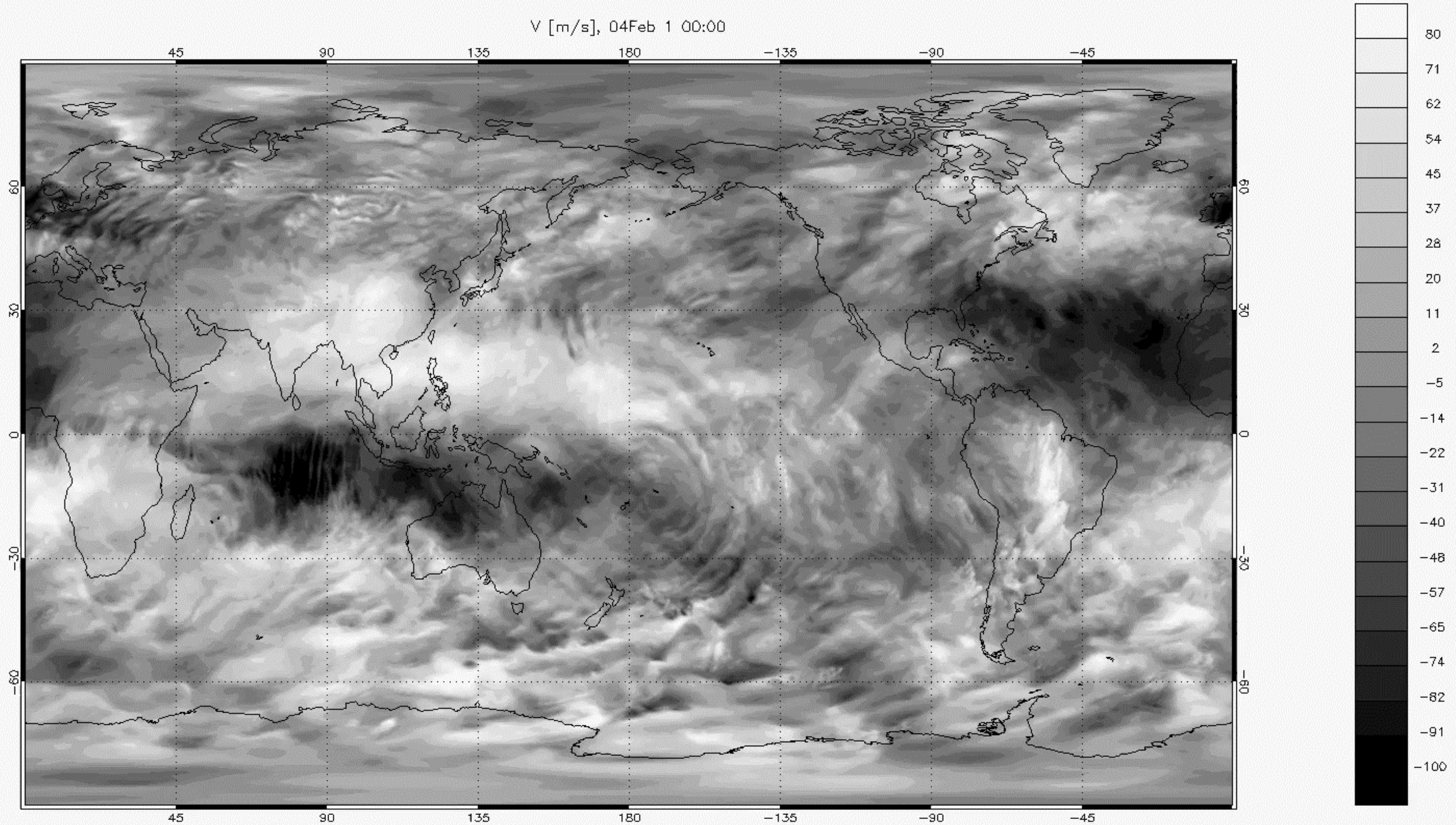


Orography

Deep Convection

Atmospheric Waves

Gravity Waves (GWs)

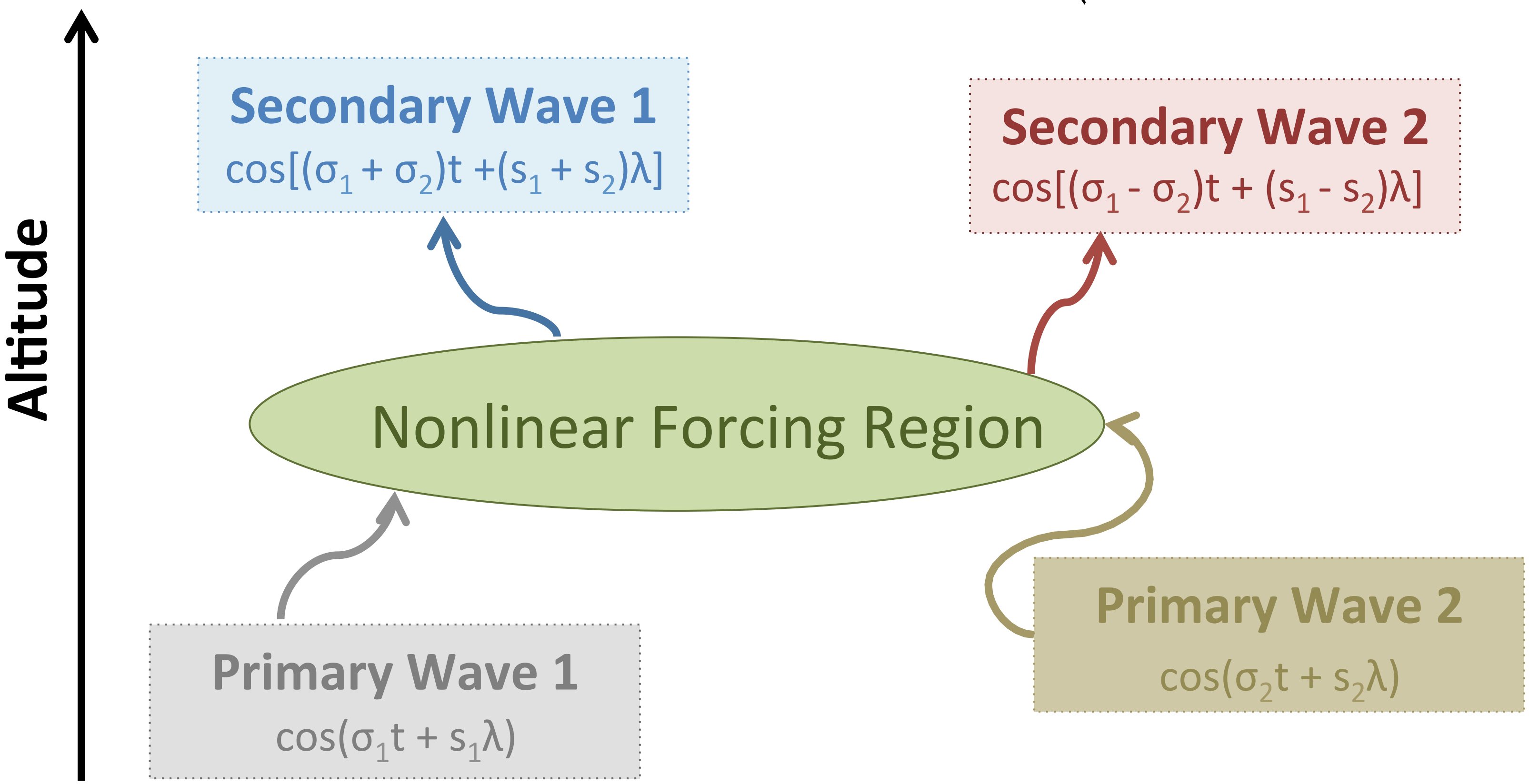


Liu, H.-L., J. M. McInerney, S. Santos, P. H. Lauritzen, M. A. Taylor, and N. M. Pedatella(2014), Gravity waves simulated by high-resolution Whole Atmosphere Community Climate Model, Geophys. Res. Lett., 41, 9106–9112, doi:10.1002/2014GL062468.

Atmospheric Waves

Nonlinear Wave Interactions

$$\cos\left(\sigma_1 t + s_1\lambda\right) \cdot \cos\left(\sigma_2 t + s_2\lambda\right) \begin{array}{l} \nearrow \cos\left((\sigma_1+\sigma_2)t + (s_1+s_2)\lambda\right) \\ \searrow \cos\left((\sigma_1-\sigma_2)t + (s_1-s_2)\lambda\right) \end{array}$$



Observation of Wave Field

Ground-based methods

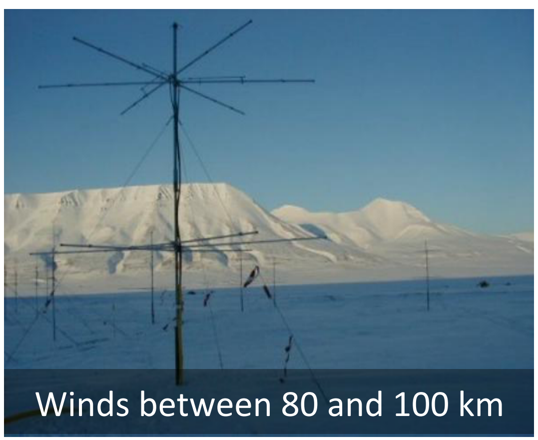
Incoherent scatter radars

MLT temperatures and winds at 100-120 km, but only in intervals of 2 to 10 days

Resonance lidars

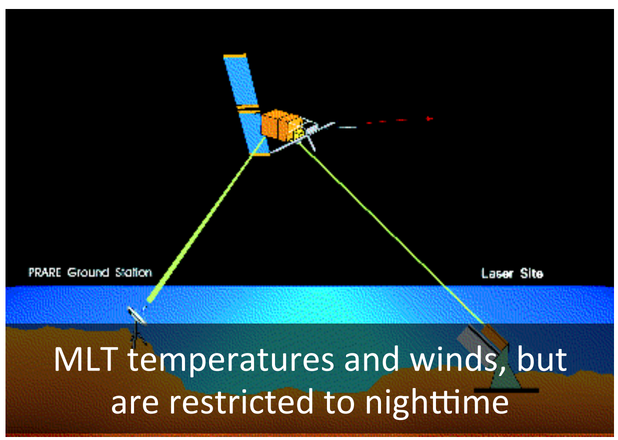
Temperatures and winds both day and night, but not continuously

MF and meteor radars



Winds between 80 and 100 km

Passive optical methods



MLT temperatures and winds, but are restricted to nighttime

Advantages

1. Ability to distinguish waves over short time periods
2. Information on vertical structure

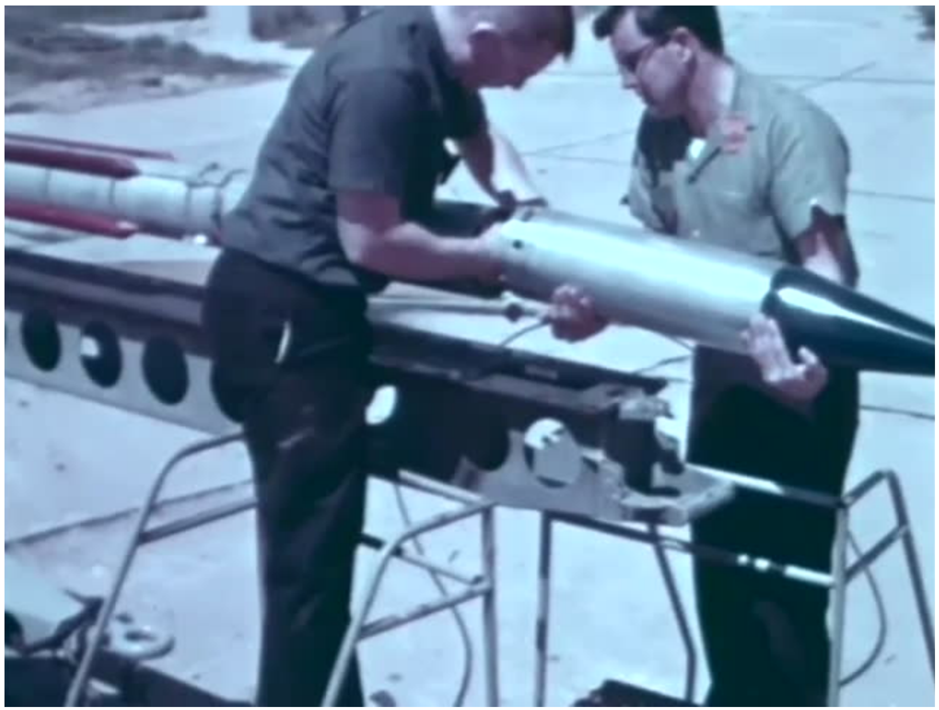
Disadvantages

1. Lack of information on the latitude-longitude structure
2. Inability to distinguish between global- and local-scale waves

Observation of Wave Field

Historical Side Note

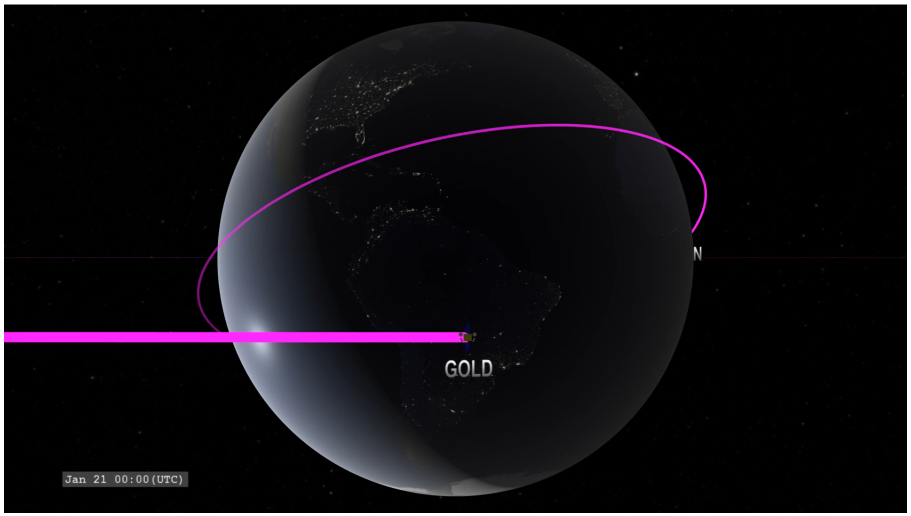
Studying Thermal Tides with… Grenades



Review lecture - Rocket studies of atmospheric tides
G. V. Groves Proc. R. Soc. Lond. A 1976 351
437-469; DOI: 10.1098/rspa.1976.0151. Published 8 December
1976

Observation of Wave Field

Space-based methods



Low Earth Orbiting Satellites

Changing Longitude & Latitude

Advantage

- **Latitude-longitude coverage** – The lower the inclination, the more rapid the orbit precesses with respect to the Sun (e.g., 120 days for $i = 70^{o}$)

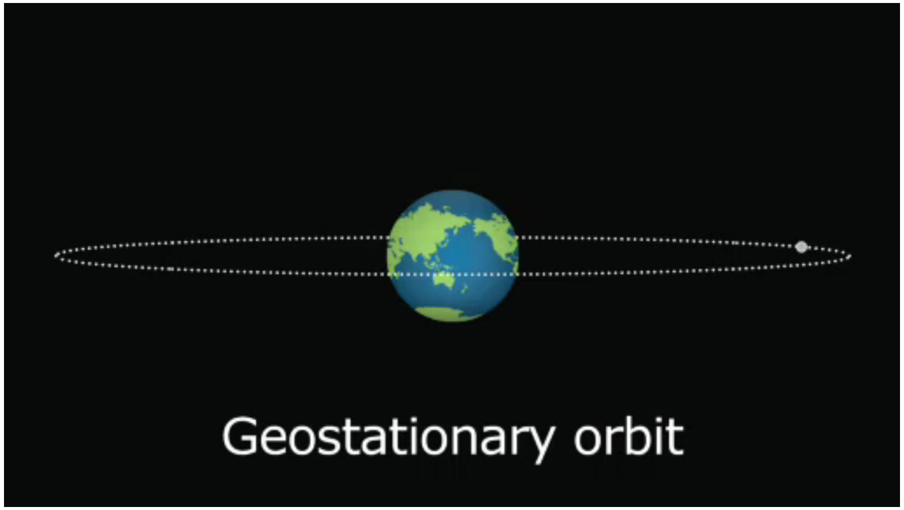
Disadvantages

- **Sampling** – Due to inherent variability of atmospheric system within the 24-hour local time coverage

- **Aliasing** – Zonal mean and other longer-period waves can alias into the derived tidal field and be perceived as local time changes

Observation of Wave Field

Space-based methods



Geostationary Satellites

Constant Longitude

Advantage

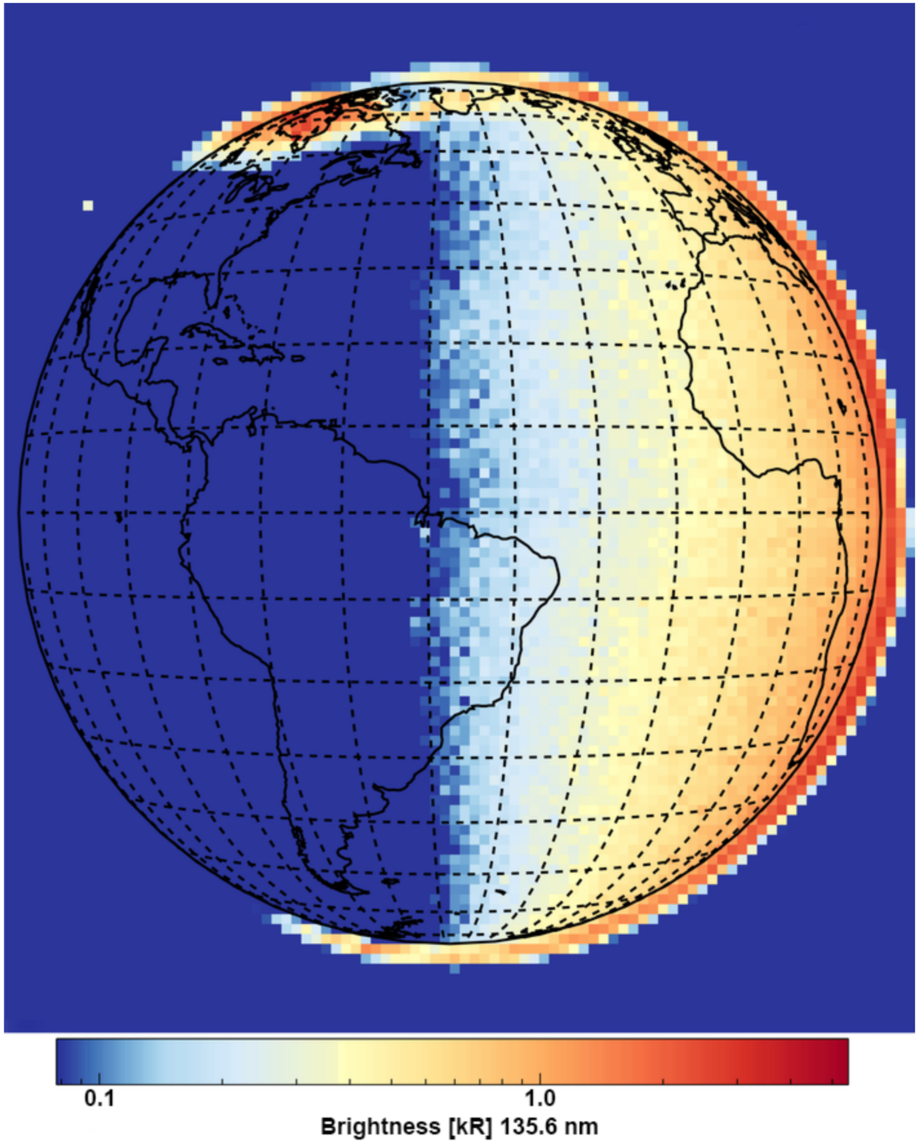
- **Local Time coverage** – Observes waves as they develop and change in place, separating time and spatial variability

Disadvantages

- **Longitude Coverage** – Cannot observe far side of the Earth and complicates derivation of tides

Observation of Wave Field

Initial GOLD Observations



Exploring the Ripples of Earth's Upper Atmosphere: Waves & Tides

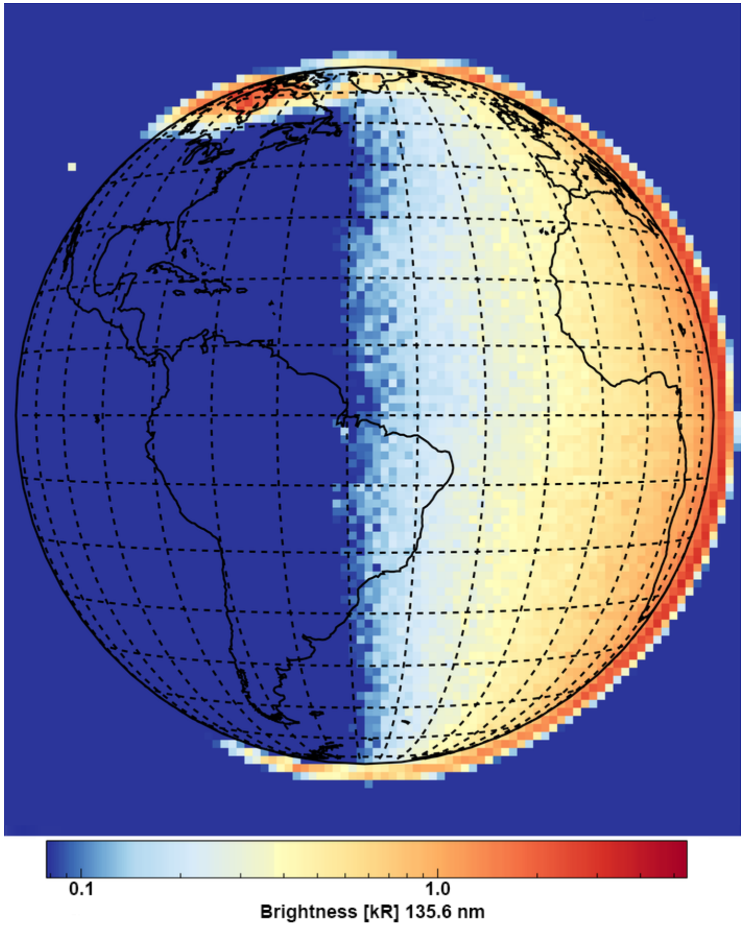
Dr. Katelynn R. Greer, University of Colorado – Boulder

- **Variability in the Thermosphere is due to both incoming energy from above (the Sun) and from below (atmospheric weather)**
- **Thermal Tides and Gravity Waves help connect the lower and upper atmosphere**
- **We use different observational techniques to sense waves and tides from the ground and space**

Exploring the Ripples of Earth's Upper Atmosphere: Waves & Tides

Dr. Katelynn R. Greer, University of Colorado – Boulder

Questions?



GOLD
Global-scale Observations of the Limb and Disk

LASP
Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**