Atmospheric Gravity Waves, and how do we observe them? – Part I

Jie Gong (Jie.Gong@nasa.gov)

NASA Goddard Space Flight Center


How many wave trains can you see from this photo?
Photo taken out of my office @ Greenbelt, MD

Outlines

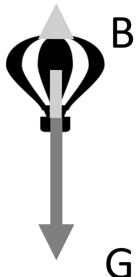
1. Introduction of gravity waves
2. Importance of gravity waves
3. Major gravity wave sources
4. Gravity wave propagation
5. Modeling of Gravity wave impact
6. Satellite observation of gravity waves (w/ eclipse-GW example)
7. Radiosonde observations of gravity waves (w/ eclipse-GW example)
8. Gravity wave observational window
9. Summary

PART I (items 1–5)

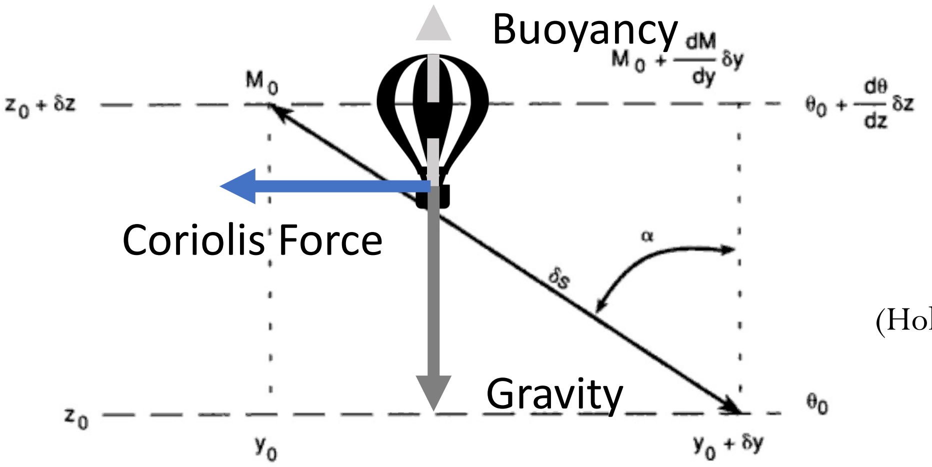
PART II (items 6–9)

1. What are gravity waves?

- Waves occurring in a stably stratified fluid; buoyancy acting as the restoring force (pure internal gravity wave)



- If modified by rotation, Coriolis force also acts as the restoring force (inertia-gravity wave)

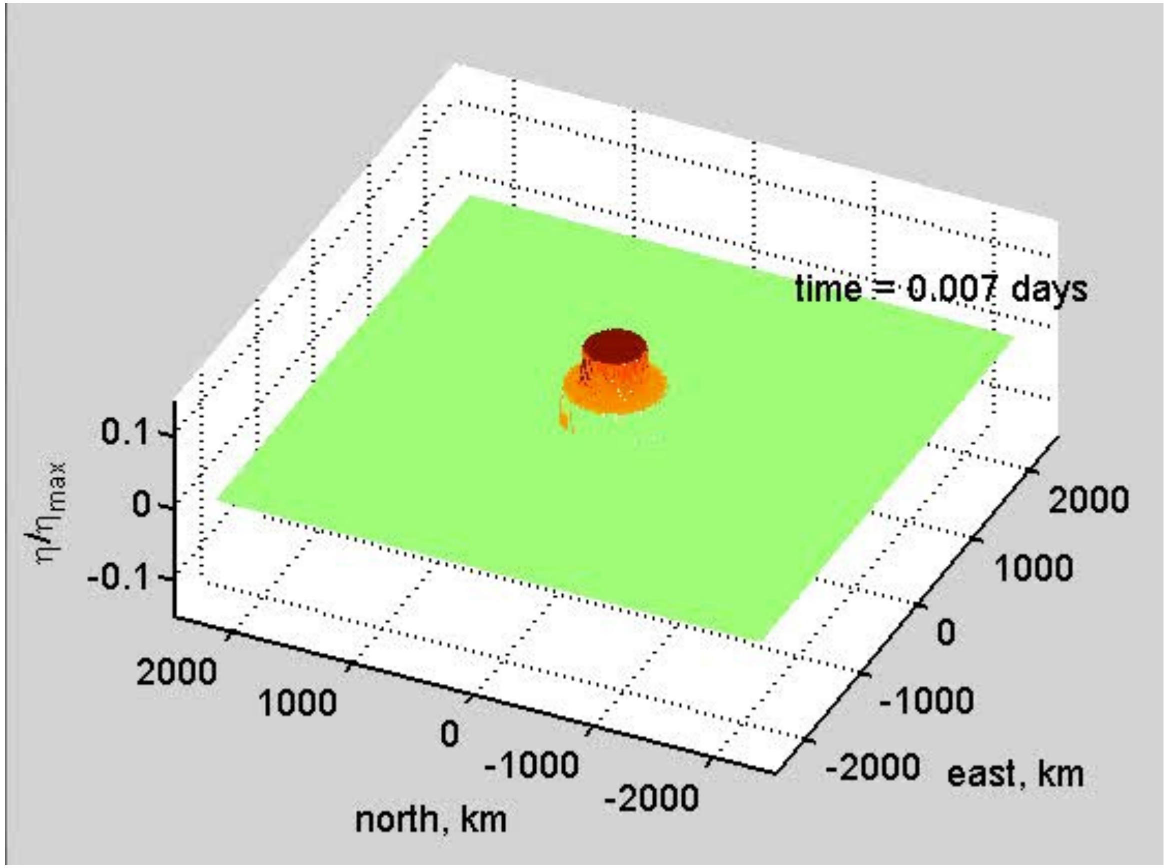


(Holton, 2004, Fig. 7.11)

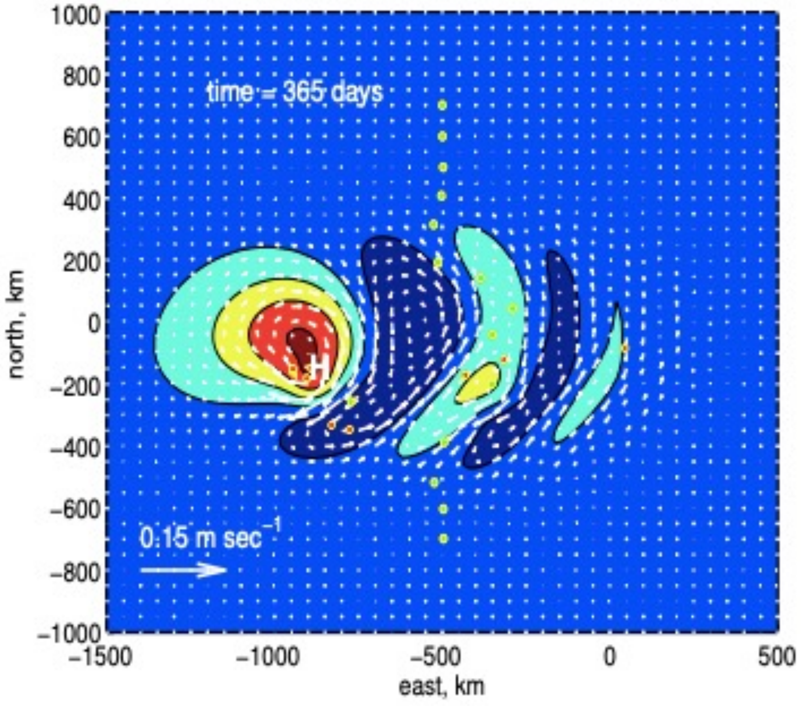
Coriolis force: on a rotating sphere, Coriolis force is always to the right (left) of the moving direction of a parcel in the Northern (Southern) hemisphere

- Period: buoyancy oscillation period – inertial period (10min - 1day)
- Horizontal wavelength: 10 – 1000s km
- Vertical wavelength: 0.1 – 10s km

How latitudinal change of Coriolis force (called “beta-plane”) generate inertial gravity waves

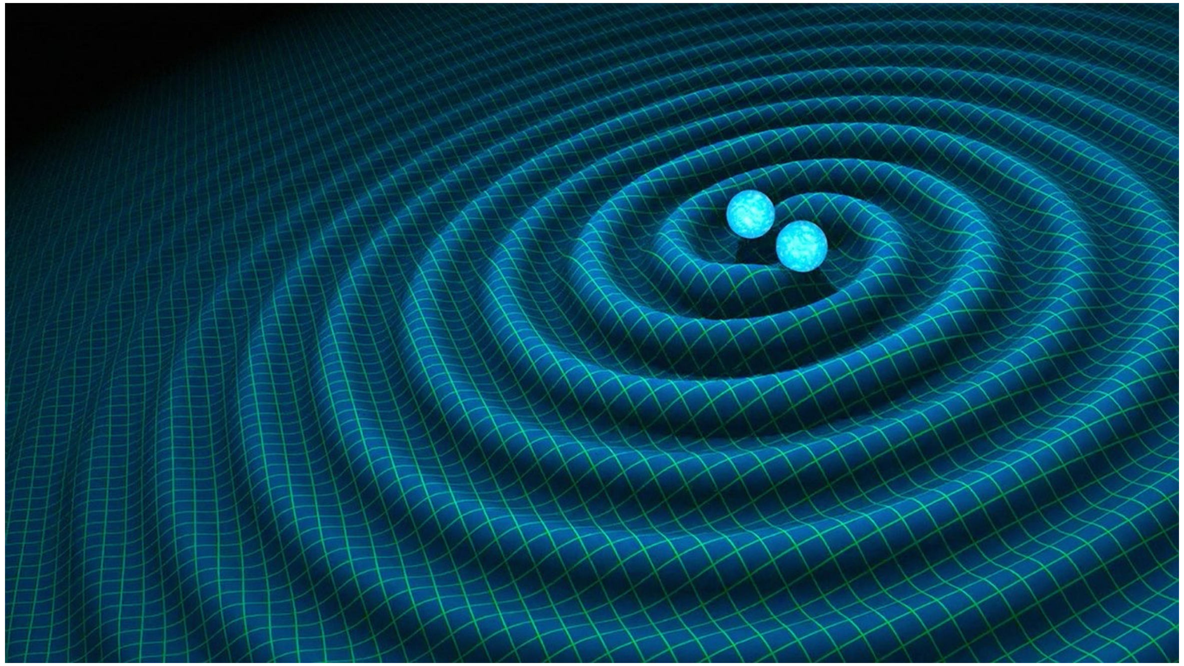


Bird-eye view



https://ocw.mit.edu/courses/res-12-001-topics-in-fluid-dynamics-spring-2022/mitres_12_001_act_p3.pdf

Are gravity waves the same with gravitational waves?



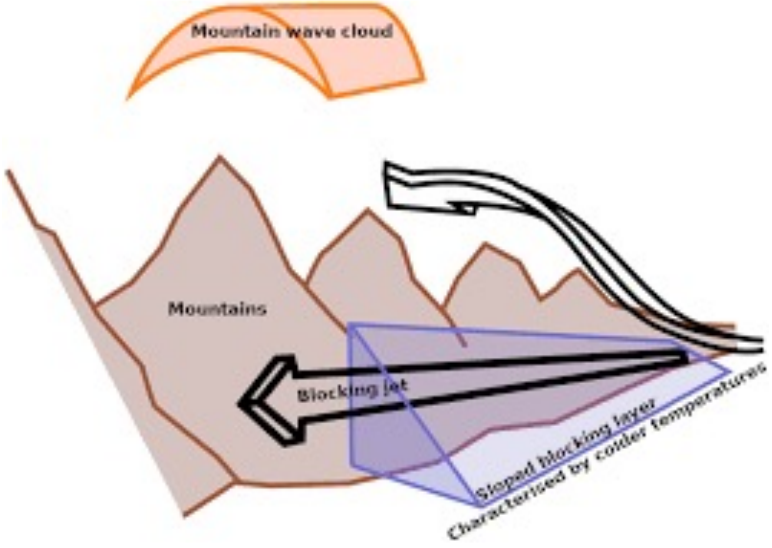
2. Why are gravity waves important?

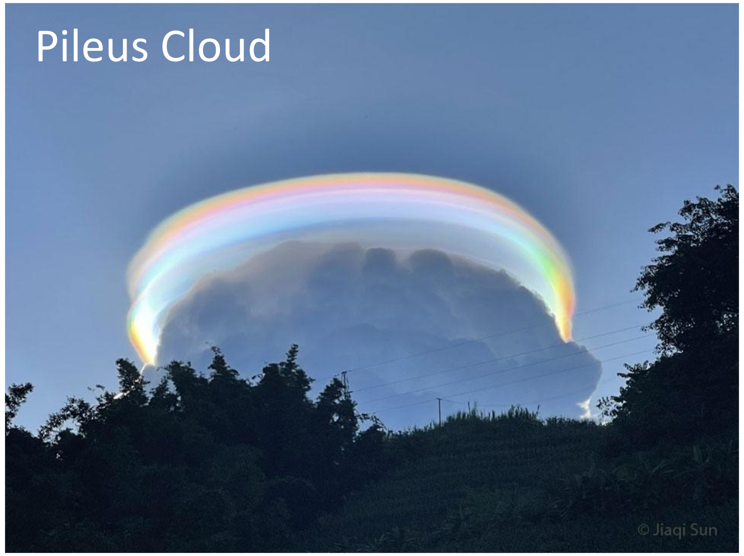
- Transport/redistribute energy and momentum from the source (often lower atmosphere) to the sink (often upper atmosphere)
- Therefore, GWs play critical roles in shaping the middle atmosphere dynamics (e.g., mesosphere wind reversal, quasi-biennual oscillation)
- Local effects:
  - Induce turbulence – important for mixing of chemical species and water vapor (e.g., clear air turbulence, polar stratospheric cloud, polar mesosphere cloud)
  - Modulate or initiate synoptic weather (e.g., gravity wave front)

Extraordinary lenticular cloud over the Mt. Fuji

(Geldenhuys, 2022, ASL)

https://www.aerotime.aero/articles/23079-extraordinary-lenticular-clouds-mount-fuji-mountain





Pileus Cloud

https://science.nasa.gov/iridescent-pileus-cloud-over-china

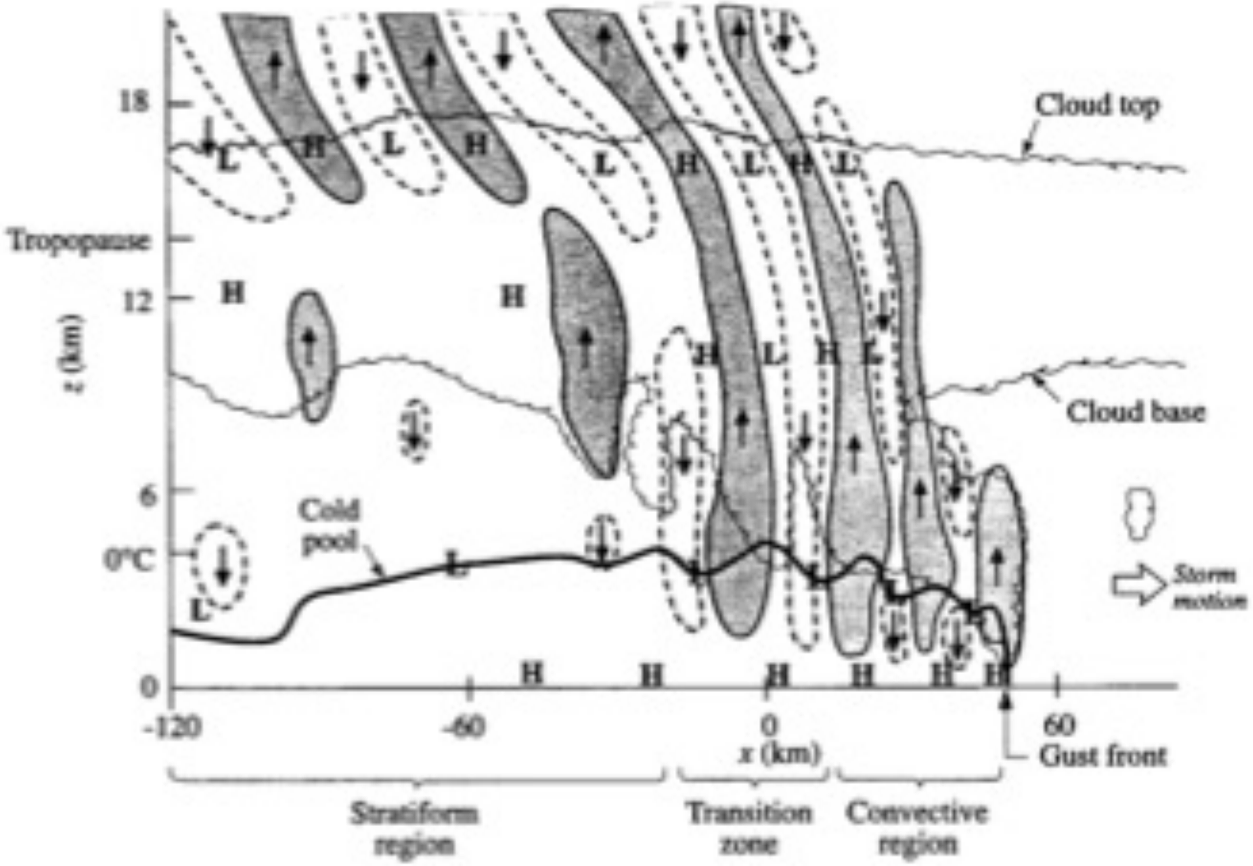

Morning glory cloud

Photo credit: *Mick Petroff*

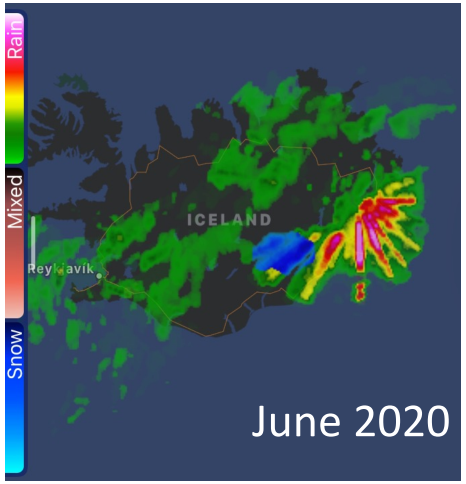

Kelvin-Helmholtz wave cloud

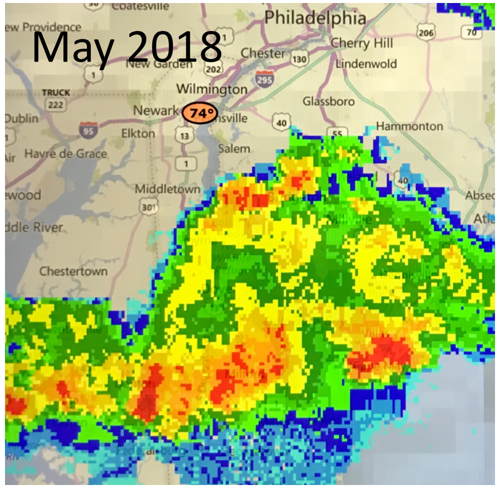
Photo credit: *UCAR/NCAR*

Gravity wave modulating weather systems and formation of new convective cells

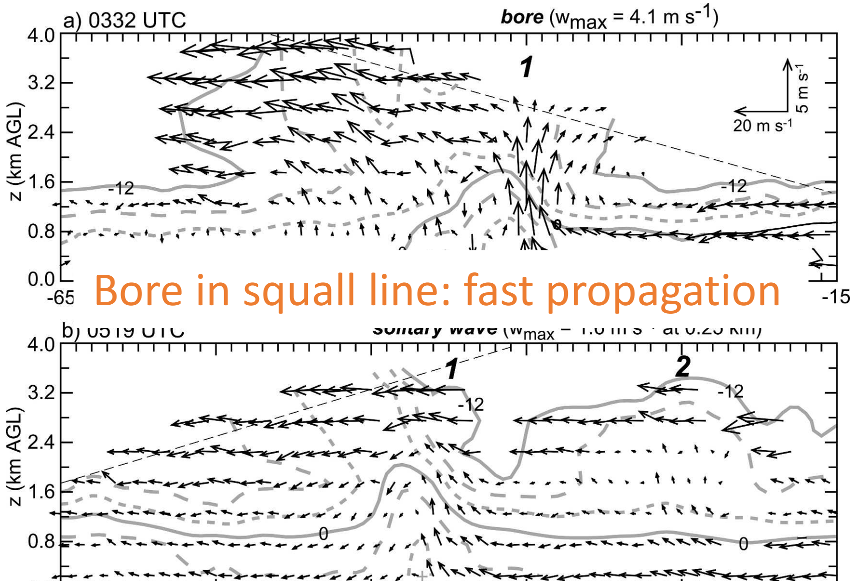


(Yang and Houze, 1995, MWR)





Screenshots for two cases from NOAA CLIME app

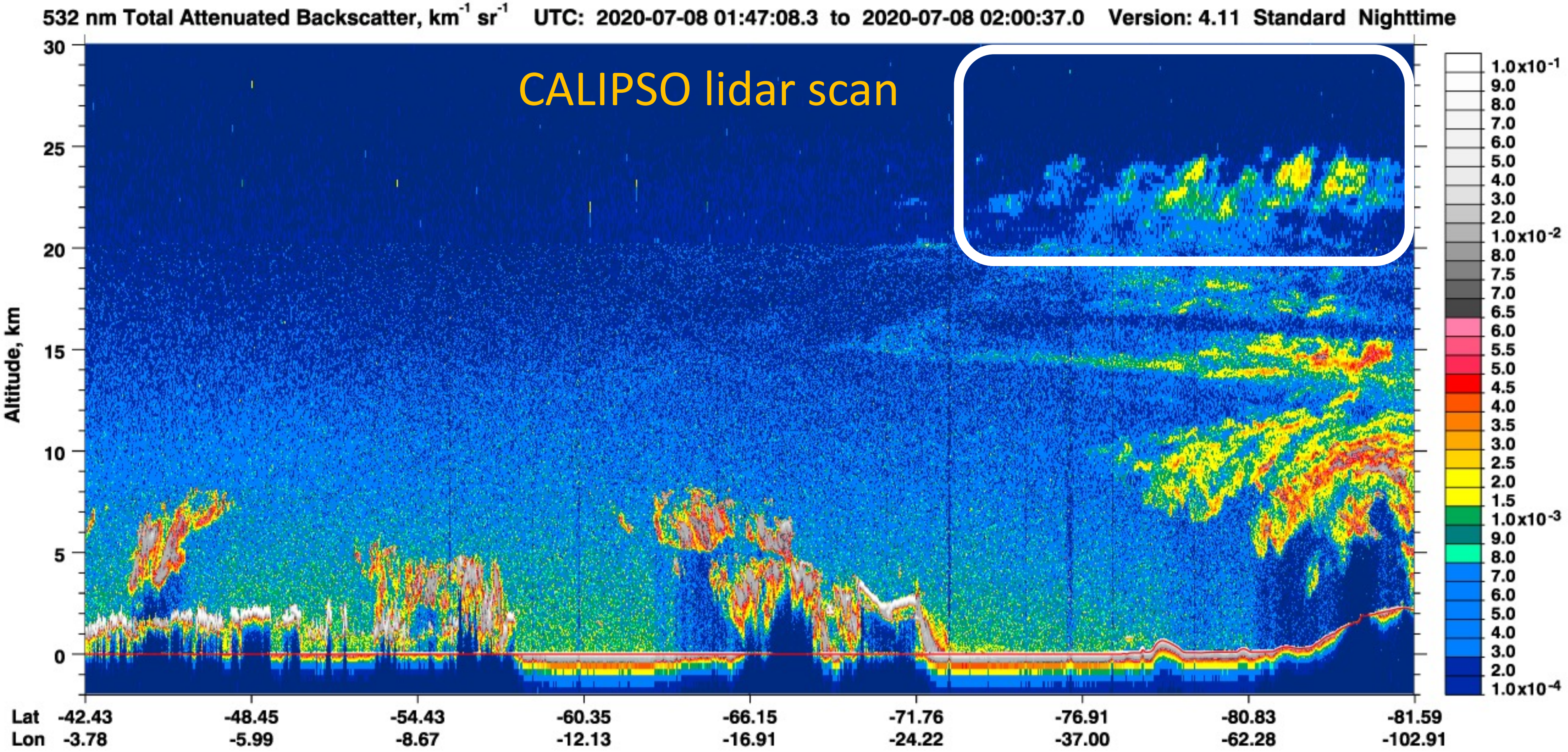


Bore in squall line: fast propagation

Solitary GW in squall line: slow propagation

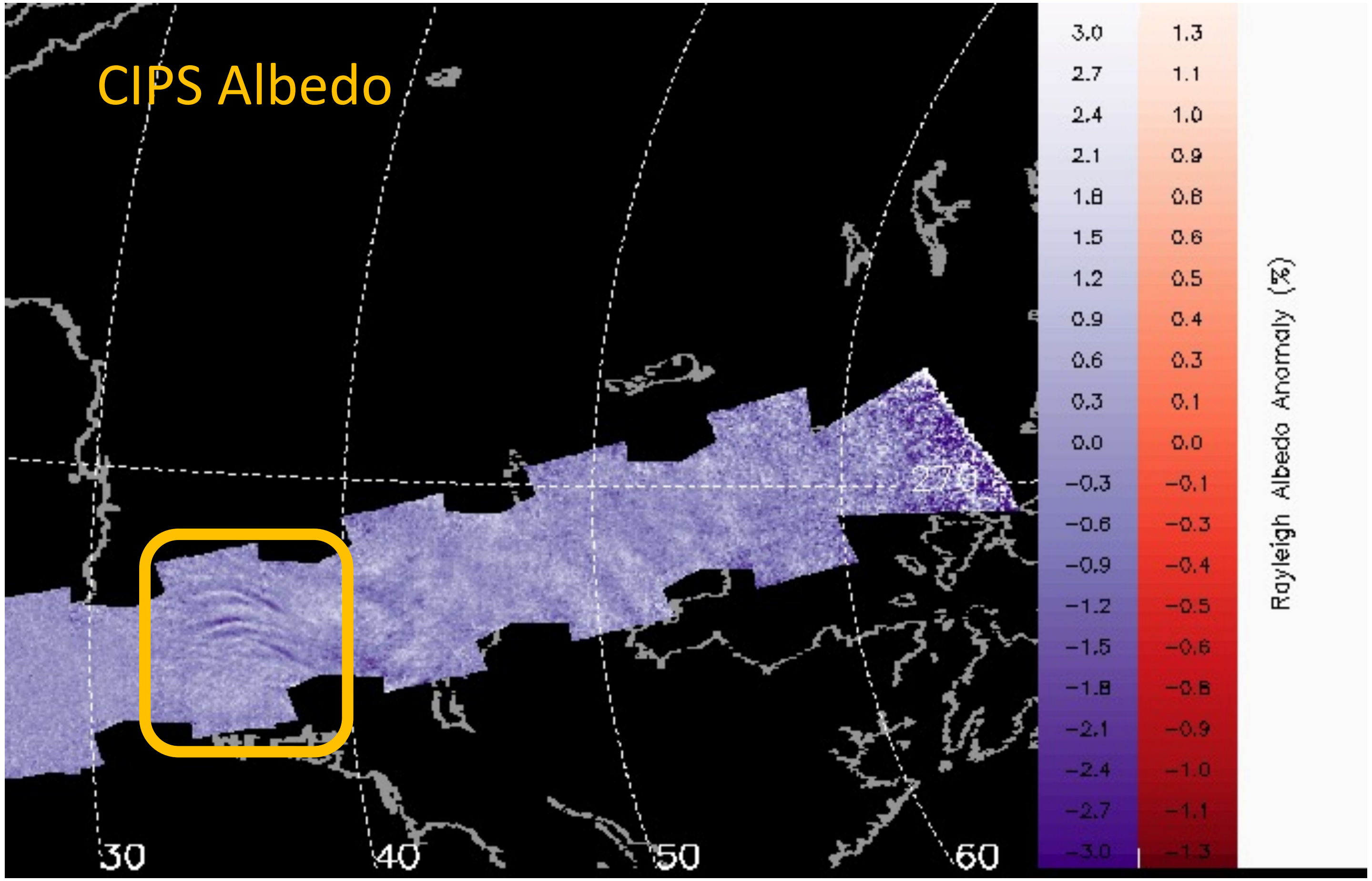
(Knupp, 2005, JAS)

Winter polar stratospheric cloud (PSC) – catalyst for ozone depletion



https://www-calipso.larc.nasa.gov/data/BROWSE/production/V4-11/2020-07-08/2020-07-08_01-20-14_V4.11_3_1.png

Summer polar mesospheric cloud (PMC) – atomic hydrogen or water vapor



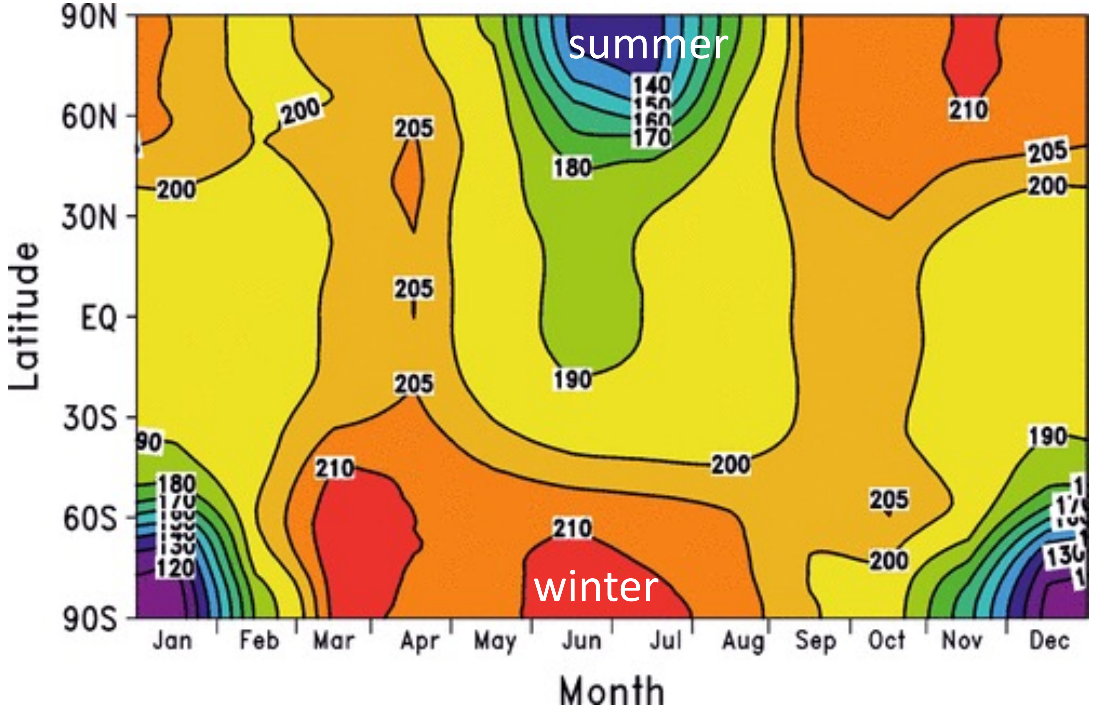
https://lasp.colorado.edu/aim/

https://ece.vt.edu/research/annual-report/annual-report-2022/edge-of-clouds.html

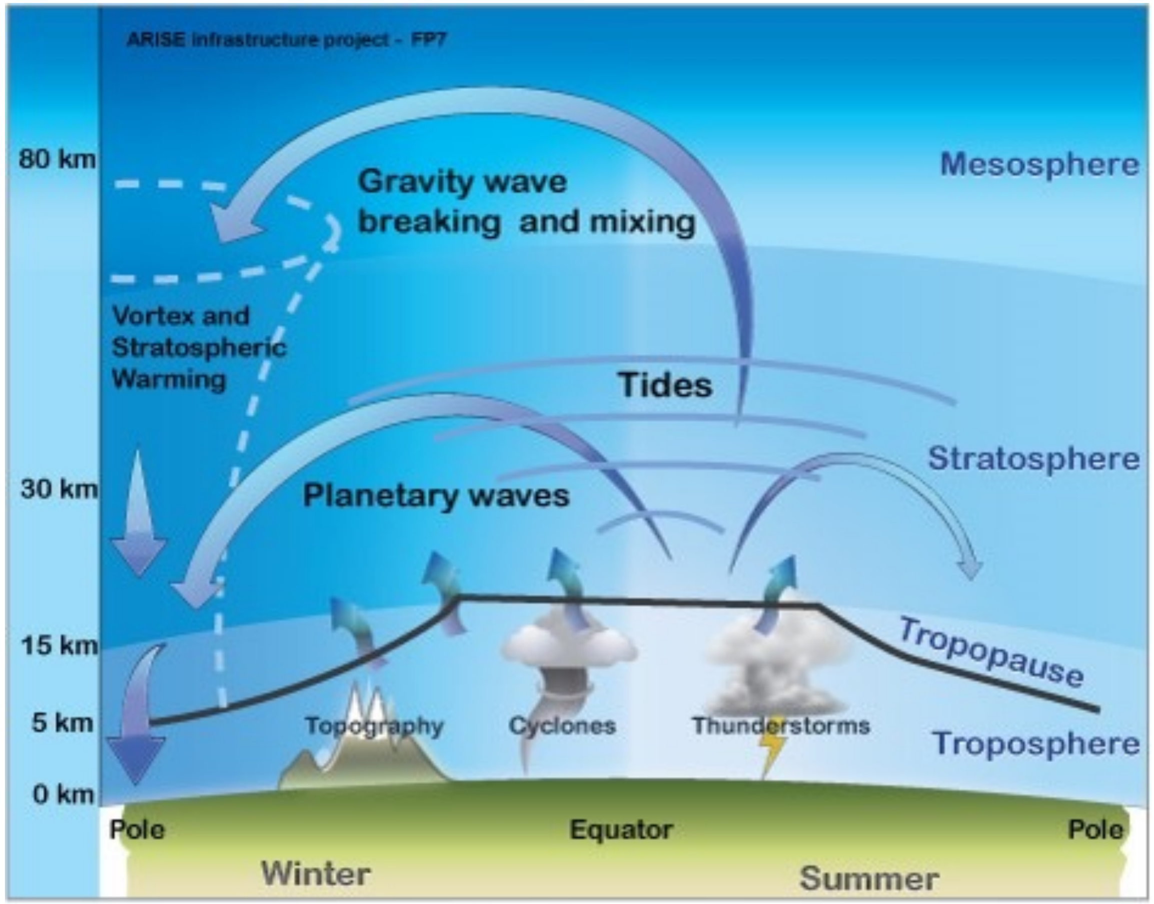
Why do clouds form in winter polar stratosphere, but in summer polar mesosphere?

Mesosphere (87 km) temperature climatology

Summer pole is the coldest!



(Plane et al., 2015, Chem. Rev.)

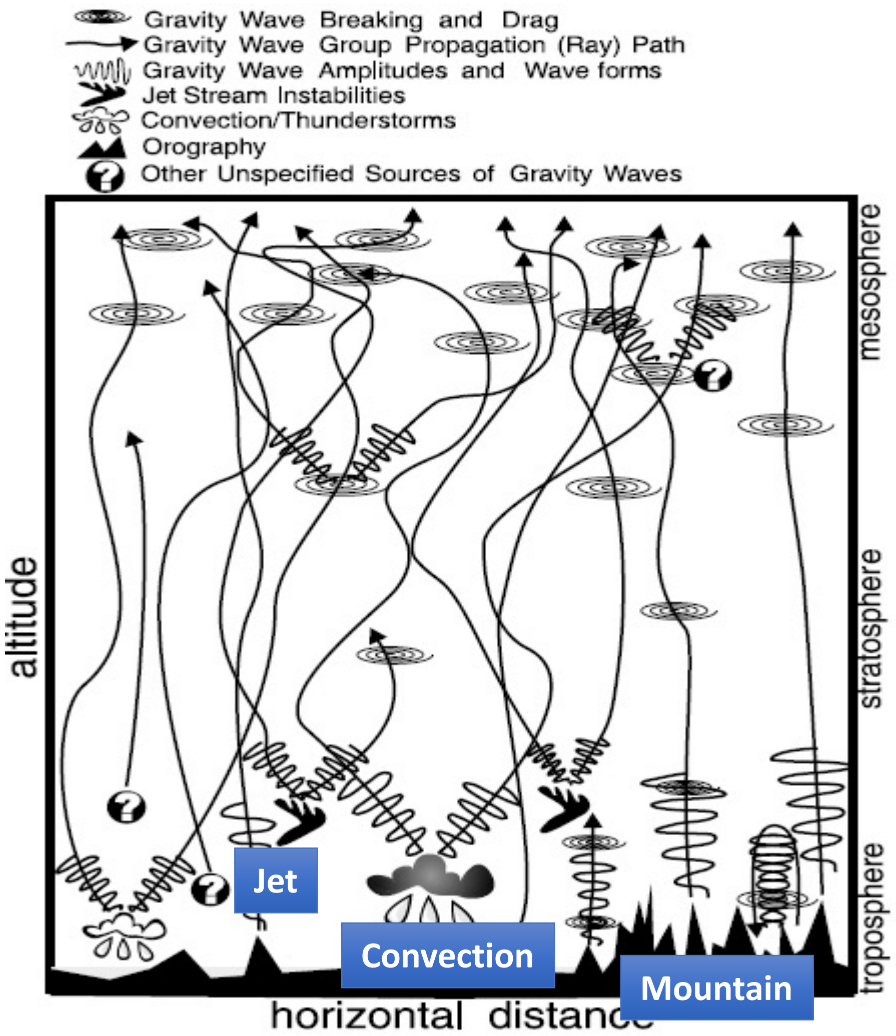


https://lasp.colorado.edu/home/mag/research/middle-atmosphere-dynamics/

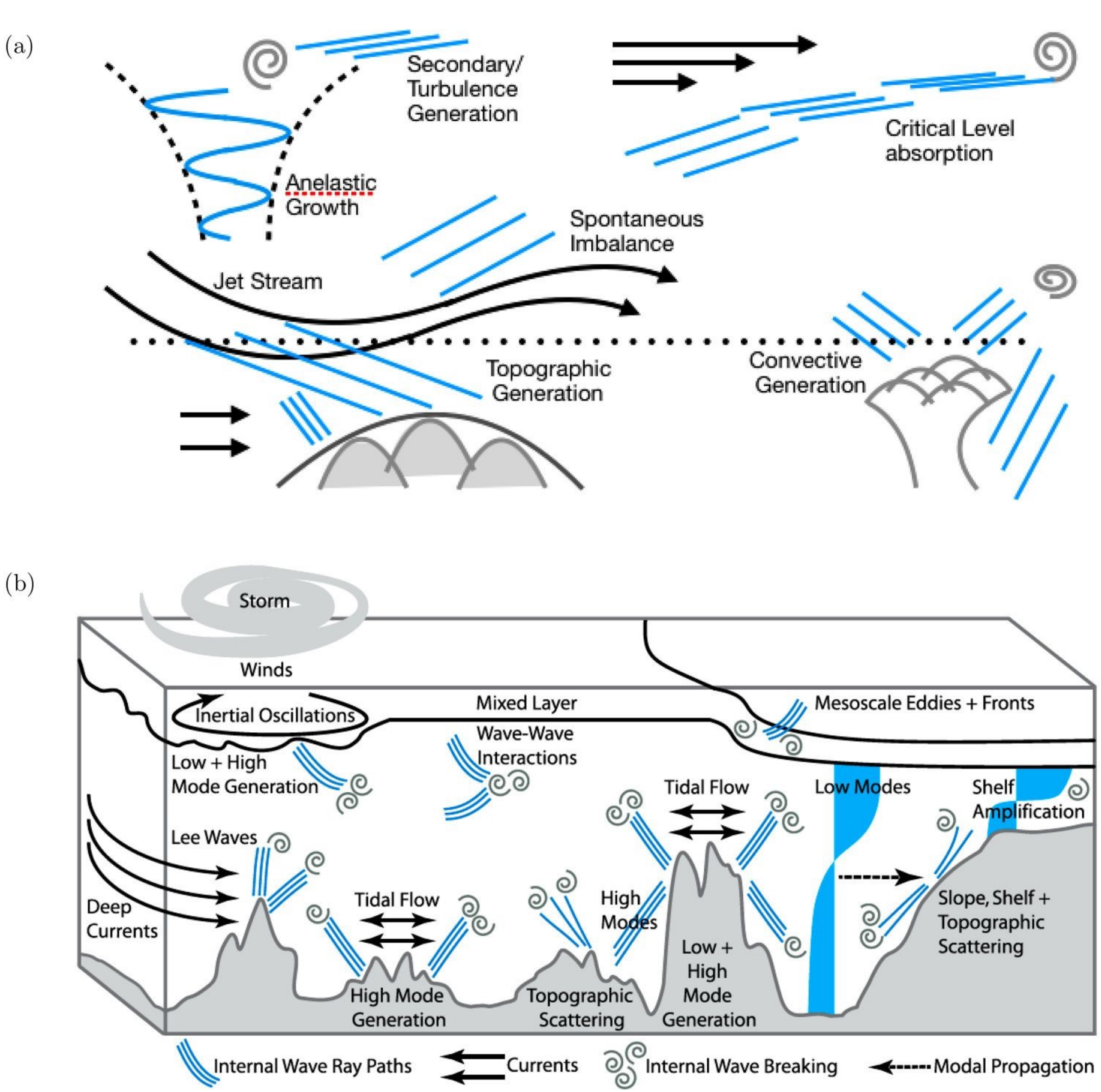
3. Major gravity wave sources

- Gravity waves (GWs) serve as a critical mechanism for lower-upper atmosphere coupling through the vertical propagation and breaking

- GWs contribute significantly in shaping the mesosphere circulation



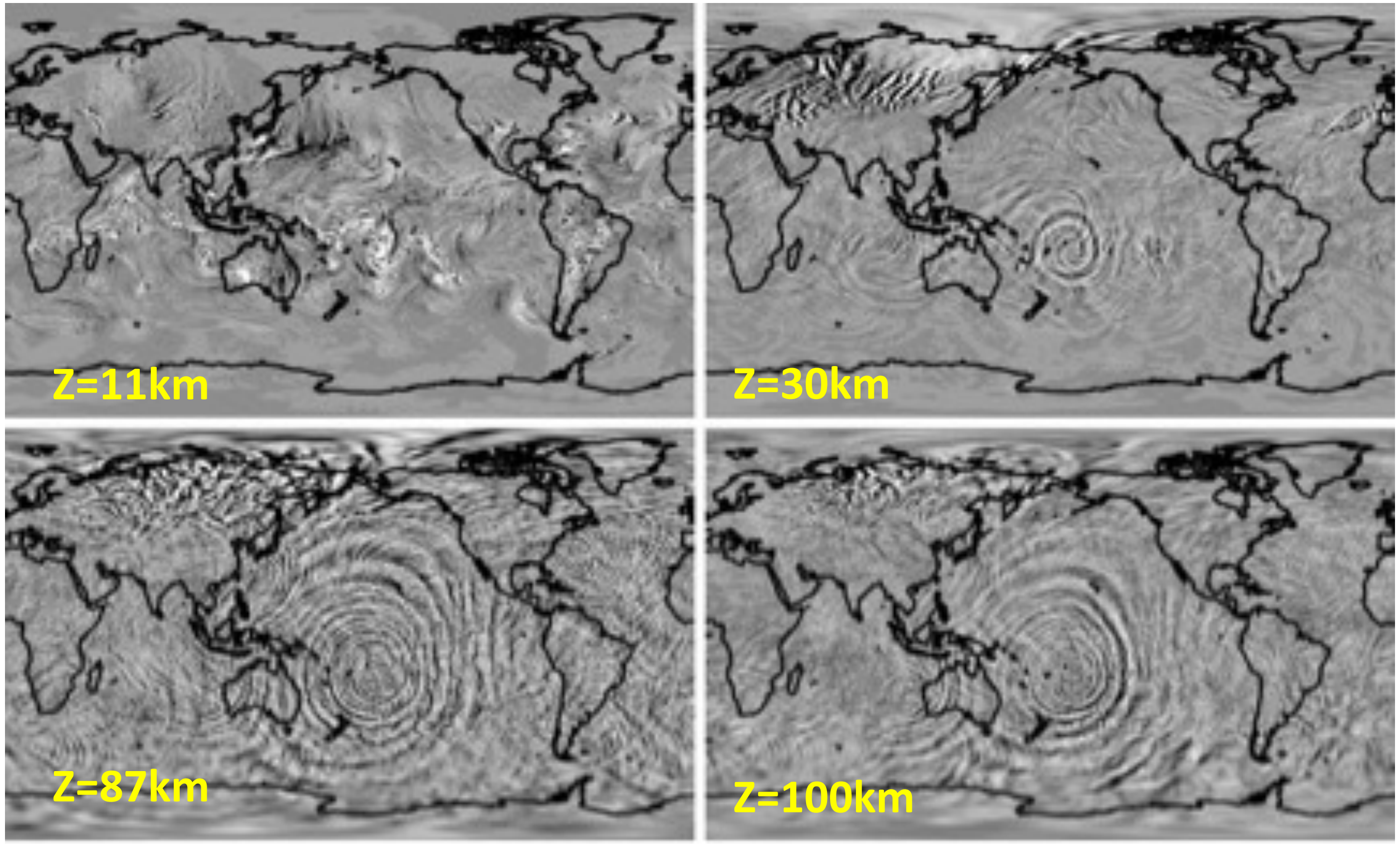
(Kim et al., 2003, Atm-Ocn.)



Atmosphere

Ocean

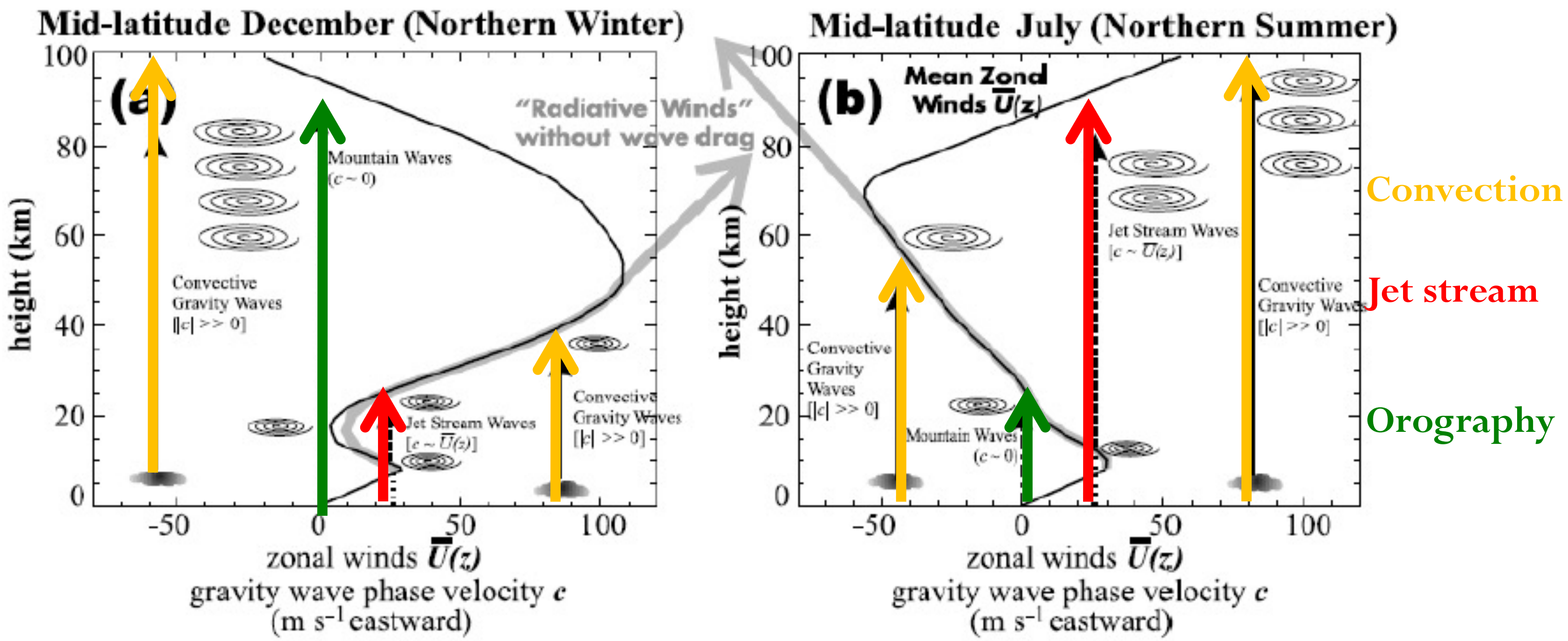
(Sutherland et al., 2019, Phys. Rev. Fluid)



A WACCM-X simulation that illustrates how gravity waves were kicked off by a typhoon to the east of Australia build as they travel toward space (Liu et al., 2014, GRL).

4. Gravity wave propagation

- Gravity waves are drags to the mean flow
- Gravity wave drags are currently partially parameterized in state-of-the-art GCMs, which are poorly constrained by observations.



(Kim et al., 2003, Atm-Ocn.)

$$\overline{p'w'} = -\bar{U}(z)(\bar{u} - c)\overline{u'w'}$$

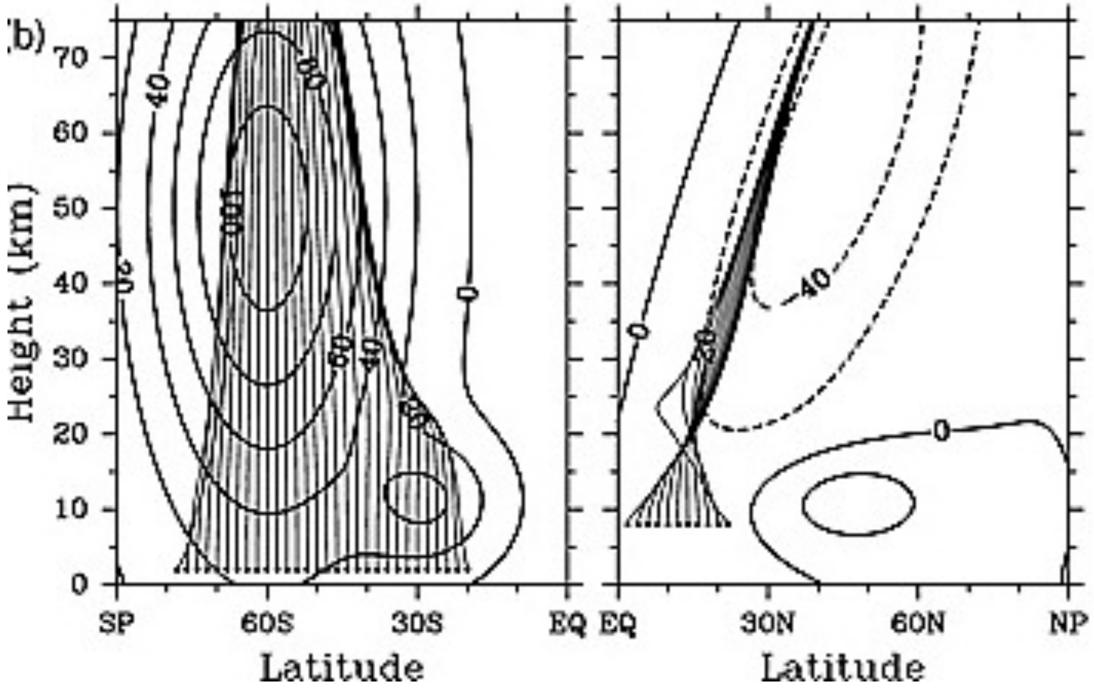
Energy flux

Momentum flux

Break when phase speed equals background wind

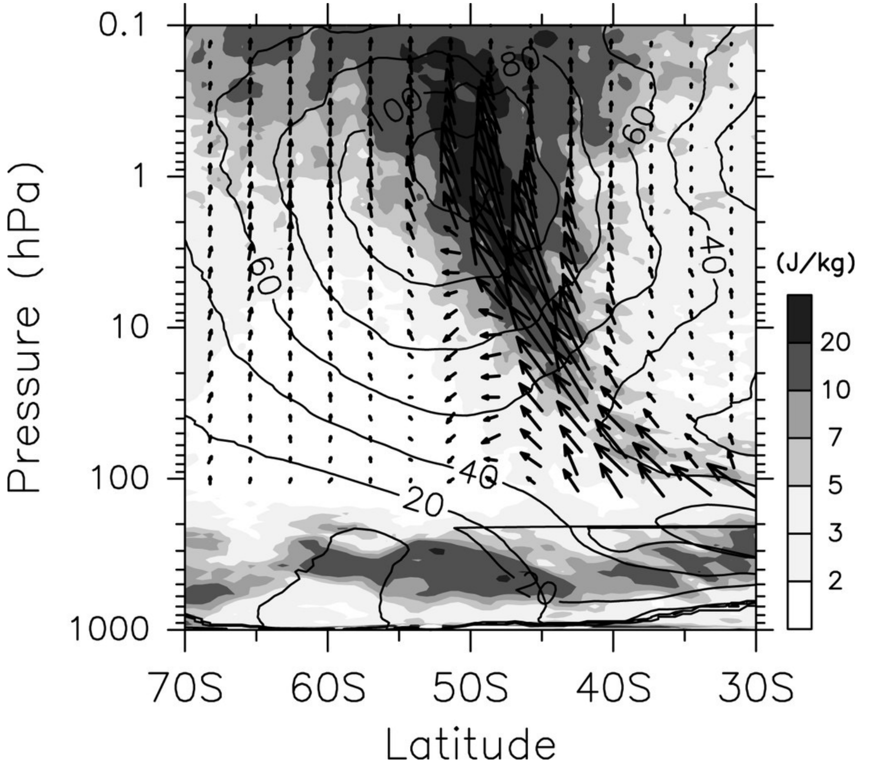
Gravity wave propagation is slantwise instead of vertical…

With fixed background winds, gravity wave rays (think grey lines) tend to propagate into the jet core



(Sato et al., 2009, GRL)

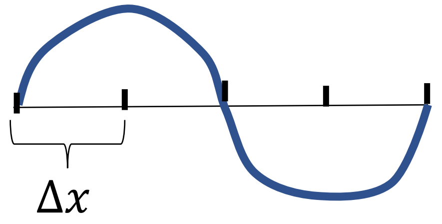
The resolved gravity wave energy flux also propagates into the jet core



(Sato et al., 2012, JAS)

5. Modeling of gravity wave impact

- Gravity wave wavelengths span a wide range:
  - Horizontal wavelength: 10 – 1000s km
  - Vertical wavelength: 0.1 – 10s km
- Mesoscale or cloud-resolving model horizontal resolution: 3 – 30 km
- Global model horizontal resolution: 10 – 250 km
- Vertical grid: 100s m to 1-2 km
- Rule of thumb for smallest resolvable waves: 6 X grid size, so small-scale gravity waves cannot be resolved and need to be parameterized



- 4 X grid size (i.e., Δx) corresponds to the smallest resolved waves
- However, every model has some dissipation terms to stabilize the model, hence 6 X grid size is a more realistic estimation

Open question for you: what is the largest wave that can be resolved?

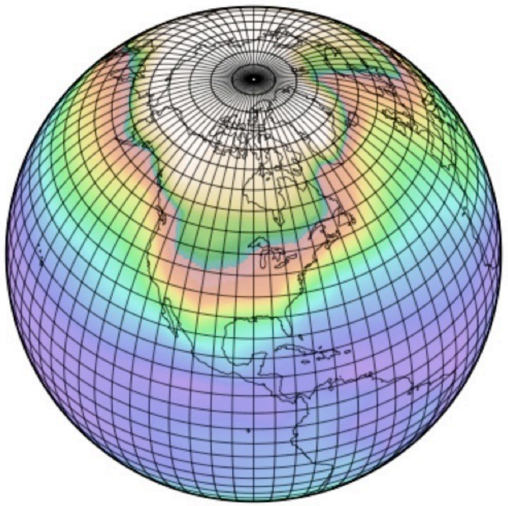
What is model parameterization?

- Small physical or chemical processes that cannot be resolved at model grid scale have to be parameterized.
- Can you think of some physical processes that model probably cannot (fully) resolve and hence need to be parameterized?
    - Turbulence processes
    - Cloud microphysical processes (e.g., water vapor turn into droplet)
    - Convective towers
    - Cloud vertical distribution
    - Aerosol-cloud interaction
    - All chemical reactions
    - Soil evaporation
    - Gravity wave drag
    - etc ….

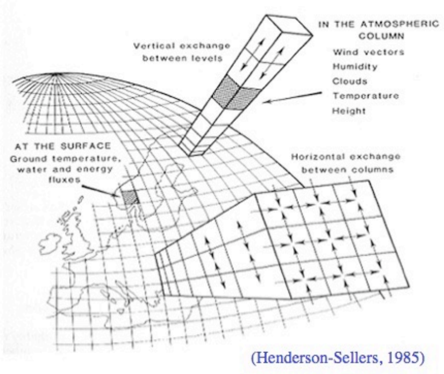
Challenge for gravity wave drag (GWD) parameterization

- Slantwise propagation vs. column-wise simulation: we need accurate and fast cross-grid talk to enable slantwise GW propagation

Grid Point Models

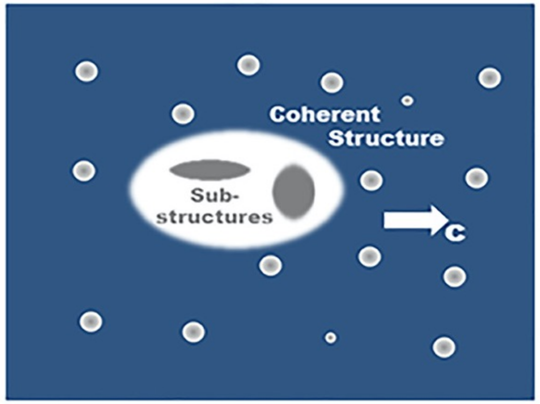


Possible solution: ray-based parameterization



https://serc.carleton.edu/eet/envisioningclimatechange/part_2.html

- Some GWD sources are also sub-grid scale, e.g., deep convection, topography



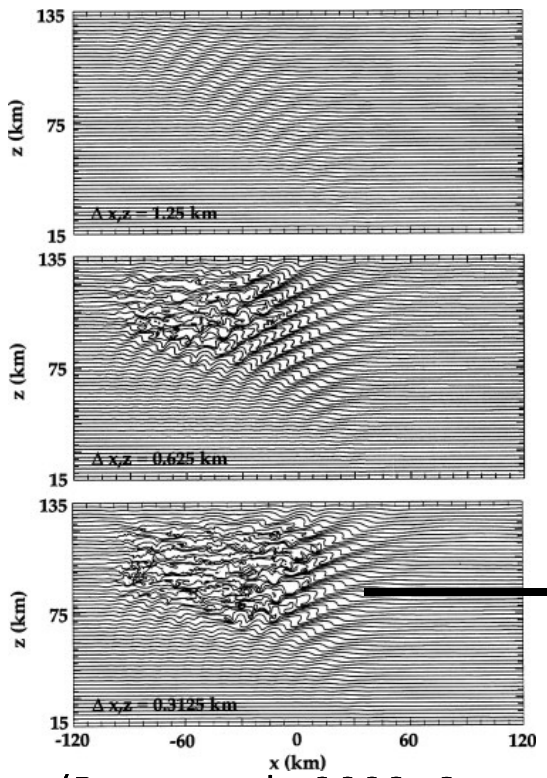
Slantwise Layer Overturning

(Moncrieff, 2019, GRL)

- Wave intermittency is a heavily tuned parameter

Challenge for GWD parameterization (cont’d)

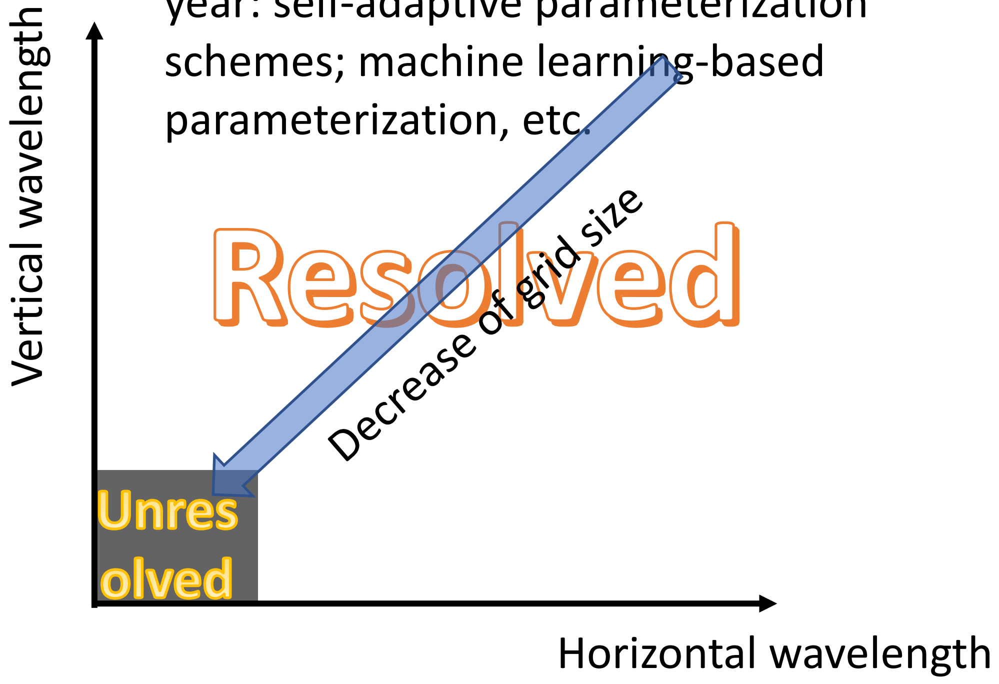
- Ever-changing model grids vs. ever-tuning GWD parameters



(Prusa et al., 2008, Comp. & Fluid)

It’s soon a chaos when you let all kinds of waves propagate freely in the model!

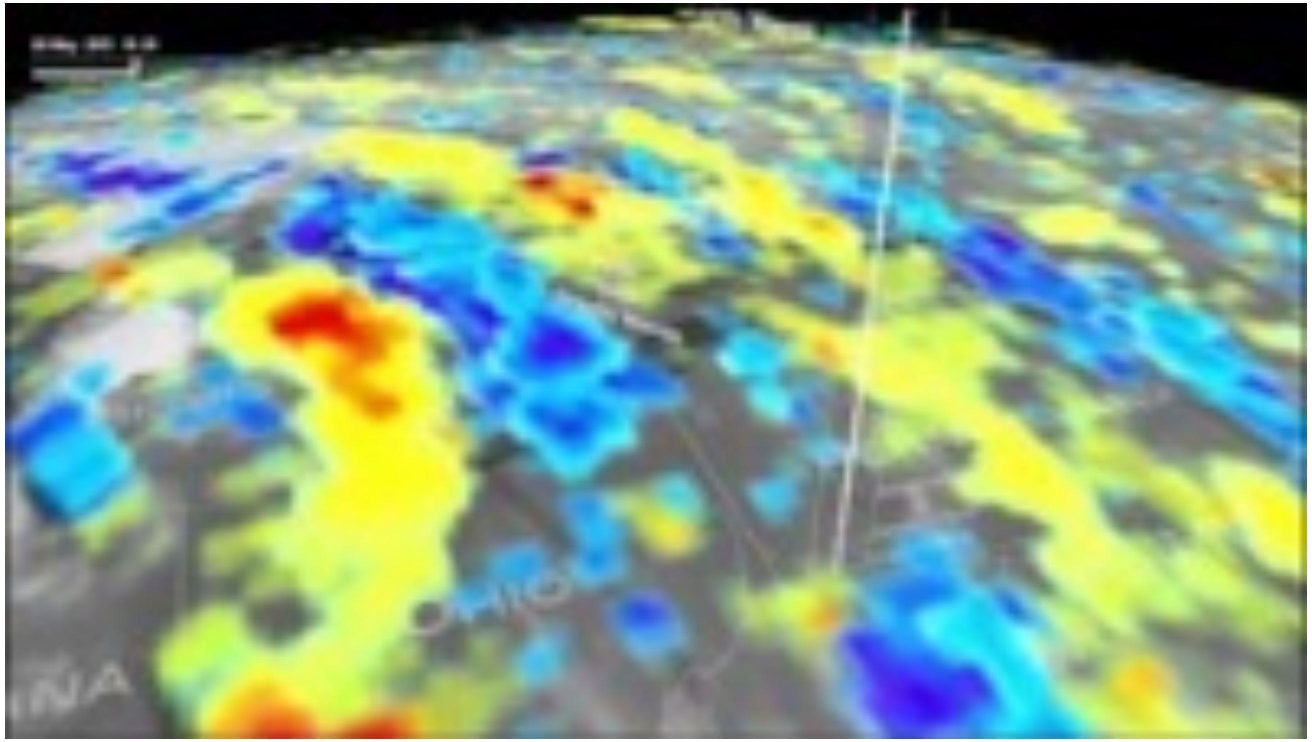
Possible approaches proposed in recent year: self-adaptive parameterization schemes; machine learning-based parameterization, etc.



- Secondary GW generation at the mesopause is a key mechanism for upper atmosphere coupling, but is merely considered in climate models.

In the next class, we will see how we observe atmospheric gravity waves using satellite, radiosonde, etc., in the context of solar eclipse…

- Let’s end this class with a spoiler video



A tornado gravity wave case that I studied with my colleagues

(If video doesn’t work, click the link: https://www.youtube.com/watch?v=2SfHs3O8Y7M)

References

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Homework sample questions

1) When a rising balloon passes through a gravity wave front, which way do you think its trajectory will look like?
   (A) up-down oscillation (B) slantwise oscillation (C) spiral oscillation
2) The vertical oscillation component of gravity wave originates from a balance between gravity and buoyancy. What forces balance on the horizontal direction?
3) Can you name a few atmospheric gravity wave sources? Can you name a few oceanic gravity wave sources?
4) Can you lay-out a few reasons why gravity waves are important, so we need to study them?
5) Can you lay-out a few challenges for models to simulate gravity wave impacts?
6) Can you think of some processes that a typical climate model cannot resolve other than the ones listed in the slides?
7) Given a global climate model (GCM) grid size of 100 km, and the earth radius of 6371 km, theoretically what are the smallest and largest wavelength of waves that this GCM can resolve?

Sample homework answer key

1) C

2) We only need Coriolis force for the horizontal oscillation. Remember Coriolis force is always to the right in the Northern hemisphere and to the left in the Southern hemisphere of the moving direction, so itself forms the so-called inertial oscillation. You can see marine debris often gradually aggregate together into big piles. That's not only because they follow the general ocean current, but also the inertial motion looping in smaller areas at the same time.

3) <u>Atmosphere</u>: mountain/topography, deep convection (including typhoon, hurricane, tornado), jet, frontal system, solar eclipse (yes, that's one of the major drives of this campaign!), volcano eruption, tsunami, missile launch, rocket launch, …

<u>Ocean</u>: ocean surface topography, wind blowing at the ocean surface (e.g., by storms, hurricane, etc.), tsunami, underwater volcano eruption, torpedo, throwing a rock into water, tides, …

Sample homework answer key (cont'd)

4) (1) Gravity waves in the troposphere impact weather. They often play a role in modulating the formation of new convective cells and the propagation of the convective system. They are often associated with hazardous aviation scenarios like triggering clear-air turbulence, forming dangerous downdraft flow or forming cloud bands. (2) They serve as a key mechanism for the lower-upper atmosphere coupling because they transport energy and momentum from the source to the sink. (3) They perturb the temperature (and hence relative humidity or other chemical reactions that are sensitive to temperature) in the stratosphere and mesosphere, which serves as an important mechanism for the formation of PSCs and PMCs, both have strong climate impact (e.g., worsen ozone depletion). (4) gravity waves in the thermosphere and ionosphere are coupled with other variations, e.g., tides, magnetic storm, and impact communication, space weather and spacecraft operations.

5) The major challenge is that none of the model can resolve all gravity waves. Ultra-high resolution is rather a curse than a bless for resolving gravity waves as they cause instability and chaos. Modelers strive to parameterize the impact from unresolved waves, while making sure the resolved waves are reasonable and do not breakdown other things. (See slide 19 & 20 for more complete answers)

6) Open answer. Any processes that are smaller than ~ 100 km scale, or very fast/transient or very slow, but in the meantime are important to weather prediction or climate projection.

7) Smallest wave = 4 X grid size = 400 km (again, in reality 600 km is a more practical answer. Both correct)

   Largest wave = Earth's circumference / 4 = 2* pi * radius / 4 ~ 10, 000 km