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

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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

PART I

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

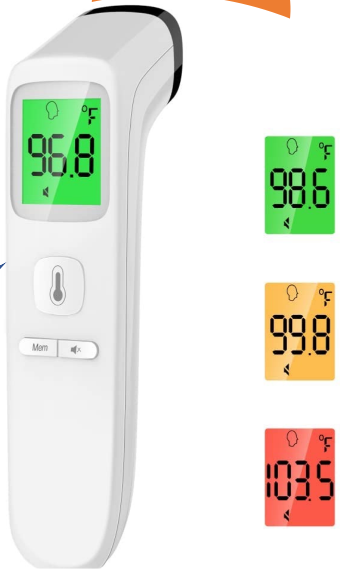
PART II

6. Satellite observations of gravity waves

- Gravity waves primarily induce temperature perturbations. Hence any temperature observations can be used
- Let’s first learn some principles of satellite “observation”
- Satellite DOES NOT directly take temperature measurements. It’s called “remote sensing”.

Can you think of something you use daily that works with remote sensing?

CT scan is a type of “remote sensing”.



Forehead thermometer is another type of remote sensing.

Does this thermometer belong to remote sensing?

(Photo credits: google image, amazon, Walgreen)

Satellite Retrieval

$$\begin{bmatrix} y_1 \\ y_2 \\ \dots \\ y_n \end{bmatrix} = f \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_n \end{bmatrix}$$

Satellite Measure ments

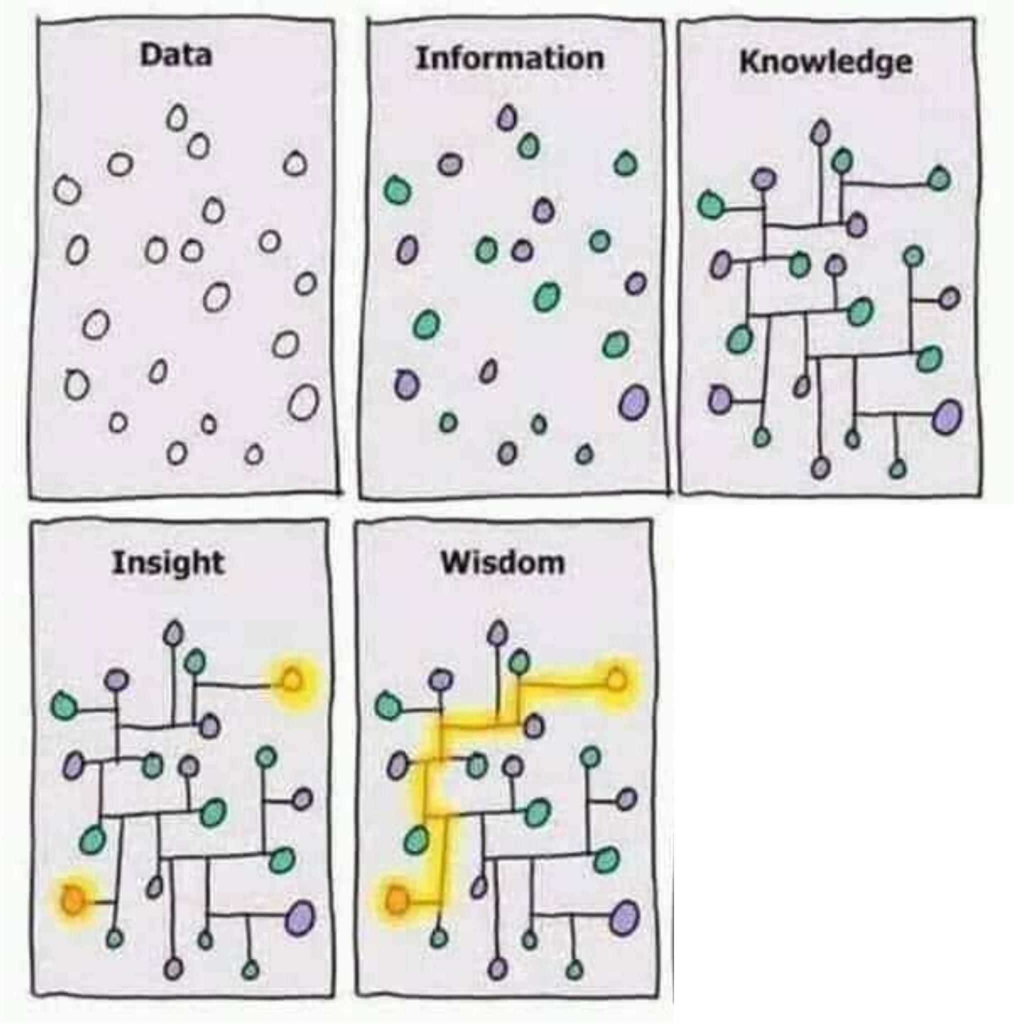
Geophysical Variables

- y: satellite direct measured quantities, such like radiance measured at different channels, photon counts, reflectance, …
- x: geophysical variables, such like temperature, water vapor, CO2, sea ice cover, aerosol optical depth, ice cloud particle size, precipitation rate, …
- f: the operator to convert geophysical variables to satellite measurements

In the simplest case, if y = ax +b, then we can easily derive the geophysical variable x = (y-b)/a

Satellite Retrieval

- However…

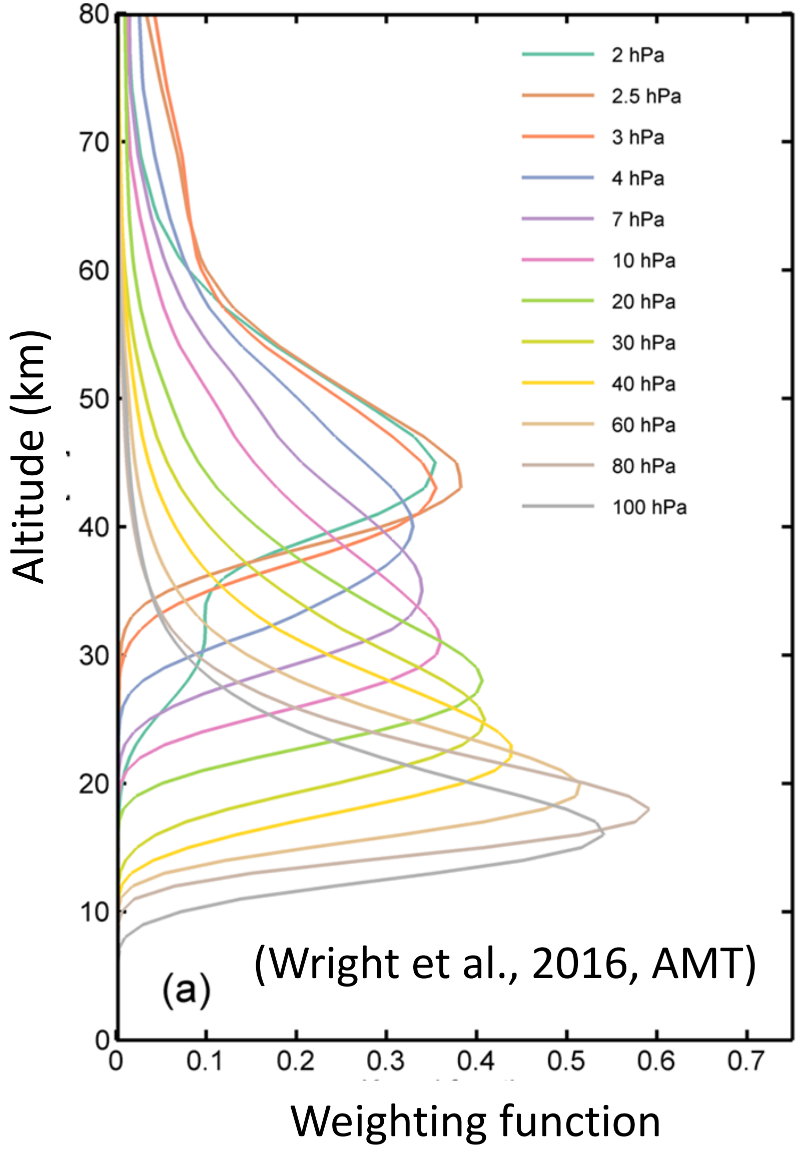


(Photo credit: google image)

$$\begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_n \end{bmatrix} = f^{-1} \begin{bmatrix} y_1 \\ y_2 \\ \dots \\ y_n \end{bmatrix}$$

- The f operator could be a complicated radiative transfer model, an empirical data-based model, a machine-learning model, etc.

An example for Atmospheric Infrared Sounder (AIRS) temperature retrieval



Level 1 Level 2

$$\begin{bmatrix} TB_1 \\ TB_2 \\ \dots \\ TB_n \end{bmatrix} = \begin{bmatrix} w_1(z) \\ w_2(z) \\ \dots \\ w_n(z) \end{bmatrix} T(z)$$

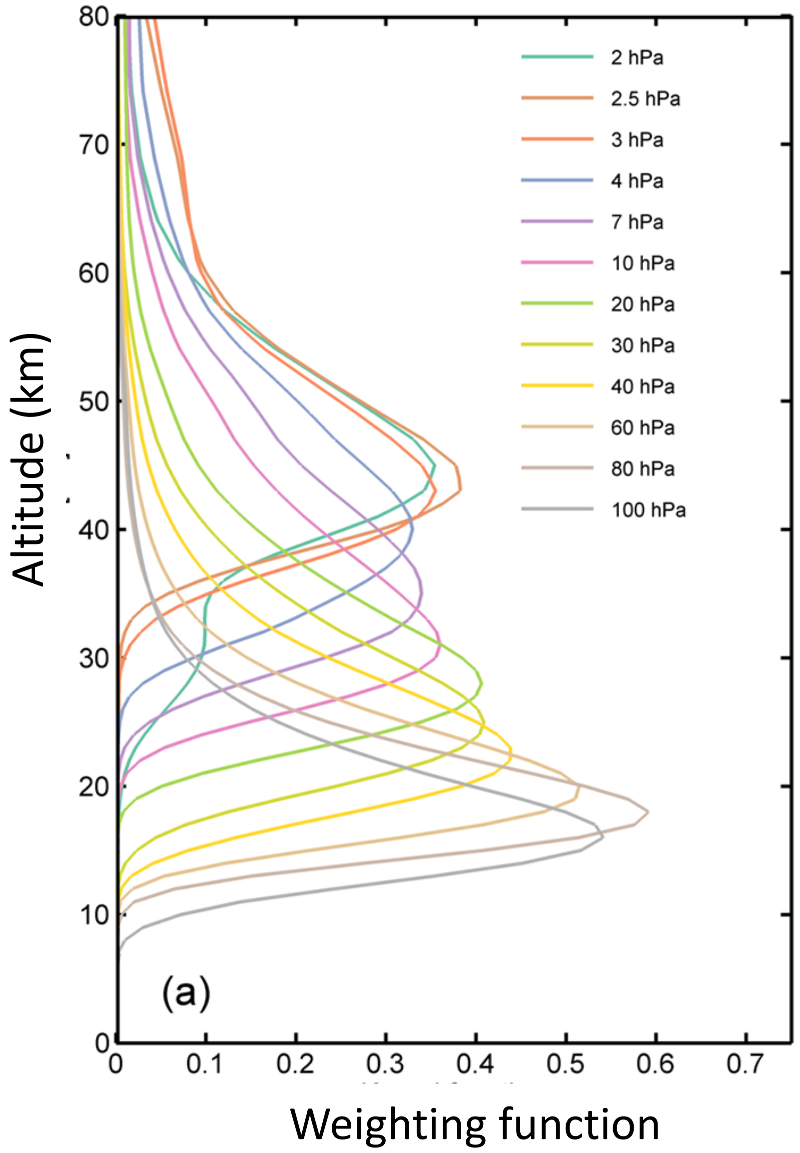
Temperature profile

Measured brightness temperature (TB) at Channel #1 to #n

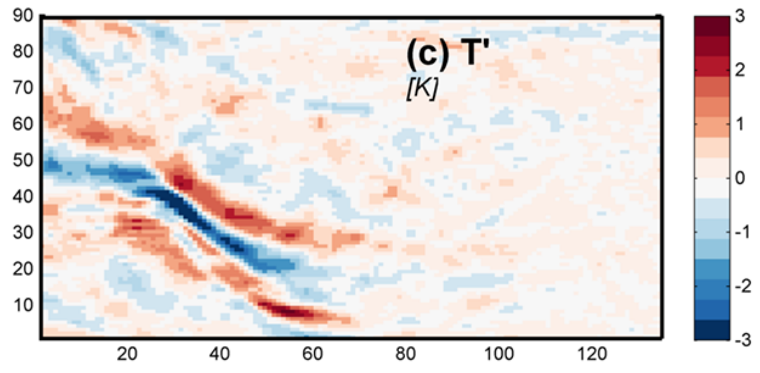
Weighting function for Channel #1 to #n

- How many vertical levels of temperature profile can be retrieved theoretically?

An example for Atmospheric Infrared Sounder (AIRS) temperature retrieval



- After retrieving the temperature profile, one needs to apply low-pass filter to remove "background" atmosphere at each level, so to let high-frequency small-scale gravity wave signals standing out.



(Wright et al., 2016, AMT)

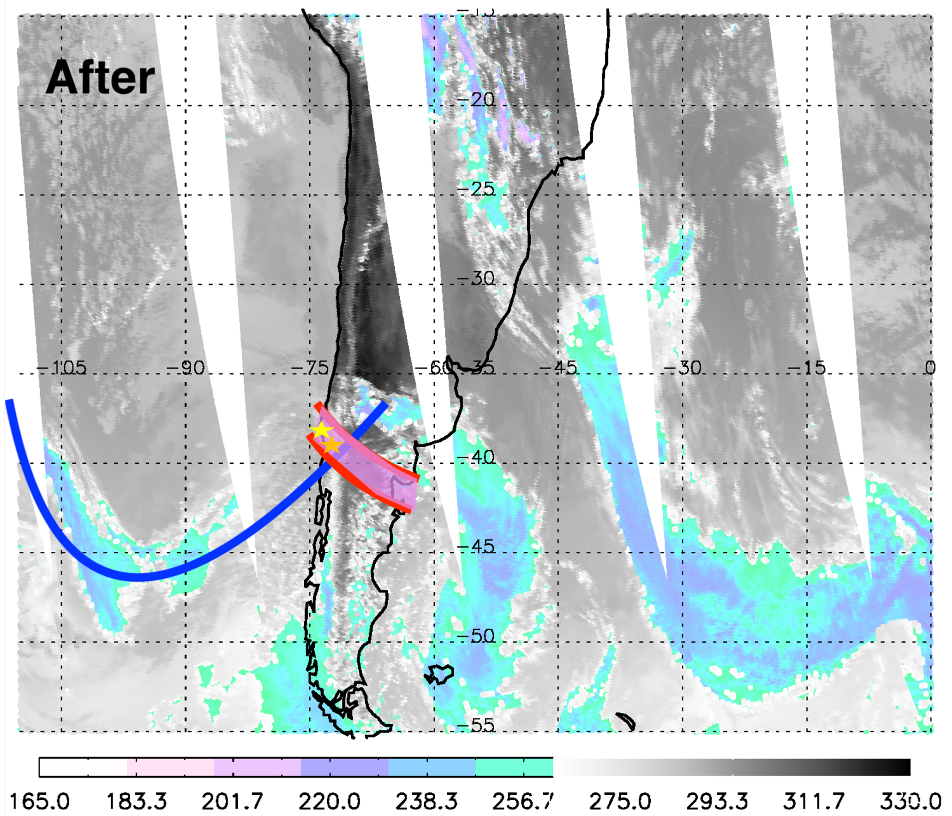
- However, retrieval process always unavoidably causes some information loss, or adding some more noises. Therefore, it's not always ideal to use the retrieved temperature for studying small-scale features like gravity waves.
- Instead, we can directly use the measurements to extract the small-scale weak information.

Solar eclipse – gravity waves are relatively weak signals

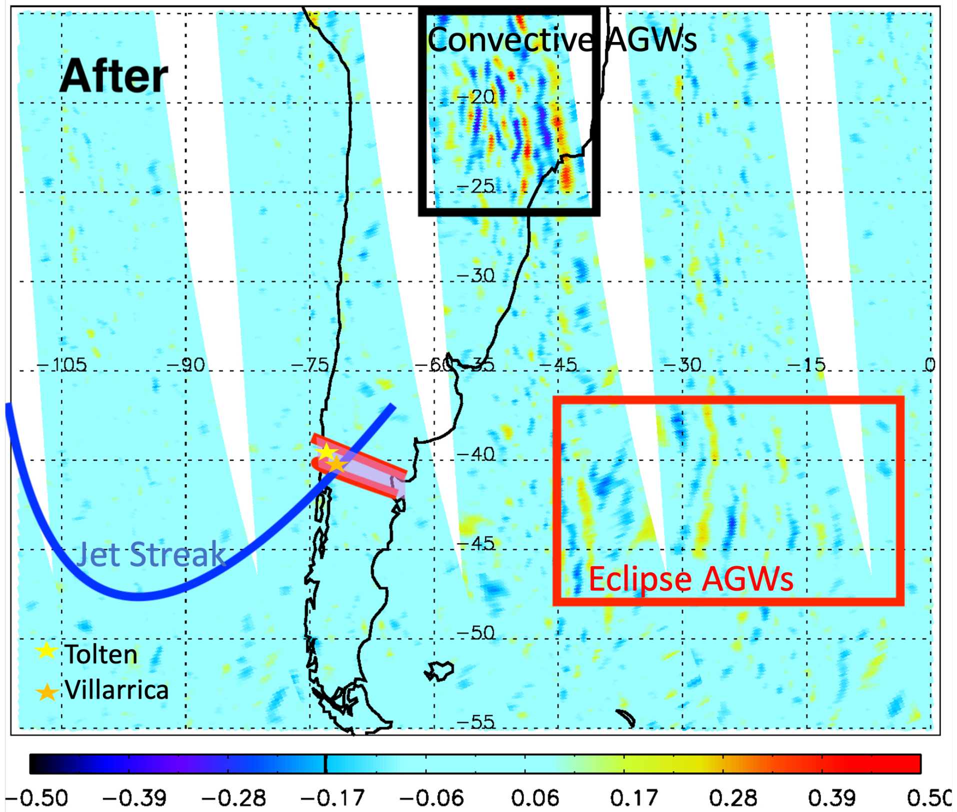
December, 2020 Total solar eclipse

Level 1 brightness temperature perturbation

(a) Weather systems in the troposphere

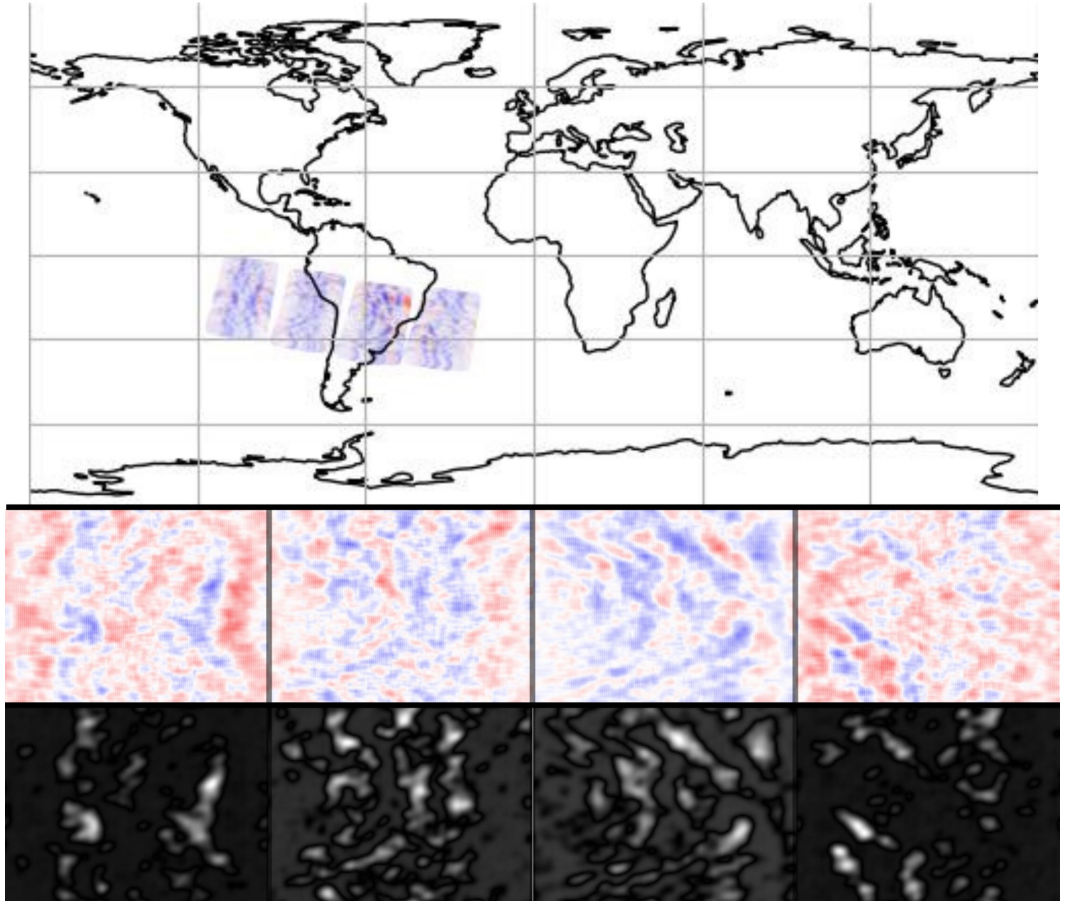


(b) 10 hPa AGW packets ~ 2 hours after the TSE

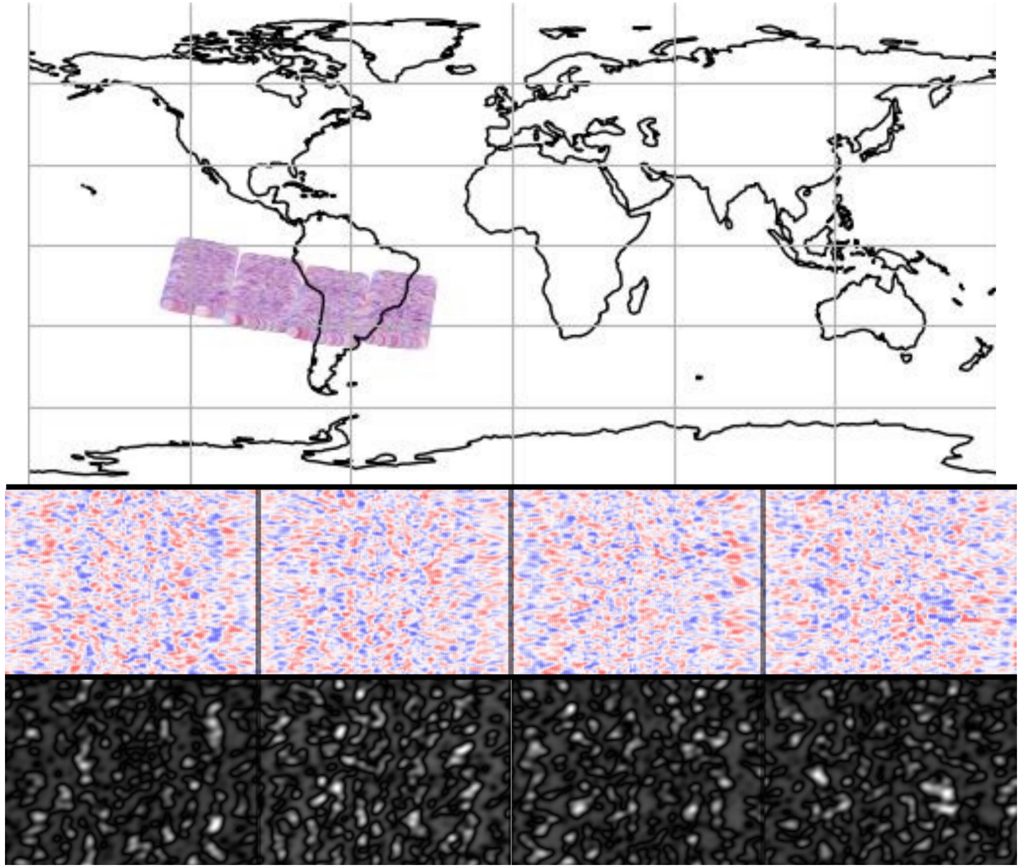


Solar eclipse – gravity waves are relatively weak signals

AIRS Level 1 brightness temperature perturbation



CrIS Level 2 retrieved temperature perturbation

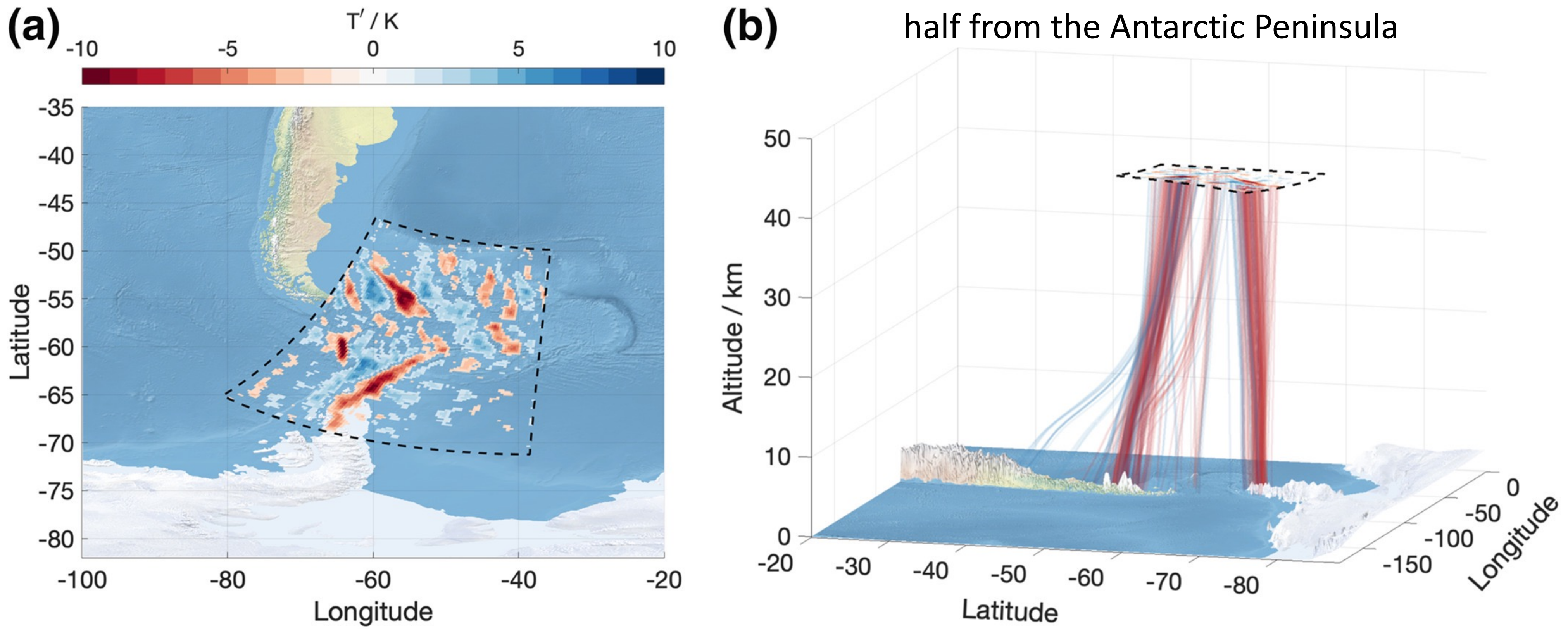


(Credit: Linkai Wu @ MBHS)

How to identify the gravity wave source? – Back-trajectory ray tracing

Mountain gravity waves seen by AIRS images

Back-trajectory ray-tracing identified half of the waves originated from the Andes, and the other half from the Antarctic Peninsula

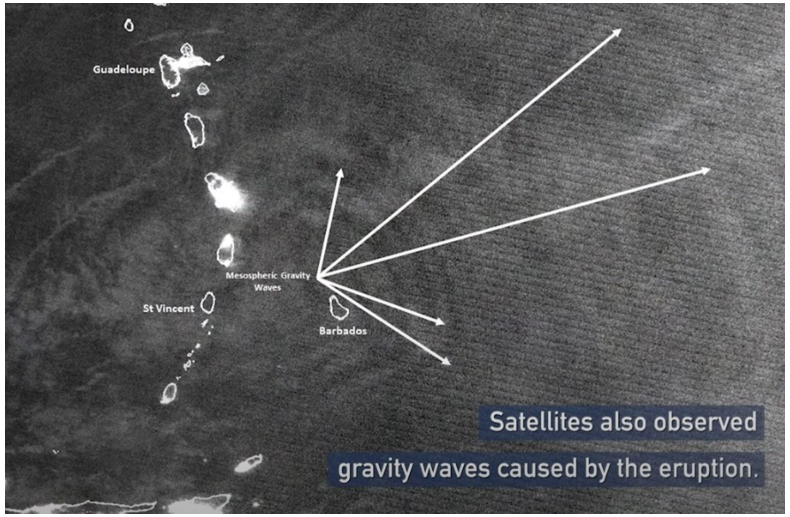


(Perrett et al., 2020, GRL)

How to identify the gravity wave source? – Clues from the wave morphology

La Soufriere volcano eruption – credit: NOAA
(If you can't click the link, the video is at https://www.youtube.com/watch?v=OUZqOubZEs0)

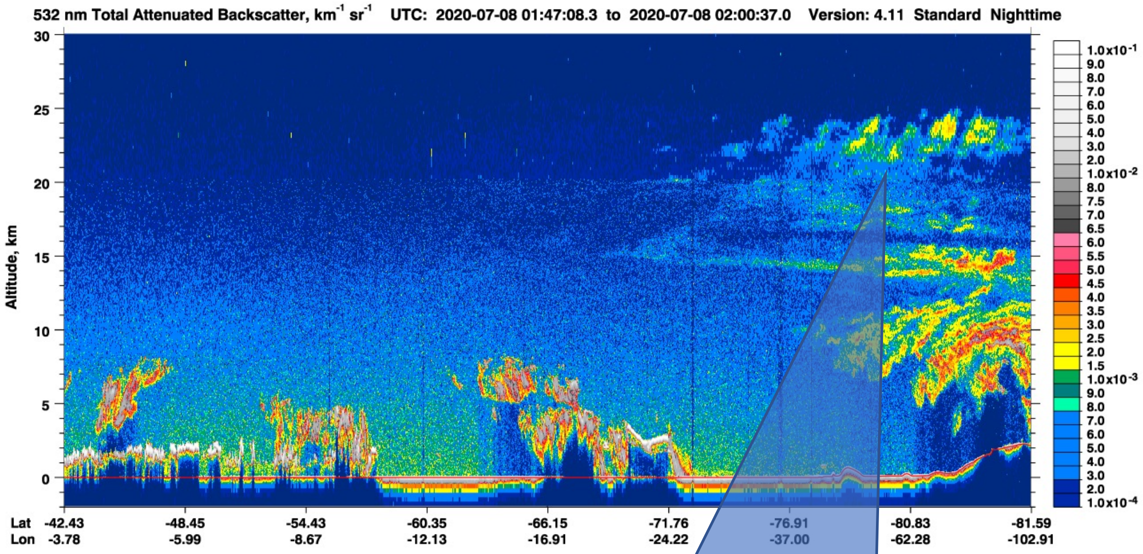
At the tropopause (~ 12 km): gravity wave modulating plume structure



In the mesosphere (~ 87 km): Gravity wave rings can be seen against city light background

Gravity wave structures can be seen sometimes in other phenomena

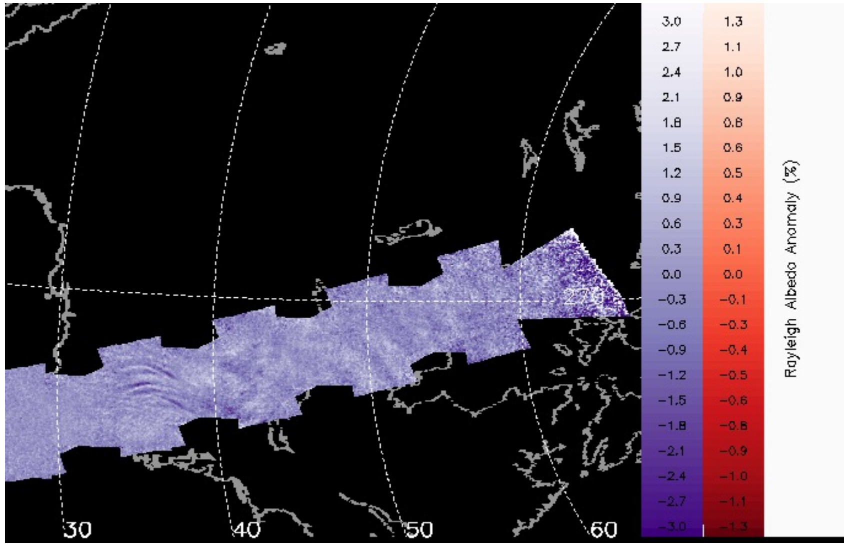
Winter polar stratospheric cloud (PSC)



For active sensor such like radar or lidar, vertical structures can be retrieved

(See Lecture Part 1 for picture origins)

Summer polar mesospheric cloud (PMC)

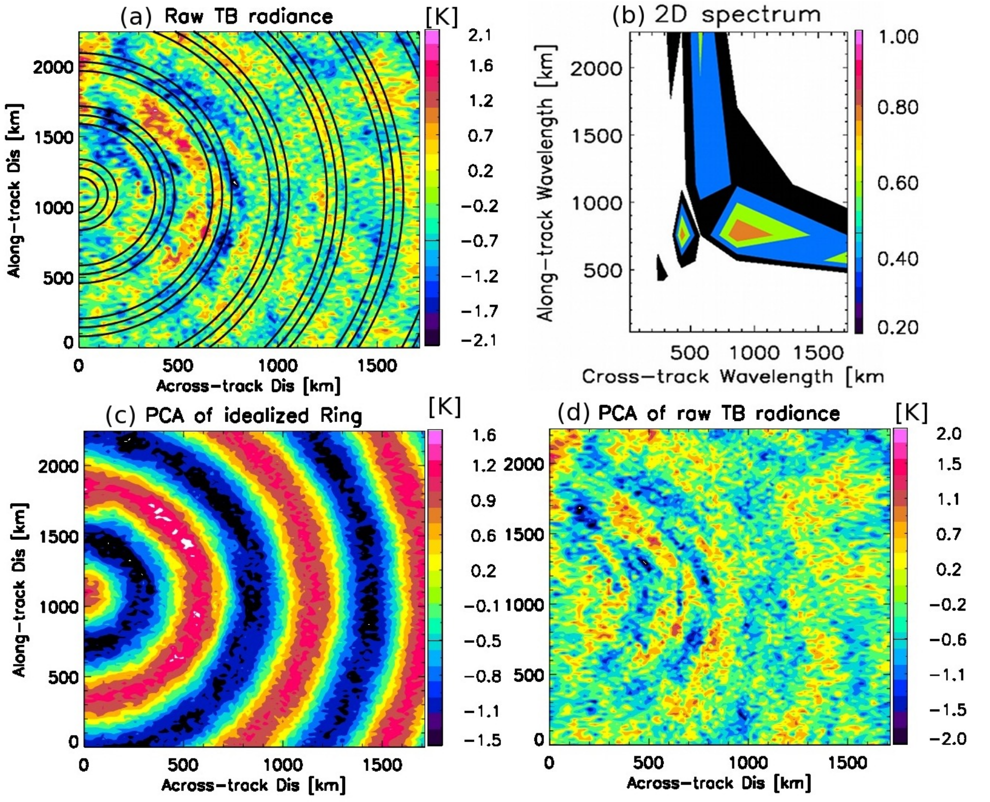


Lenticular cloud over mountain

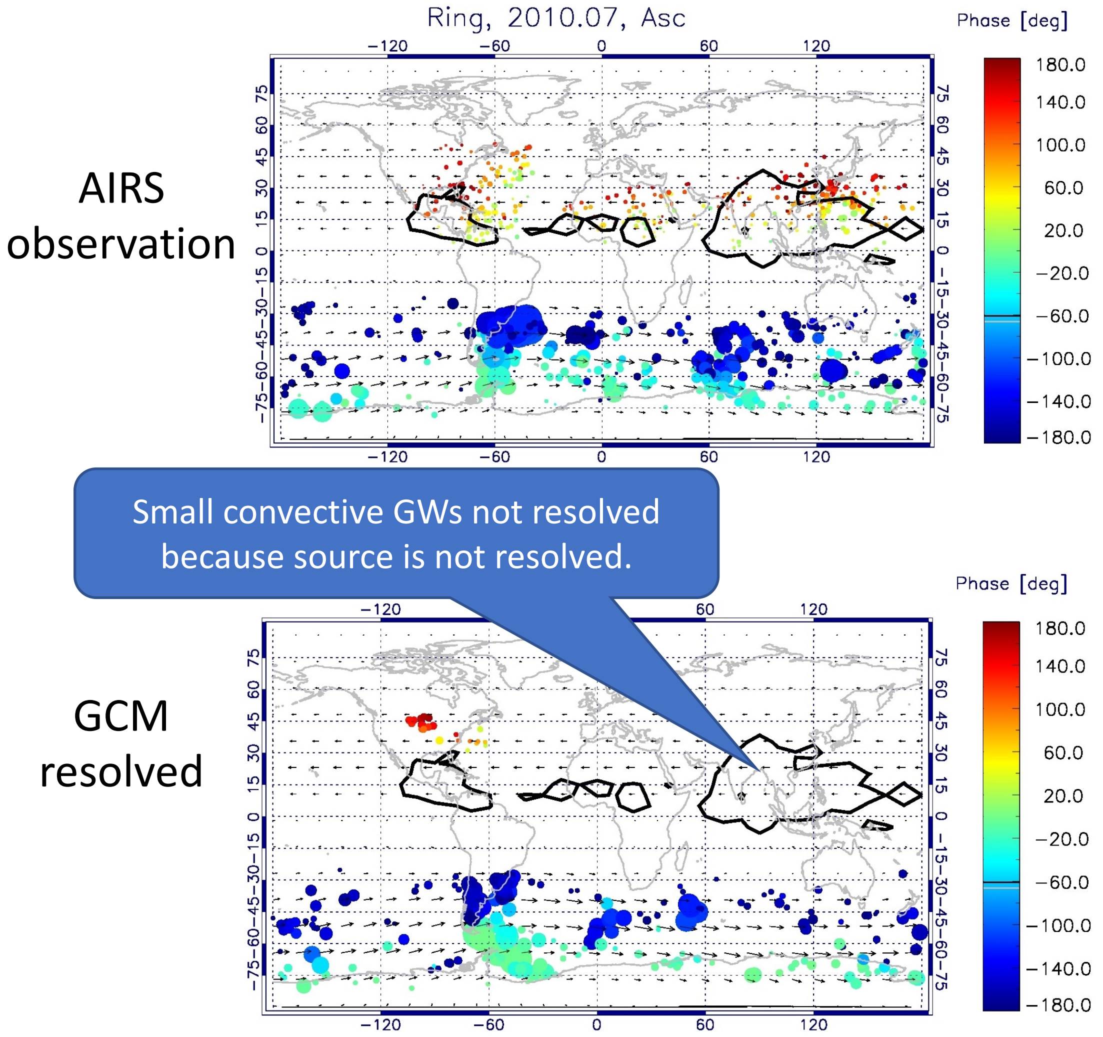
How to identify the gravity wave source? – Clues from the wave morphology

(Gong et al., 2015, JGR)

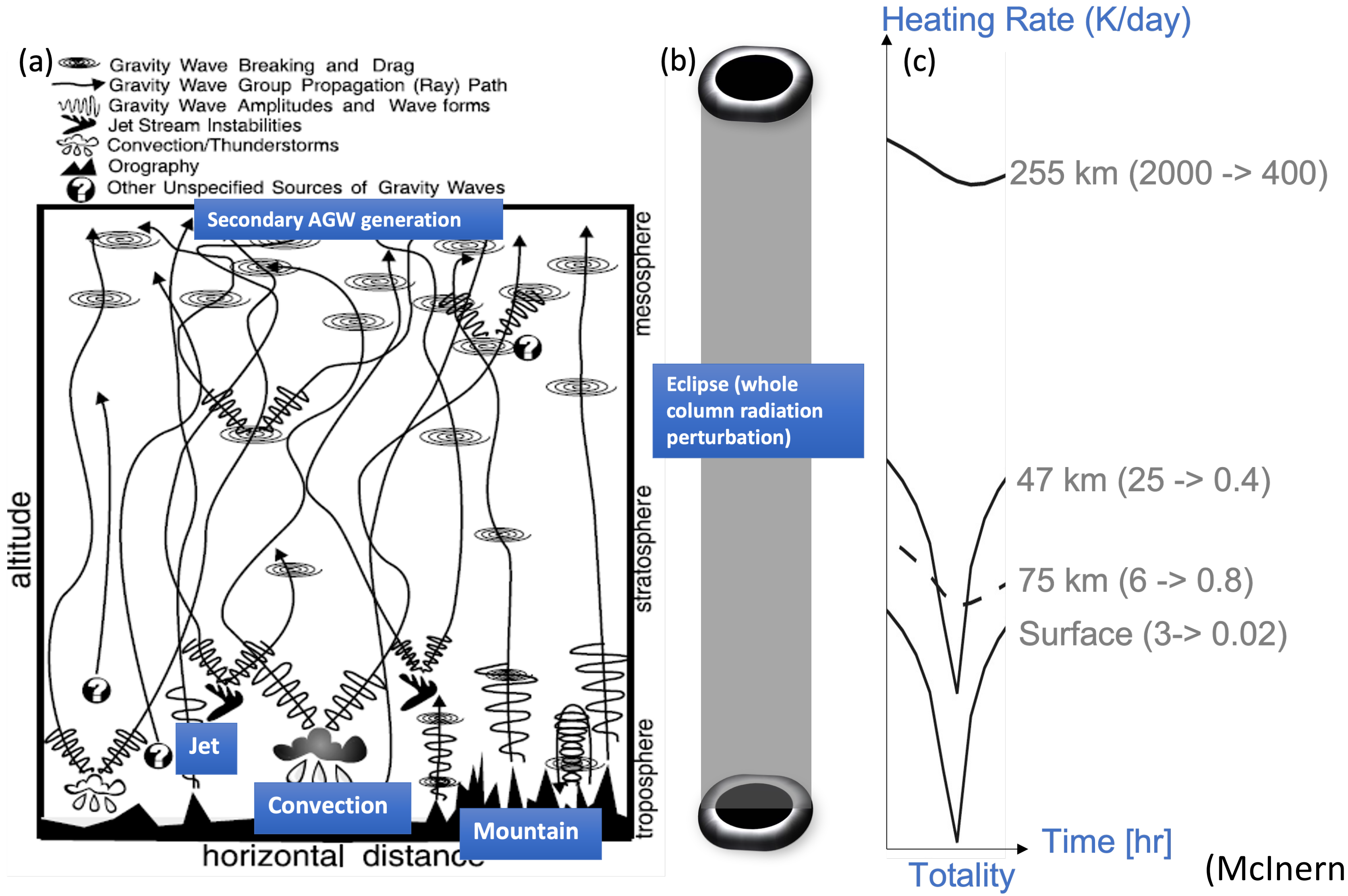
- How I identify the "half-ring" gravity waves by fitting a circle around the frame



- Now we can use machine learning approach to identify ring structures.



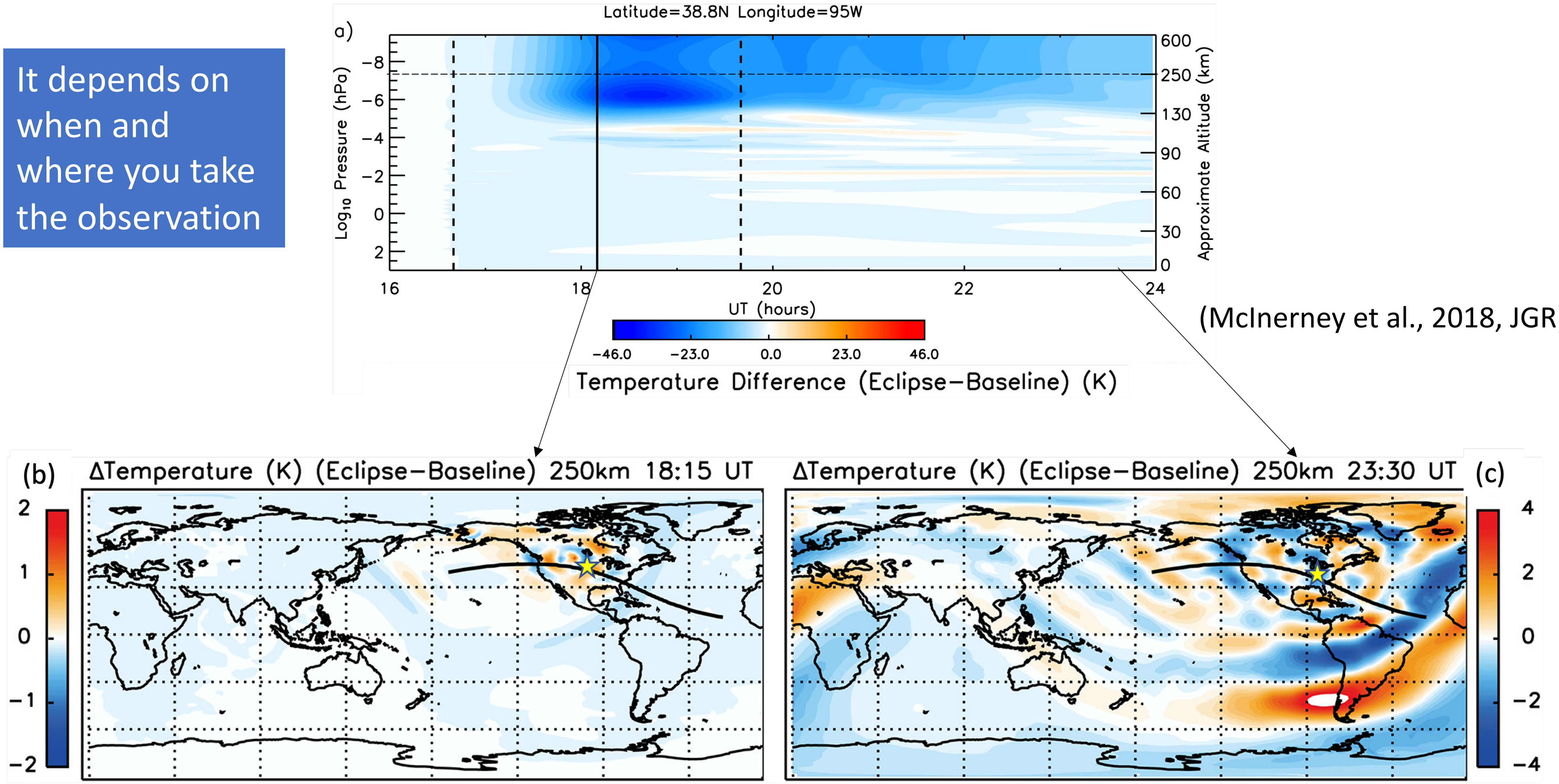
Now come back to the solar eclipse gravity waves: do you think they have ring structures?



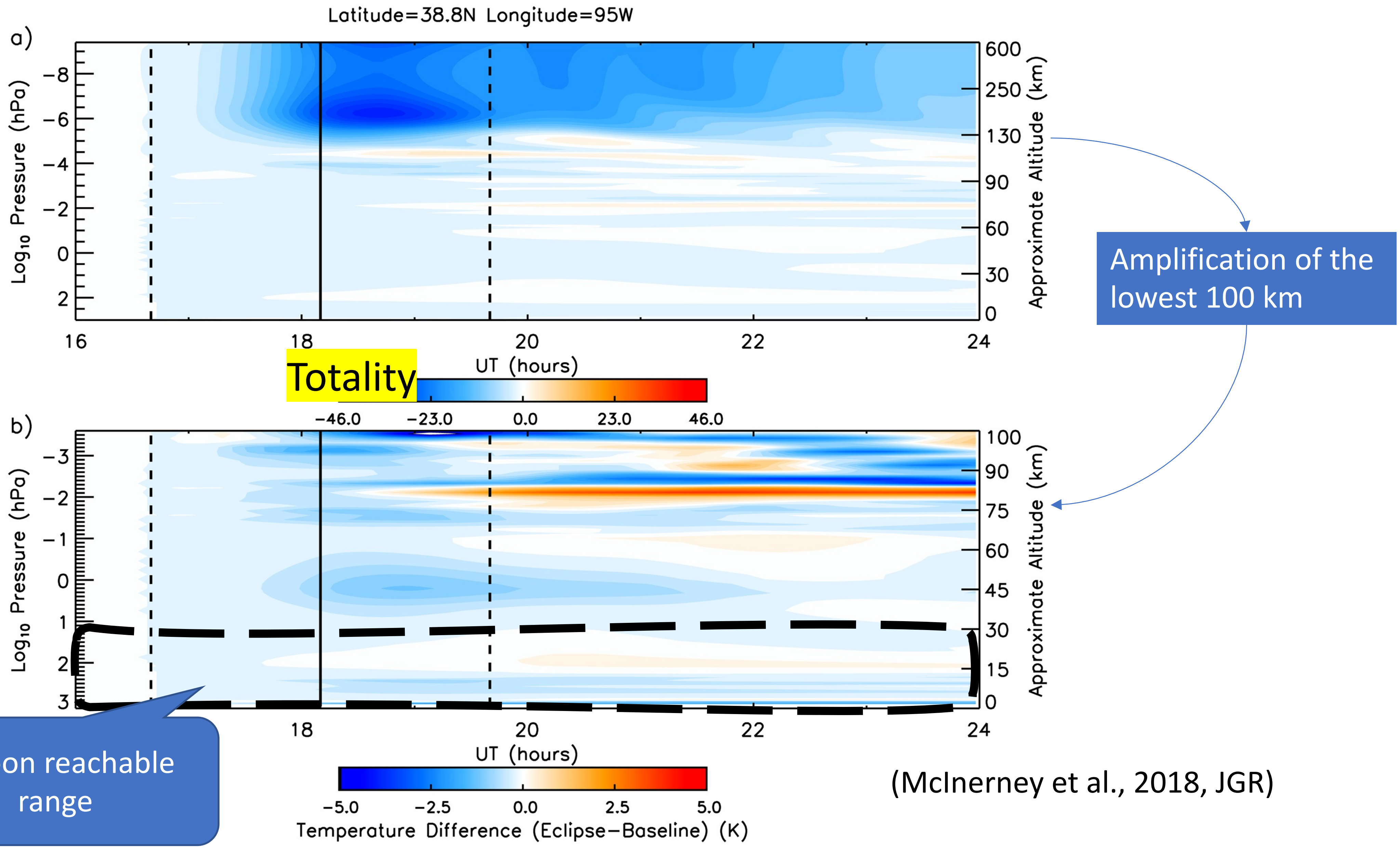
(McInerney et al., 2018, JGR)

Simulation of the 2017 total eclipse

It depends on when and where you take the observation

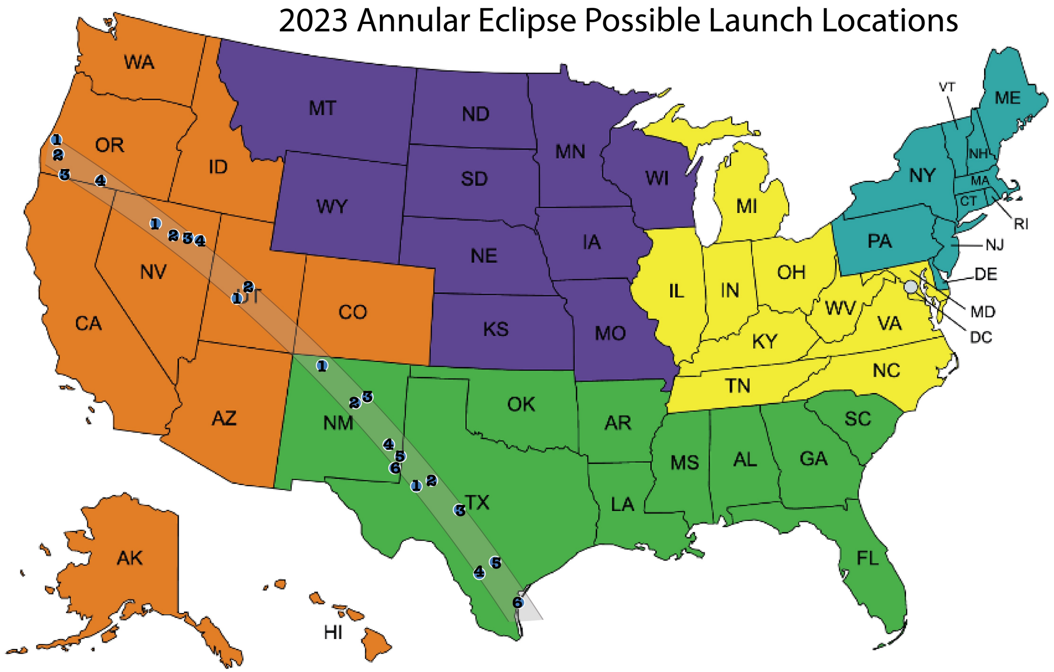


(McInerney et al., 2018, JGR)



(McInerney et al., 2018, JGR)

Possible radiosonde launching locations



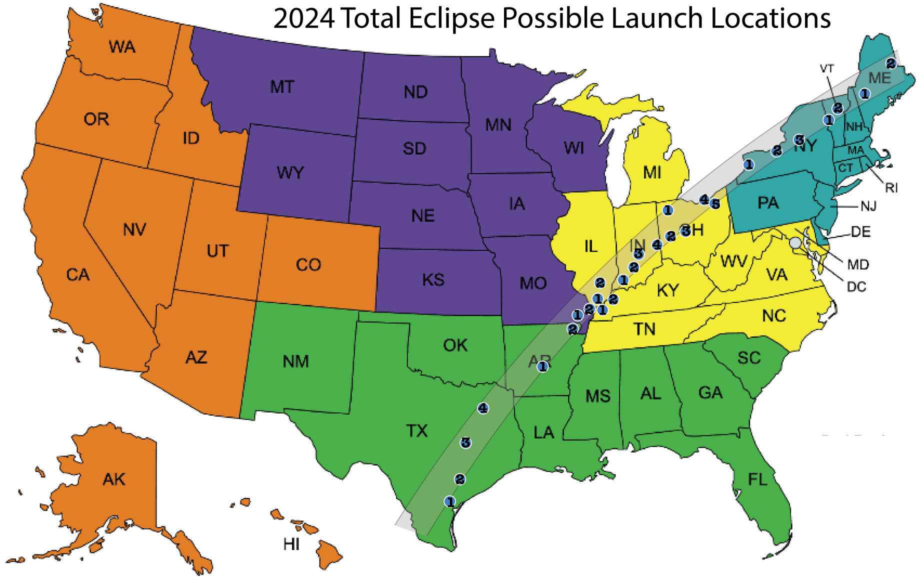
OREGON
1. Corvallis
2. Eugene
3. Medford
4. Lakeview

NEVADA
1. Winnemucca
2. Carlin
3. Elko
4. Wells

UTAH
1. Beaver
2. Richfield

NEW MEXICO
1. Farmington
2. Albequerque
3. Santa Fe
4. Roswell
5. Hobbs
6. Carlsbad

TEXAS
1. Odessa
2. Midland
3. San Angelo
4. Uvalde
5. San Antonio
6. Corpus Christi



NEW YORK
1. Buffalo
2. Rochester
3. Syracuse

INDIANA
1. Jasper
2. Bloomington
3. Indianapolis
4. Richmond

OHIO
1. Toledo
2. Dayton
3. Columbus
4. Cleveland
5. Akron

TEXAS
1. San Antonio
2. Austin
3. Waco
4. Dallas/Fort Worth

KENTUCKY
1. Paducah
2. Henderson

ILLINOIS
1. Carbondale
2. Mt. Vernon

ARKANSAS
1. Conway
2. Jonesboro

MAINE
1. Greenville
2. Presque Isle

MISSOURI
1. Greenville
2. Cape Giradeau

VERMONT
1. Burlington
2. Stowe

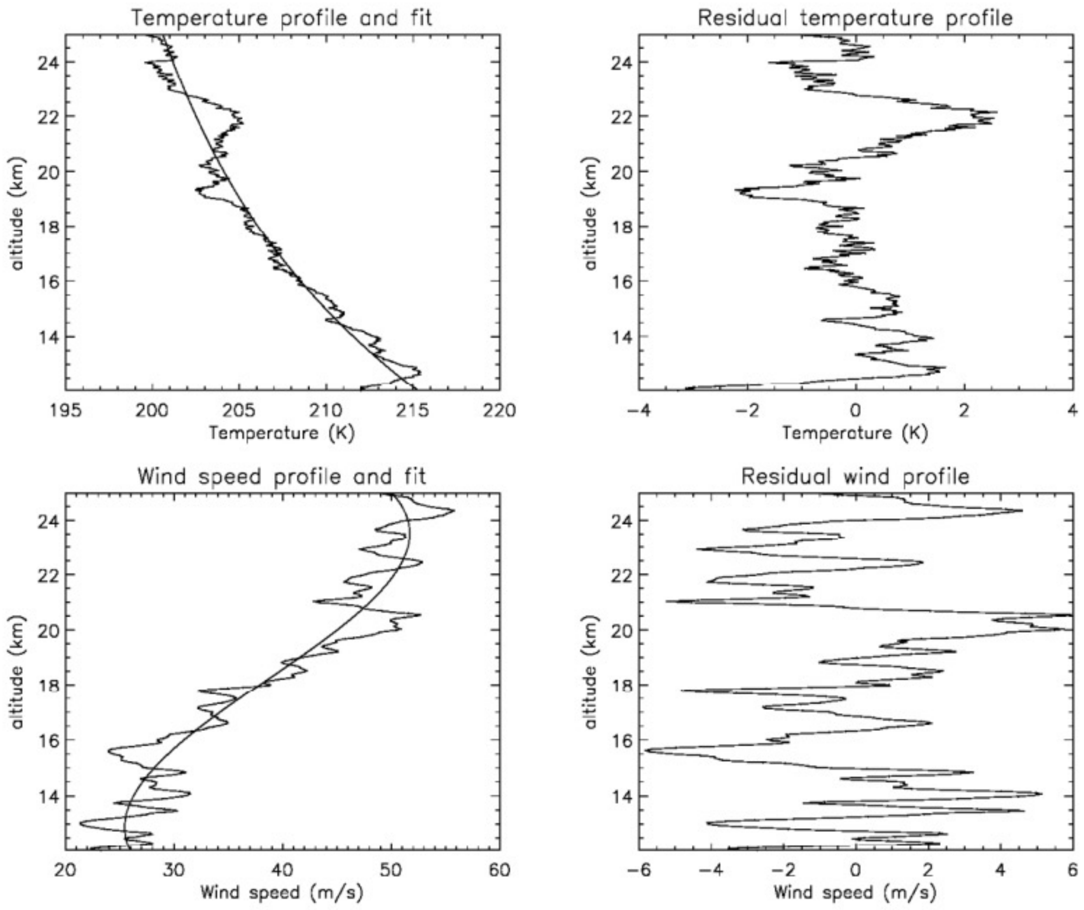
7. Radiosonde observations of gravity waves

- What variables does a radiosonde routinely measure?

  Wind (u, v, w), pressure (p), temperature (T), water vapor (wv), balloon ascending rate (asc)

- Gravity waves not only introduce temperature perturbation (T'), but also wind perturbation (u', v', w').

- The full relationship among u', v' and T' can help us retrieve the gravity wave parameters as they are tied by the wave dispersion relationship.



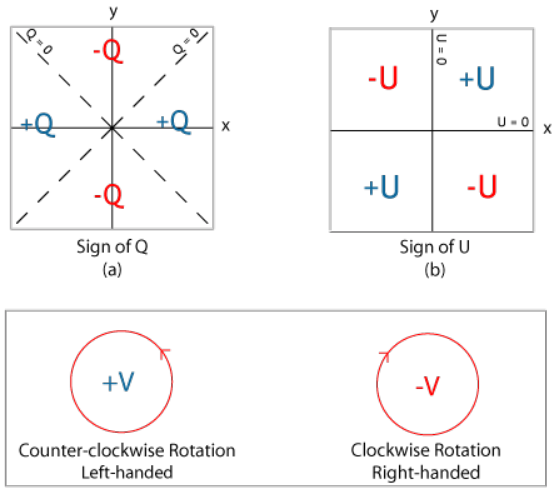
(Moffat-Griffin et al., 2020, GRL)

Polarization - the striking similarity between light and wave dynamics

Stokes parameters in electro-magnetic wave propagation

$$I \equiv \langle E_{x/a/r}^2 \rangle + \langle E_{y/b/l}^2 \rangle$$
$$Q \equiv \langle E_x^2 \rangle - \langle E_y^2 \rangle$$
$$U \equiv \langle E_a^2 \rangle + \langle E_b^2 \rangle$$
$$V \equiv \langle E_r^2 \rangle - \langle E_l^2 \rangle$$

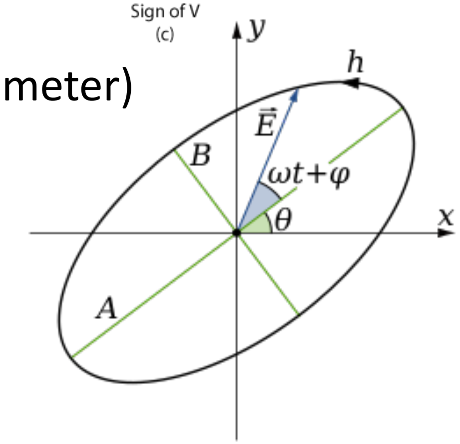
$$\hat{l} = \frac{\hat{x} + i\hat{y}}{\sqrt{2}}, \hat{r} = \frac{\hat{x} - i\hat{y}}{\sqrt{2}}$$



Sign of V
(c)

(Source: Wikipedia – Stokes parameter)

$$DoLP = \frac{Q^2 + U^2 + V^2}{I^2}$$



Stokes parameters in gravity wave

$$I \equiv \langle \widehat{u'}\widehat{u'}^* \rangle + \langle \widehat{v'}\widehat{v'}^* \rangle$$
$$D \equiv \langle \widehat{u'}\widehat{u'}^* \rangle - \langle \widehat{v'}\widehat{v'}^* \rangle$$
$$P \equiv 2Re \langle \widehat{u'}^*\widehat{v'} \rangle$$
$$Q \equiv 2Im \langle \widehat{u'}^*\widehat{v'} \rangle$$

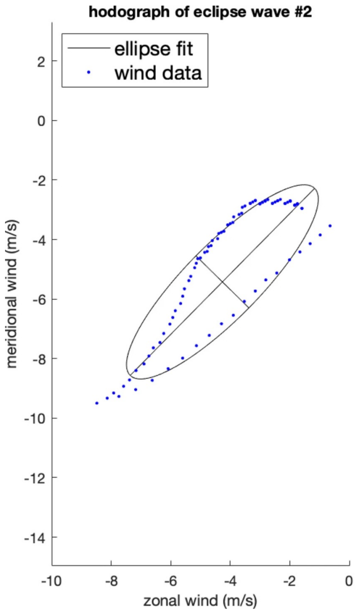
$$DoLP = \frac{D^2 + P^2 + Q^2}{I^2}$$

$\widehat{u'}$: *Fourier transformed field*

*: harmonic conjugate

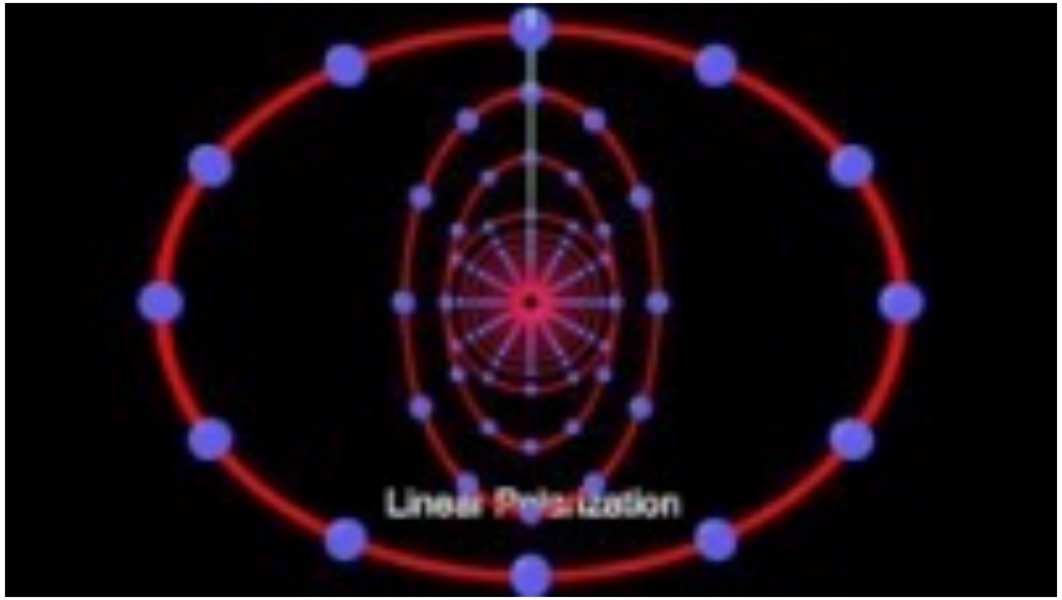
Re/Im: Real/Imaginary part

(Eckermann, 1996, JGR)



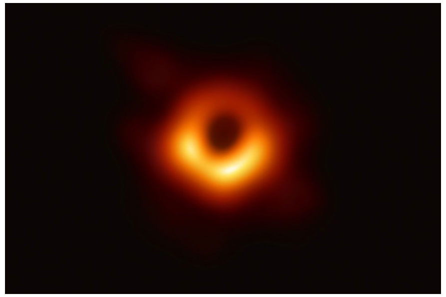
(Colligan et al., 2020, Sci. Rep.)

- This short introduction video of polarizations of waves apply to electro-magnetic wave, gravity wave, and gravitational wave.



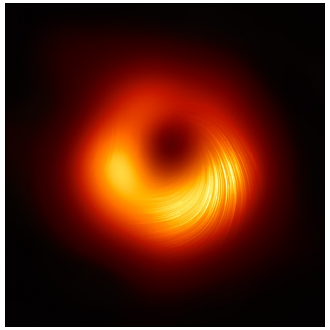
(If it doesn't play properly, please visit https://www.youtube.com/watch?v=F4stTzxYrN0)

Question for you: do you think atmospheric gravity waves are usually linearly or circularly polarized? Why? What about sunlight?



Black hole M87

(https://news.mit.edu/2019/mit-haystack-first-image-black-hole-0410)



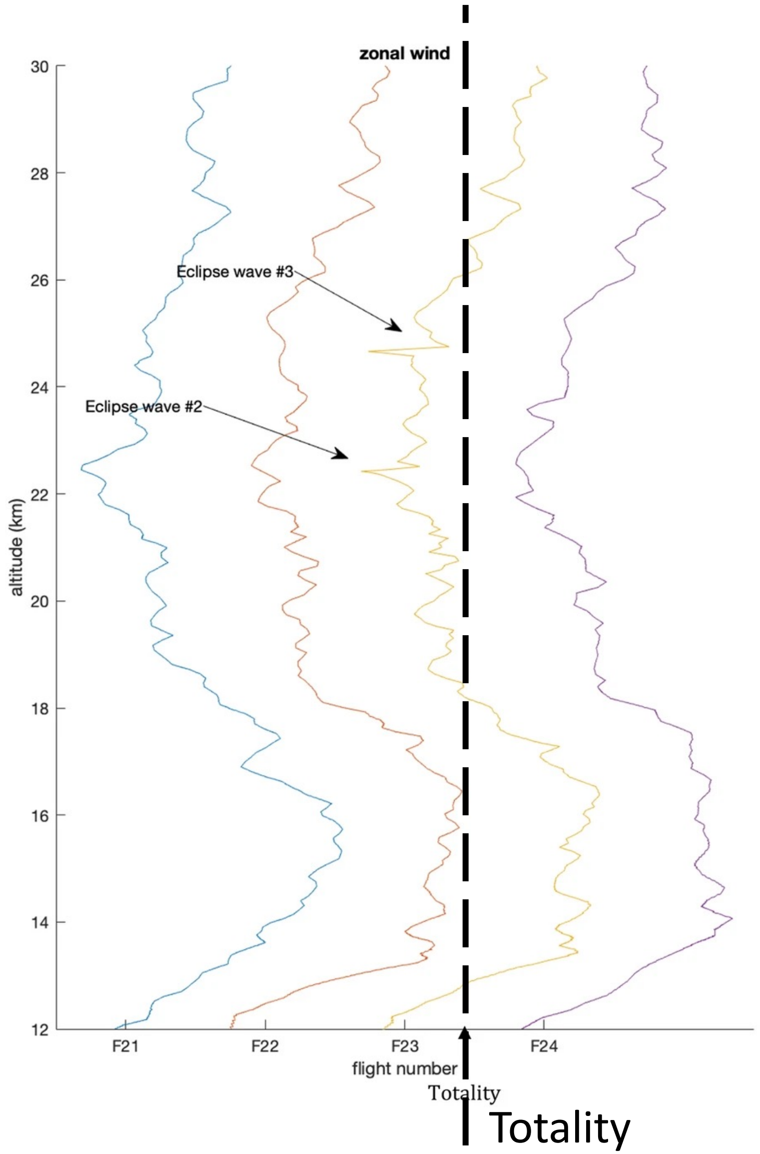
Black hole M87 seen by a polarized camera revealing details of magnetic fields

(https://news.mit.edu/2021/astronomers-image-magnetic-fields-edge-m87s-black-hole-0324#:~:text=Specifically%2C%20polarization%20allows%20astronomers%20to,extreme%20environments%20in%20the%20universe)

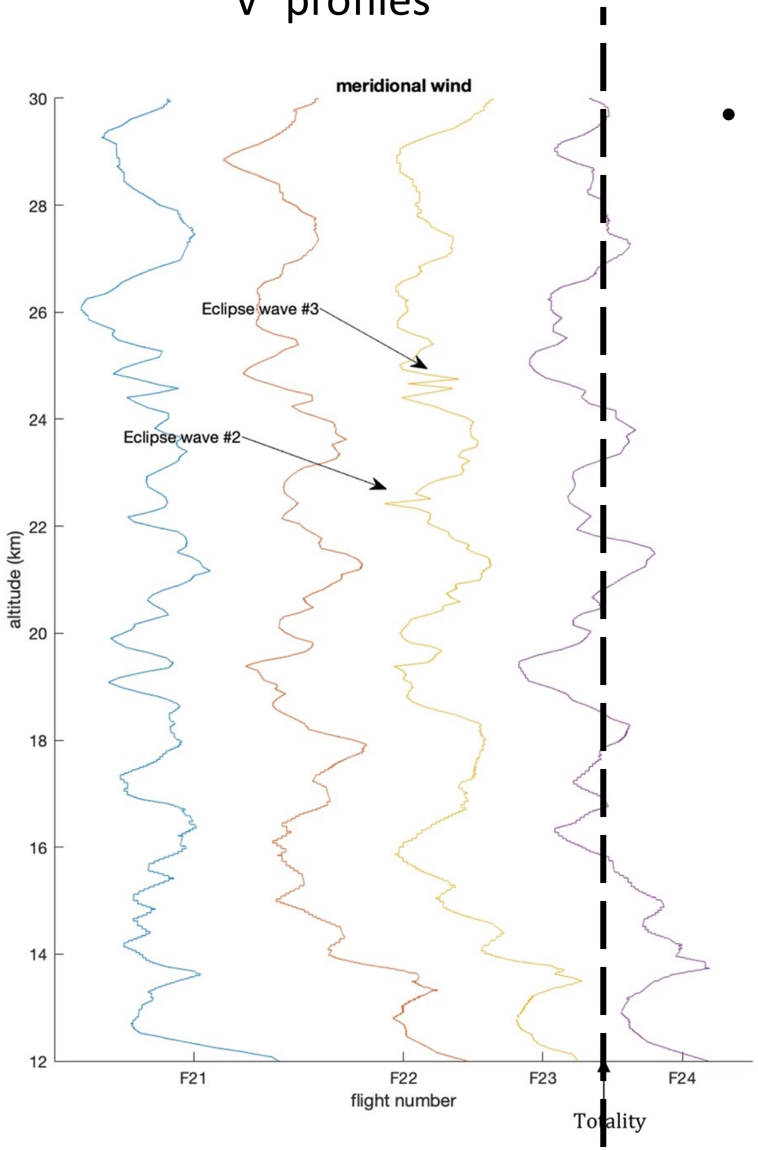
How to derive all gravity wave parameters from a single radiosonde profile?

- $DoLP = \frac{D^2+P^2+Q^2}{I^2} = \left|\frac{\hat{\omega}}{f} - \frac{1}{\bar{N}}\frac{dV_T}{dz}\right|$, from this relationship we can calculate the wave intrinsic frequency $\hat{\omega}$.
- Vertical wavelength (1/m) is inferred from Fourier spectrum of T’.
- $m^2 = \frac{(N^2-\hat{\omega}^2)K^2+(f^2-\hat{\omega}^2)\cdot\frac{1}{4H_\rho^2}}{\hat{\omega}^2-f^2}$. Since we know m and $\hat{\omega}$, we can derive horizontal wavelength (1/K).
- Kinetic energy = $\frac{1}{2}(\overline{u'^2} + \overline{v'^2})$, potential energy = $\frac{g^2}{2\bar{N}^2}\overline{\left(\frac{T'}{\bar{T}}\right)^2}$
- Momentum flux $= -\frac{\rho\hat{\omega}g}{\bar{N}^2}\overline{u'\widehat{T_{+90}}'}(1 - f^2/\hat{\omega}^2)$.
- Two more equations to solve upward propagation fraction and phase propagation direction (omitted).

U' profiles

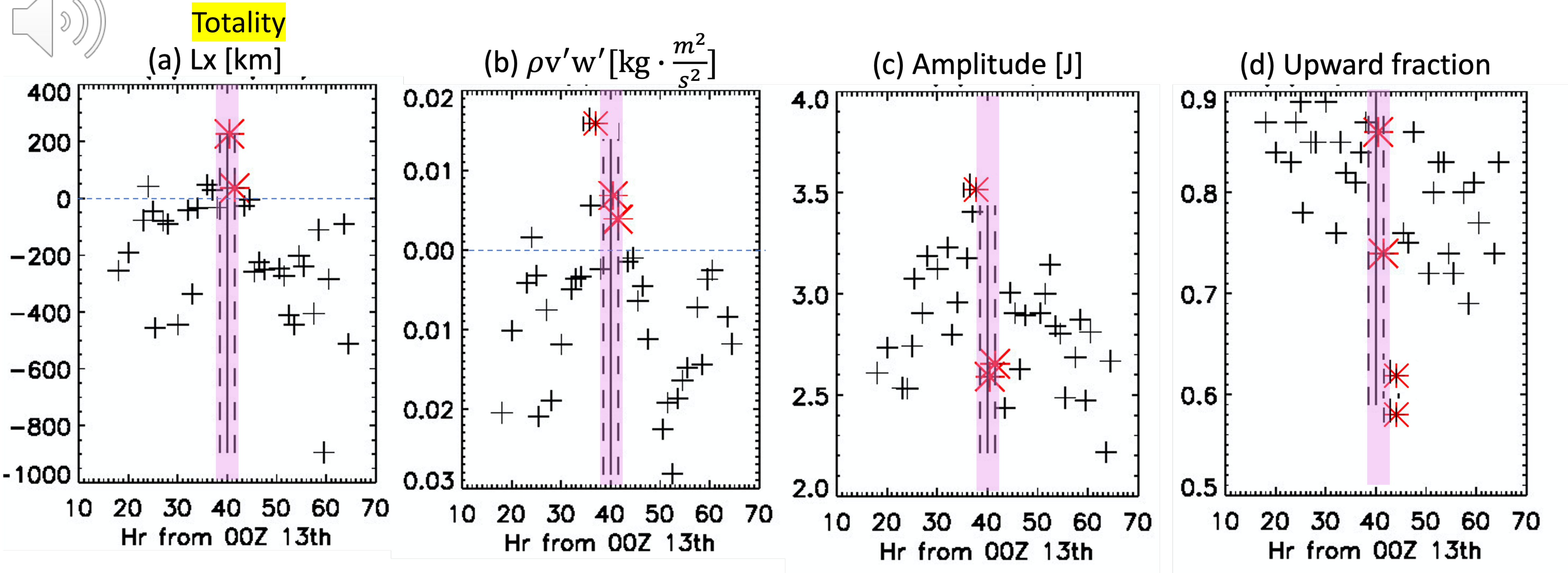


V' profiles

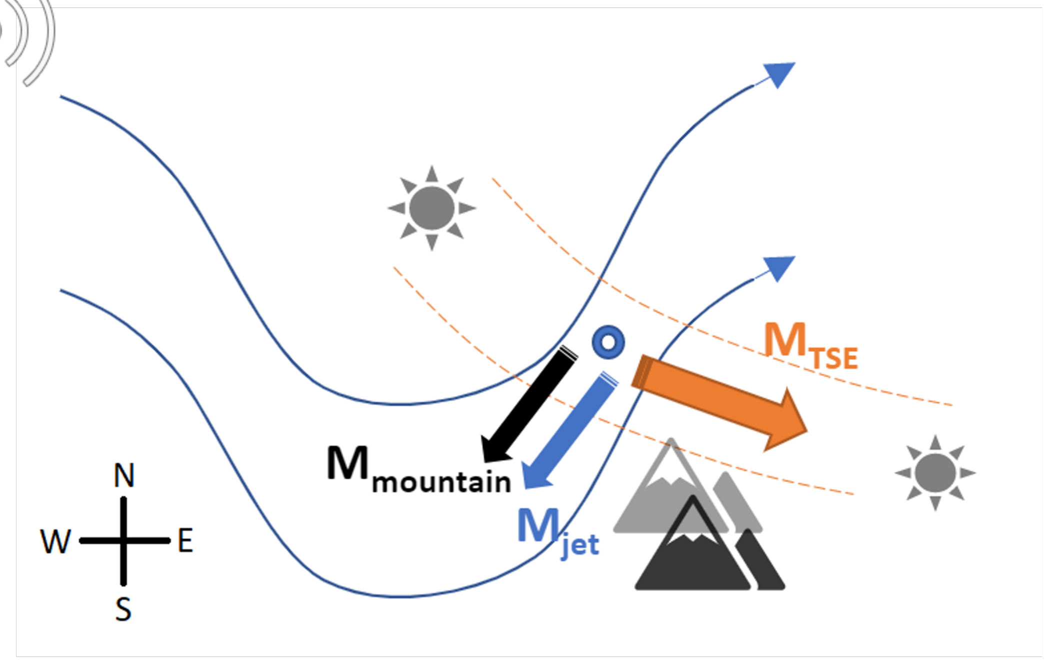


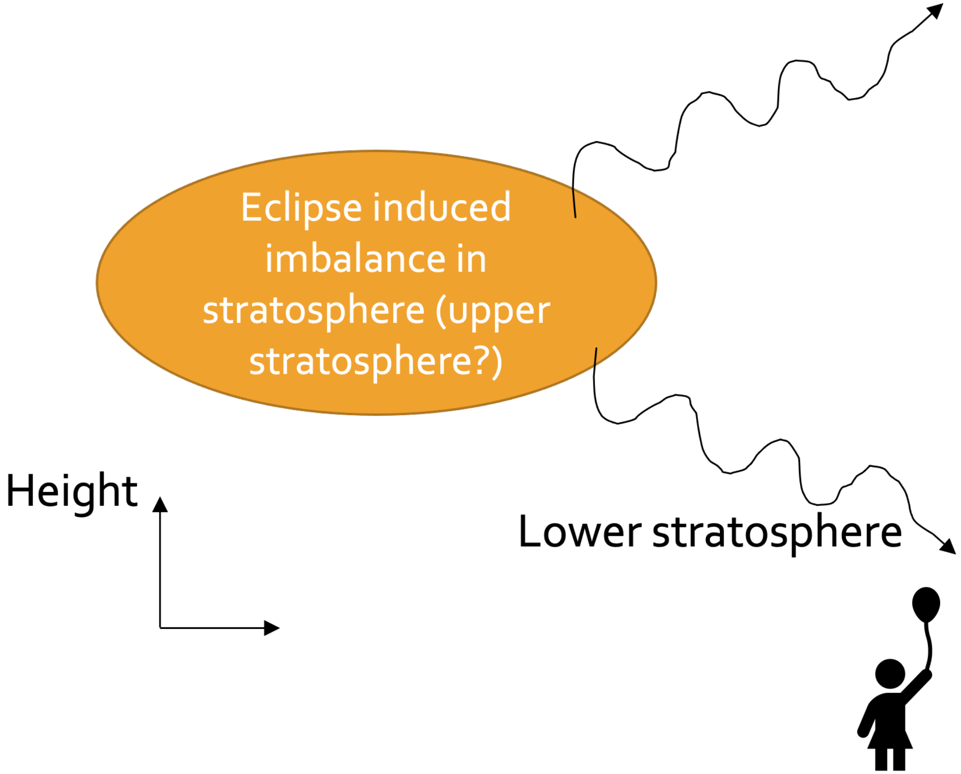
- This study from the 2017 totality campaign suggests eclipse-gravity waves were detected ~ 1 hours before the arrival of totality.

(Colligan et al., 2020, Sci. Rep.)



- Our recent study suggests eclipse-gravity waves were excited 0 – 1 hours after the totality from the 2020 total solar eclipse campaign.
- A lot more details for you to explore and discover!



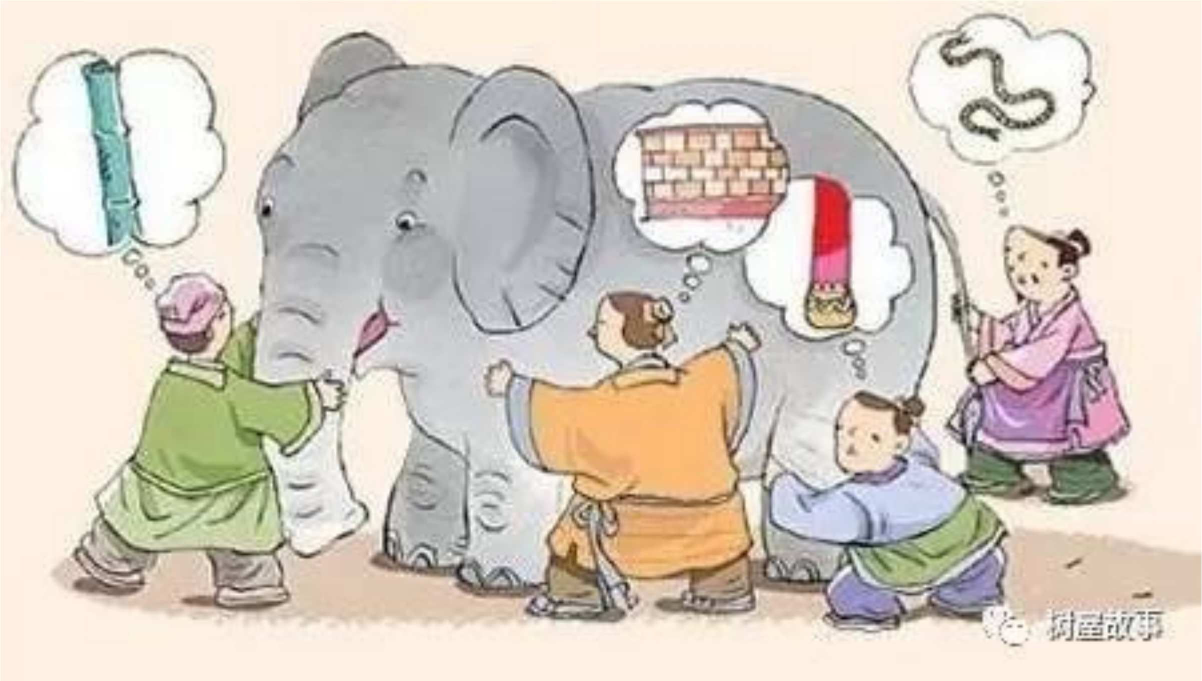


Bird-eye View

Side View

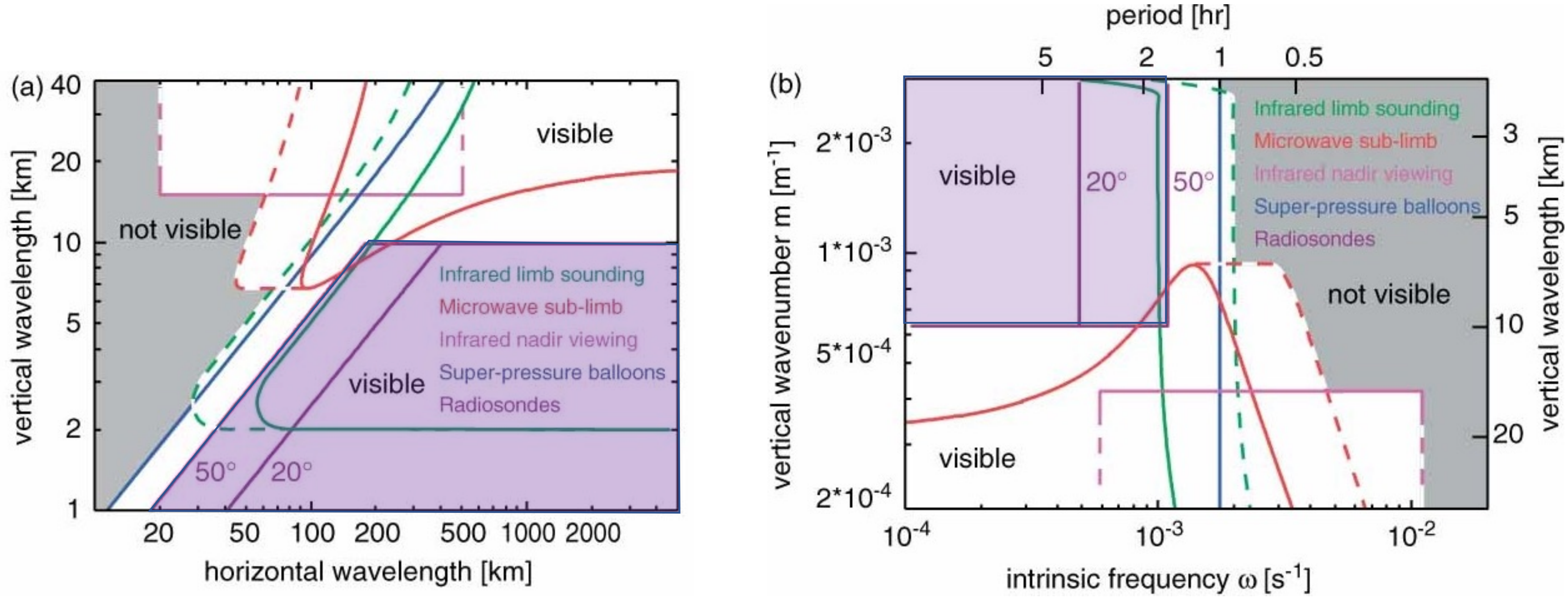
- In the last lecture, we discussed about gravity wave drag – it always tends to drag the mean flow toward its intrinsic phase speed when it was originated.
- According to the momentum flux we derived from radiosonde data during the 2020 eclipse event, the origin of the eclipse-gravity waves is hypothesized to be somewhere in the middle stratosphere or above.
- We need more observations during 2023 and 2024 campaign to help us solidify (or rule out) this hypothesis and help identify the exact source altitude.

8. Gravity wave observational window



- Blind men picturing what an elephant looks like in their mind
- It’s a commonality that people have biased opinions
- It’s also a commonality that each observational technique have biased views of the “nature” because of their limitation

8. Gravity wave observational window

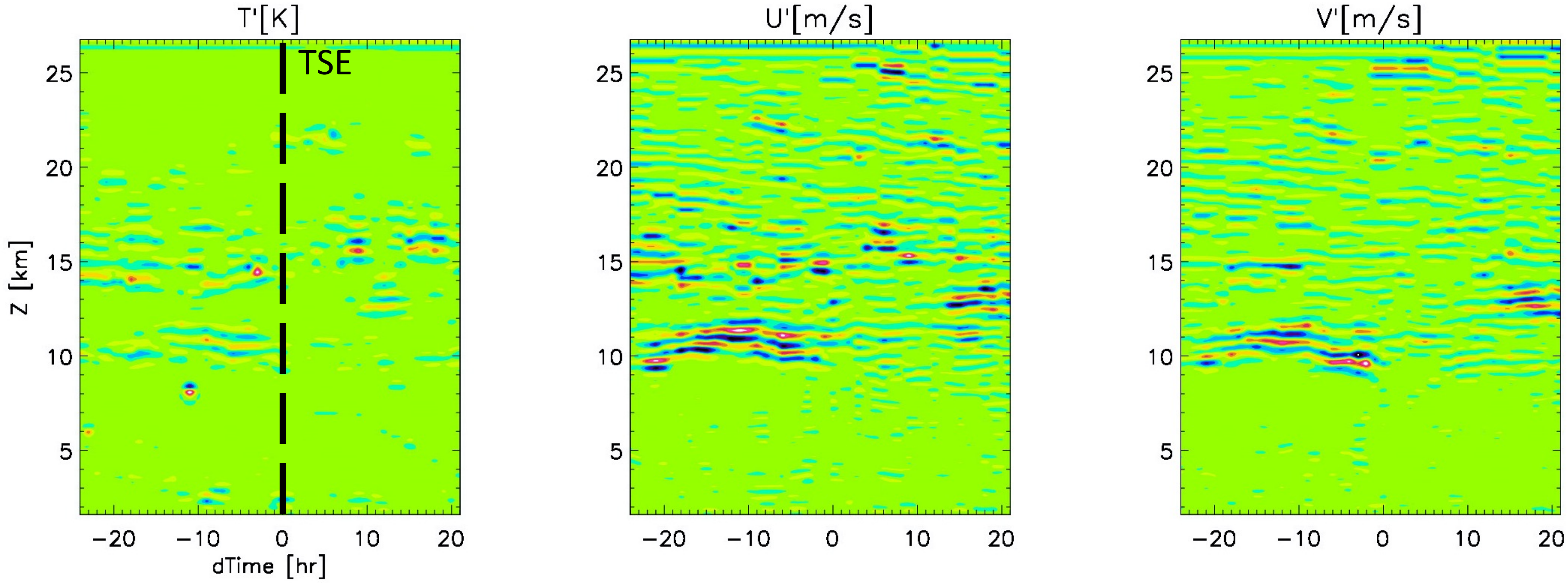


(Alexander et al., 2010, QJRMS)

- Radiosonde is particularly sensitive to gravity waves with large horizontal wavelength, short vertical wavelength, long period, slantwise propagating inertial gravity waves

7. Gravity wave observational window

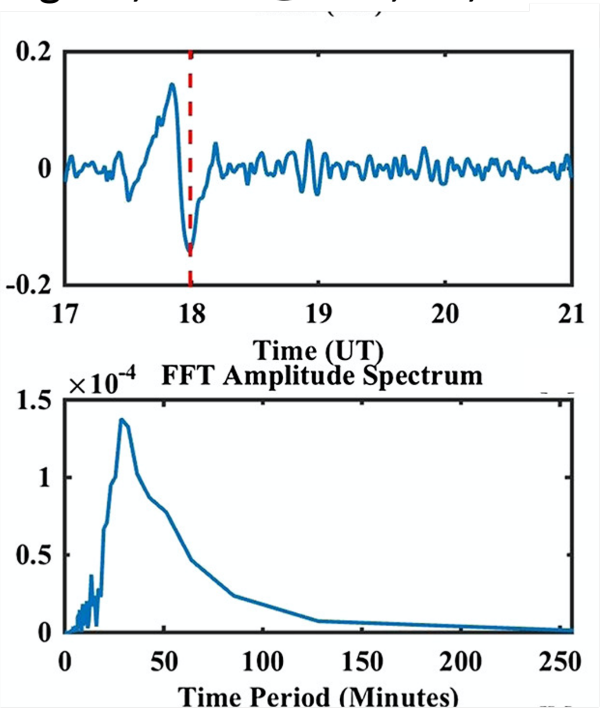
- But with multiple radiosonde frequently launched at the same site or close-by, we can form a timeseries which can resolve higher-frequency faster propagating small-scale gravity waves



(Credit: Anisa Najafabadi @ UKY)

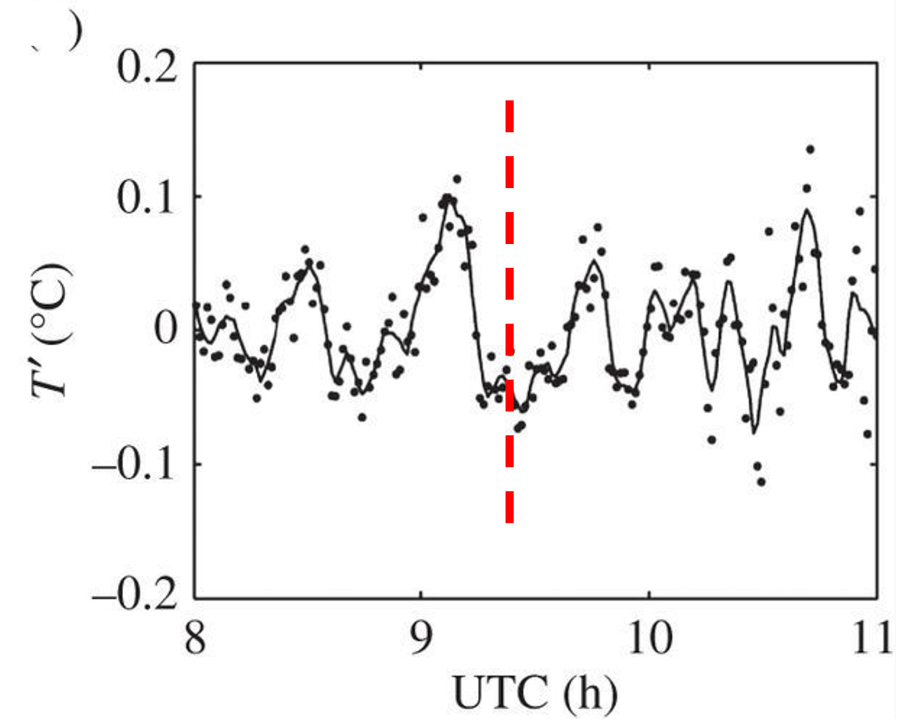
8. Other measurements that could reveal eclipse-gravity wave properties

(a) TEC perturbation in ionosphere, Aug. 21, 2017 @ Cliff, NE, USA



(Nayak and Yigit, 2017, JGR)

(b) Temperature perturbation at surface, Mar. 20, 2015 @ Reeding, UK



(Marlton et al., 2016, PTAMPES)

8. Summaries

- Atmospheric gravity waves can be generated when the atmosphere is strongly perturbed. They can only propagate in stably stratified atmosphere.
- Atmospheric gravity waves are important for weather, climate, and lower-upper atmosphere coupling.
- We can use various observational techniques to take measurements of gravity wave properties. With the help of ray-tracing modeling, we can understand the wave origin and sink. Radiosonde is among these techniques. However, none of them can give you the whole picture of gravity wave spectrum. We need to piece them together to solve the jigsaw puzzle.
- Solar eclipse brings about continuous radiative depression to the atmosphere. Hence it also excites gravity waves. The exact excitation mechanism, source altitude, propagation path, etc. are still largely unknown. We need your help to carry out the expansive 2023 and 2024 campaigns to help unveil the mysteries.

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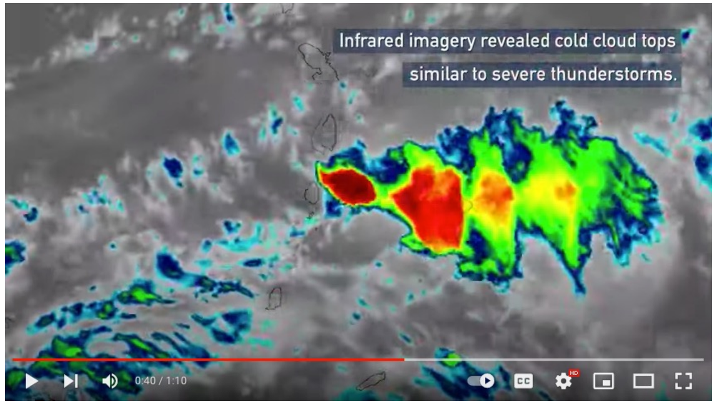
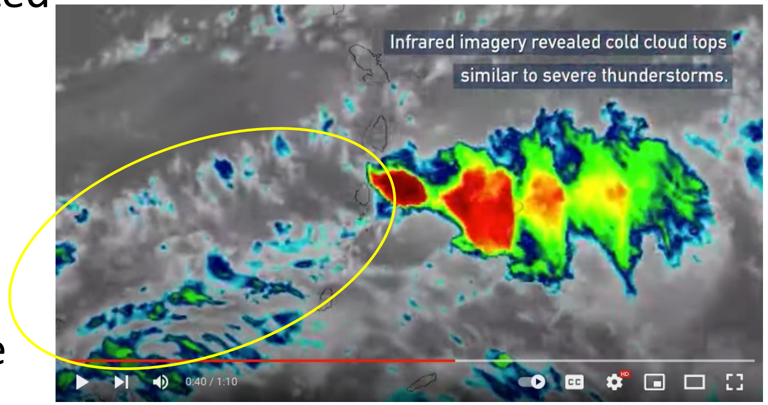
Sampled homework questions



1. In the La Soufriere volcano eruption video, one can see the structures of cloud/smoke: can you circle out areas that you think are modulated by gravity waves? (hint: colors are from infrared channels, with red/yellow being warm and green/blue being cold)
2. Do you think atmospheric gravity waves are usually linearly or circularly polarized? Why?
3. Is sunlight polarized?
4. What type of gravity waves are single radiosonde profiles particularly sensitive to?
   (A) Long vertical wavelength, short horizontal wavelength, vertically propagating ones
   (B) Long vertical wavelength, long horizontal wavelength ones
   (C) Short vertical wavelength, long horizontal wavelength, slantwisely propagating ones
   (D) Short vertical wavelength, short horizontal wavelength, small ones
5. Our 2017, 2019 and 2020 solar eclipse campaigns all launch balloons hourly. If we make a time series, what is the smallest wave period can it resolve? In 2024, we aim at 15 minutes cadence at some sites. What is the smallest wave period can we resolve if we are successful?
6. From gravity wave measurement perspective, what are your suggestions for the planning for (1) site locations (2) launch frequency (3) launch window (i.e., start and ending time with respect to the totality).

Sampled homework answer key

1. The bands to the left are probably associated with gravity waves generated by the volcano eruption (circled). The upwind propagating gravity waves quickly became stalked and help forming the cloud bands while the downwind ones can go to the stratosphere and mesosphere. The large wavy structure to the right of this screenshot is actually associated with the intermittent nature of this eruption.



2. Circularly polarized. Gravity waves have two orthogonal component: one with up-down buoyancy oscillation resulted from a balance between buoyancy and gravity. And a horizontal rotation due to Coriolis force.

3. Sunlight can be approximated as unpolarized. But that's for direct sunlight. After scattering, absorption and other processes happen in the atmosphere, the sunlight you receive is usually partially polarized.

4. C

5. 4X rule applies here. The smallest period of gravity waves that an hourly launching schedule can resolve is 4 hours. If we shrink the cadence to 15 mins, we can resolve ~ 1 hour period gravity waves. However, please note that this is only for the case of timeseries. For single radiosonde profile, we may resolve higher-frequency waves (~ 10s mins) if ascending rate perturbation is analyzed.

6. This is an open-ended question. Any suggestions with elaboration of their reasoning would work.