Atmospheric Waves Triggered by the 2022 Hunga Tonga Eruption

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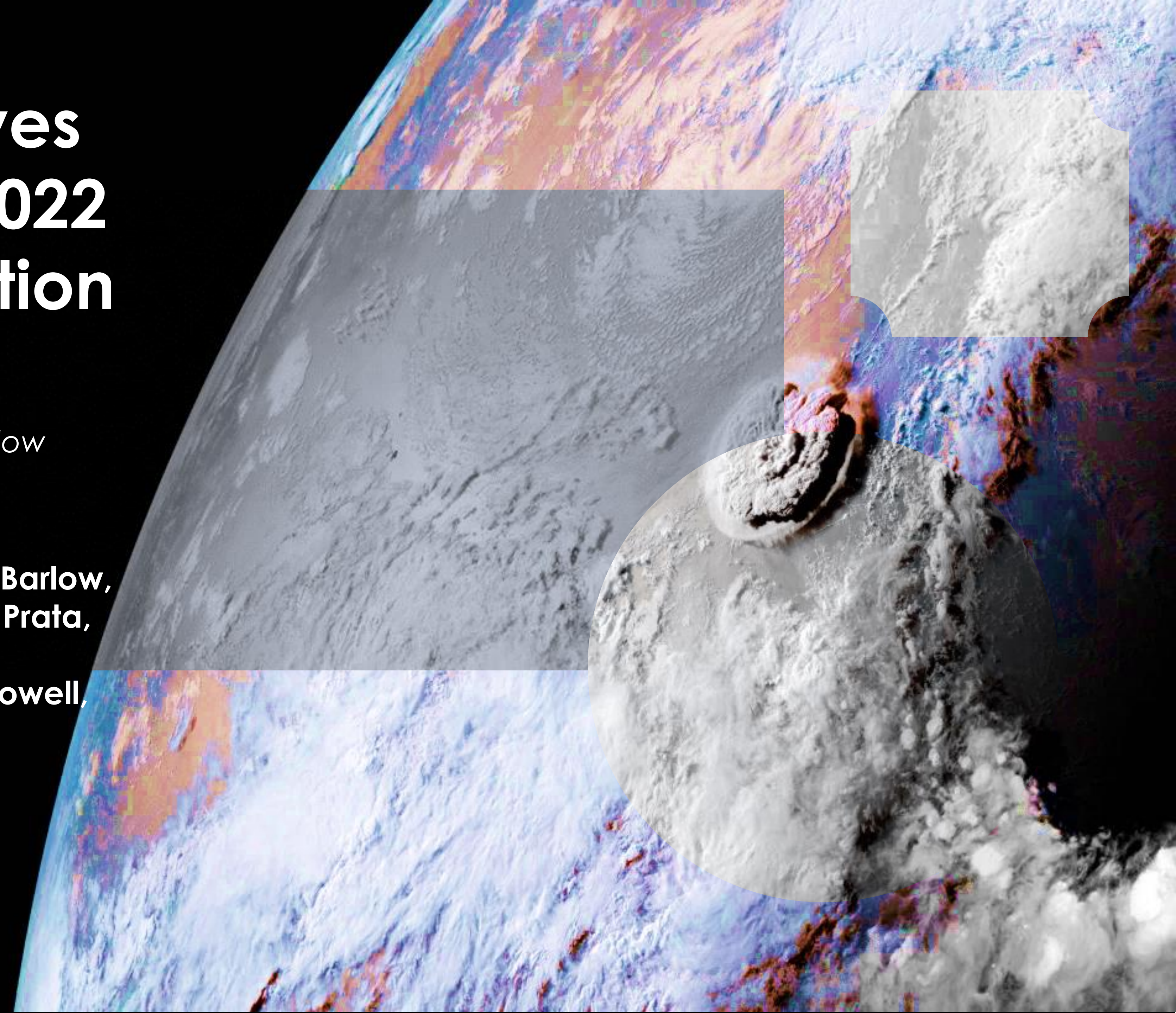
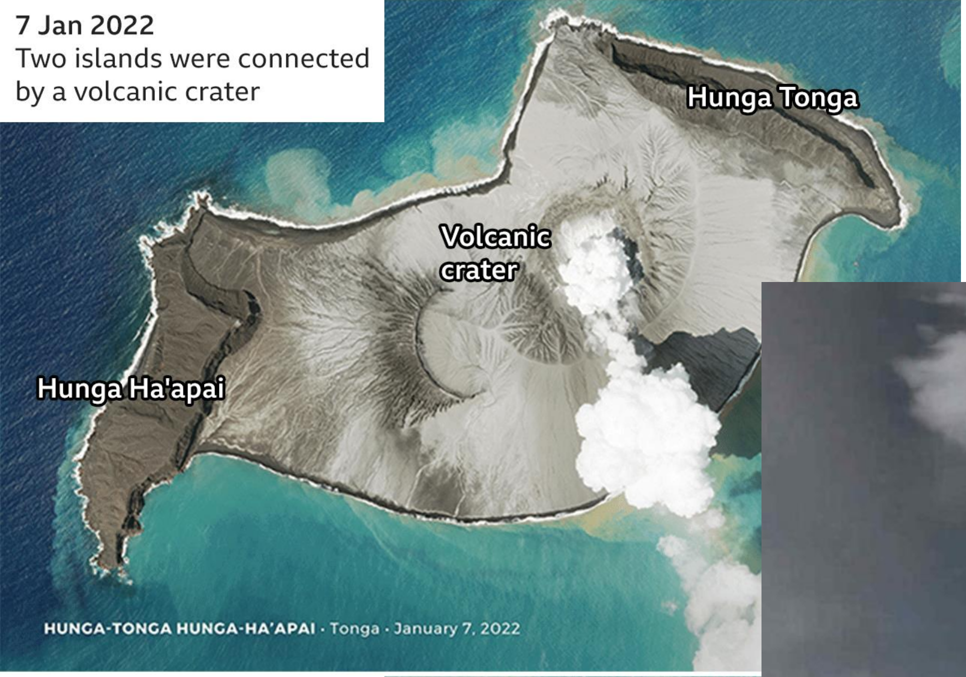
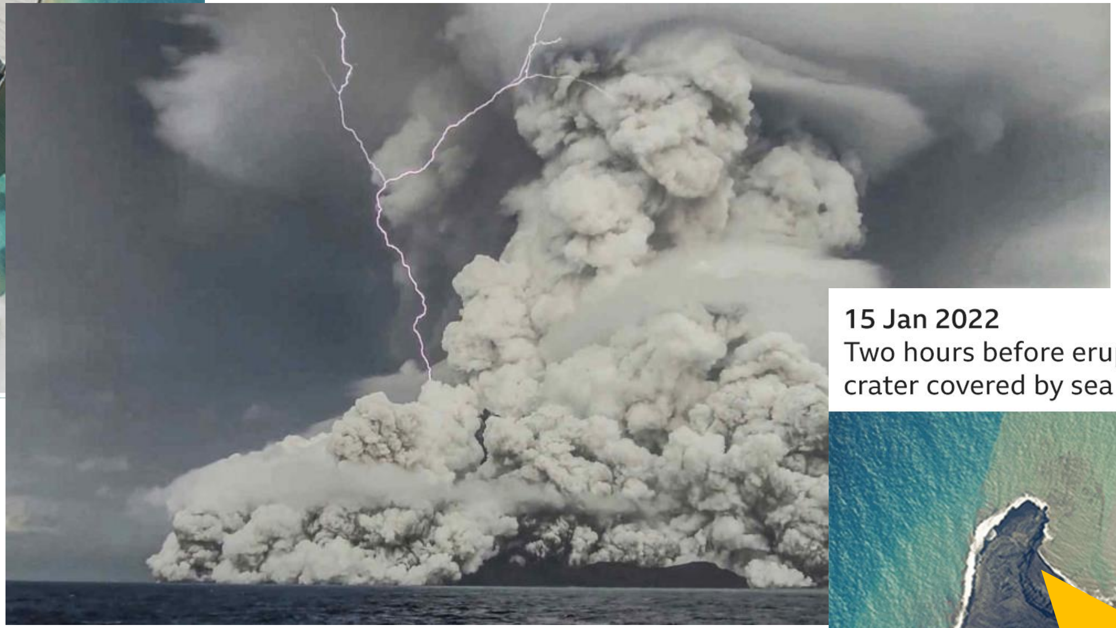


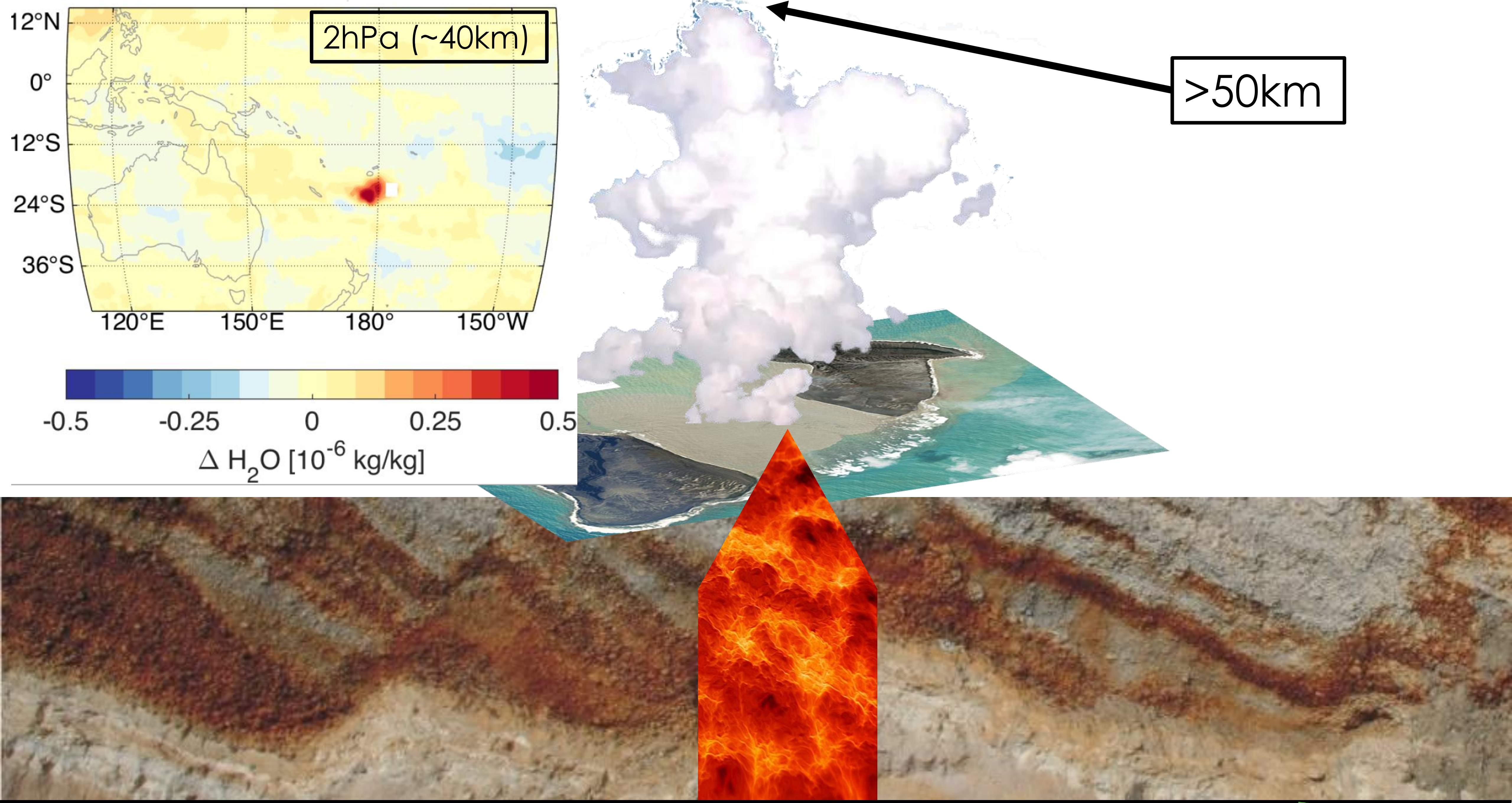
THE ROYAL SOCIETY

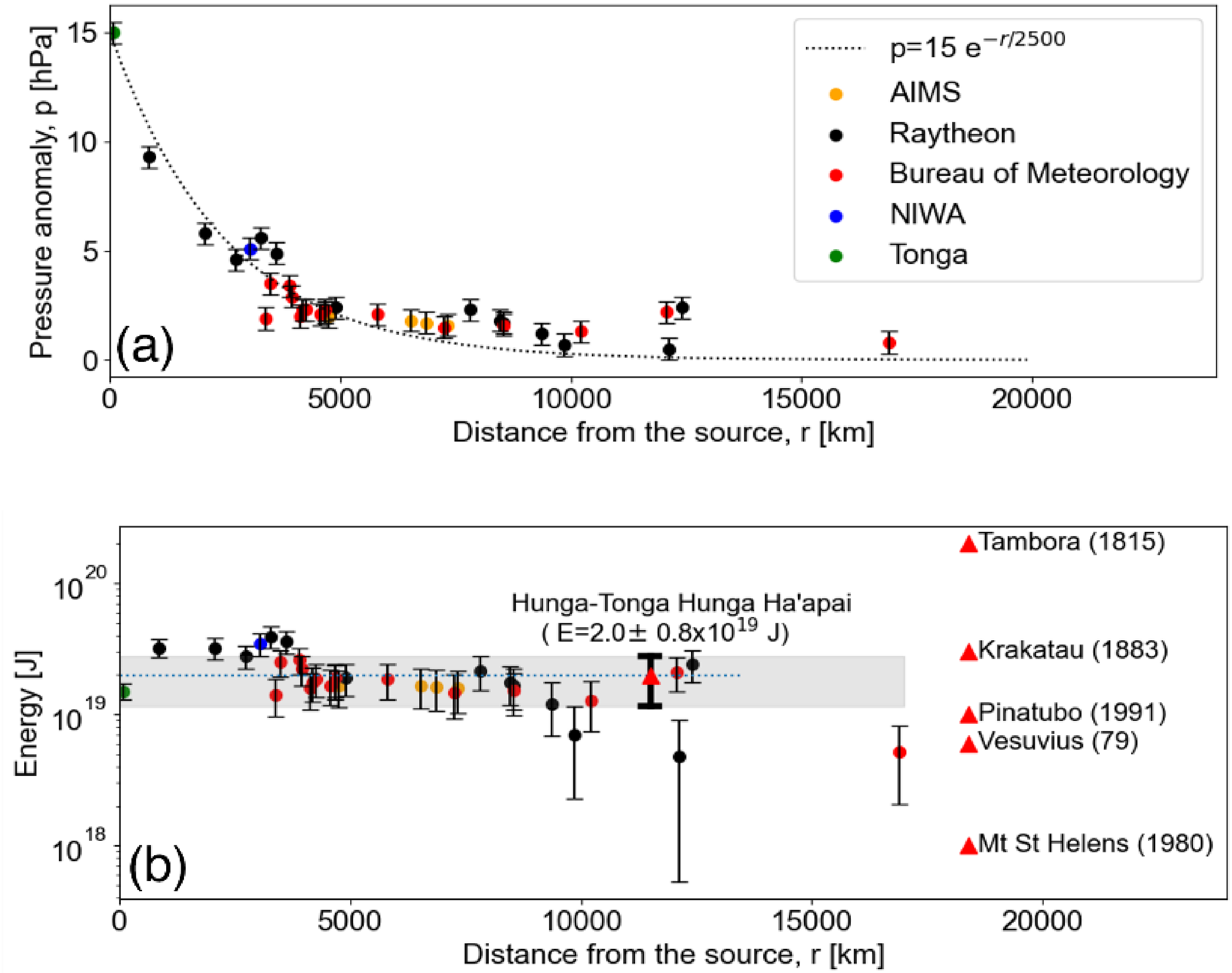




Source: Copernicus/ESA/Sentinel Hub, PlanetLabs, Maxar

BBC


2hPa (~40km)
12°N
0°
12°S
24°S
36°S
120°E
150°E
180°
150°W
-0.5
-0.25
0
0.25
0.5
Δ H_2O [10^{-6} kg/kg]
>50km



Pressure data repository: doi:10.5281/zenodo.6575810

Waveform based on a nuclear explosion:

Posey and Pierce (1971)

$$E = 13p\sqrt{[r_e \sin(r/r_e)]H_s}(CT)^{3/2}$$

=> **~20±8 EJ**

Waveform based on previous volcanoes:

Gorshkov (1960)

$$E = \frac{2\pi H_s \sin(\theta)}{\rho c}\int p^2\, dt$$

=> ~10 EJ

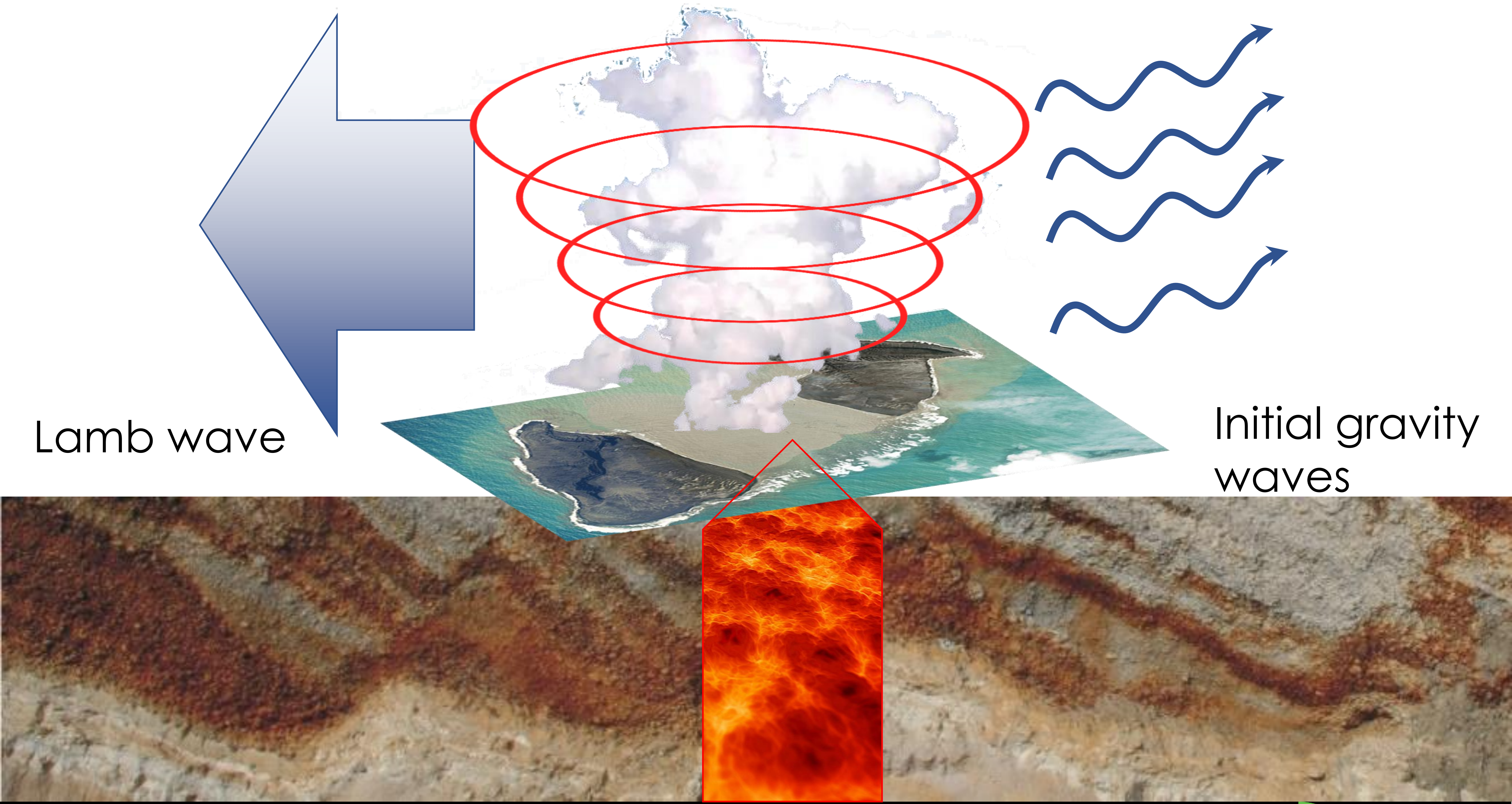
Assume uniform pressure force:

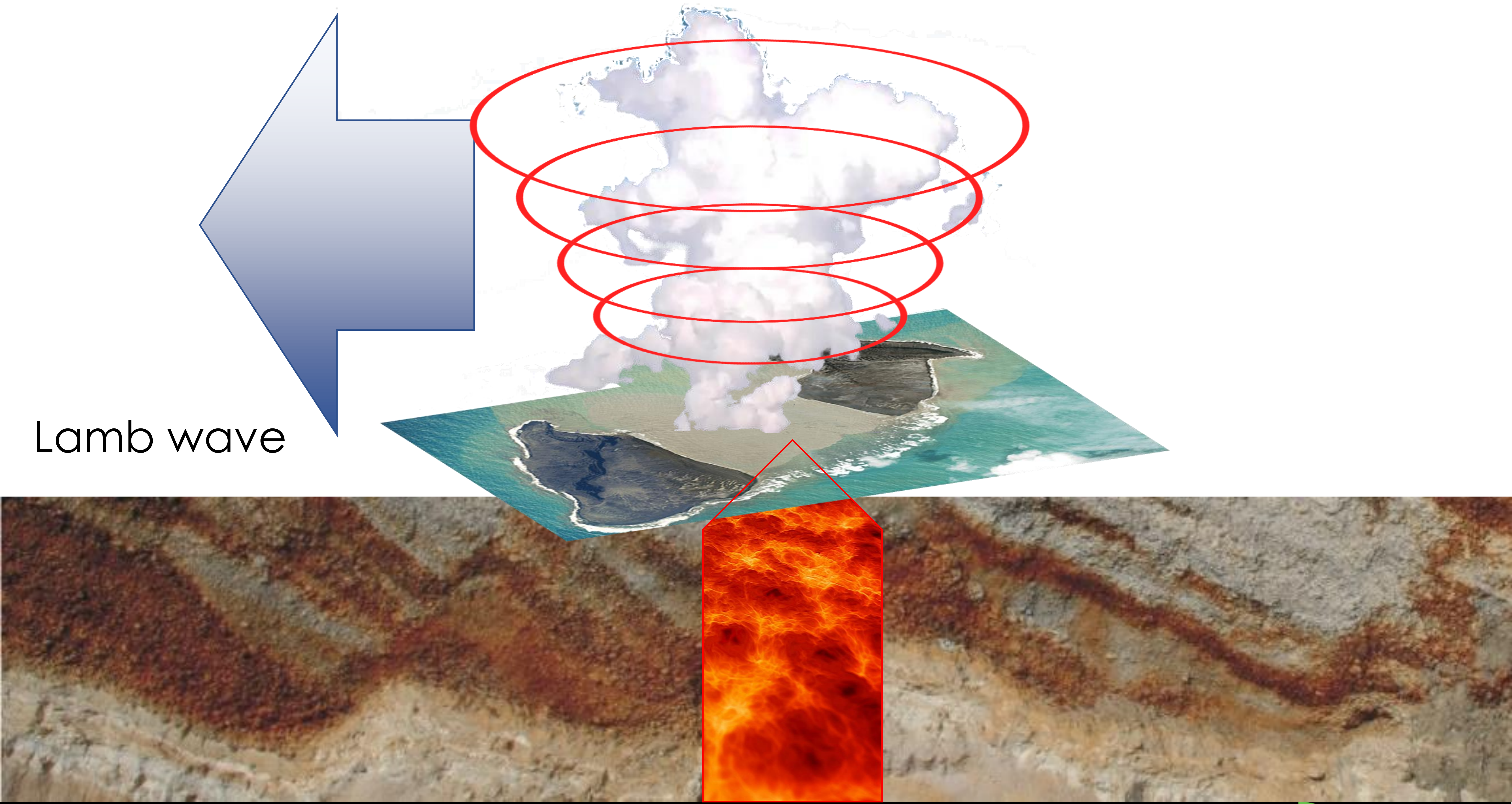
$$E = pAh_c.$$

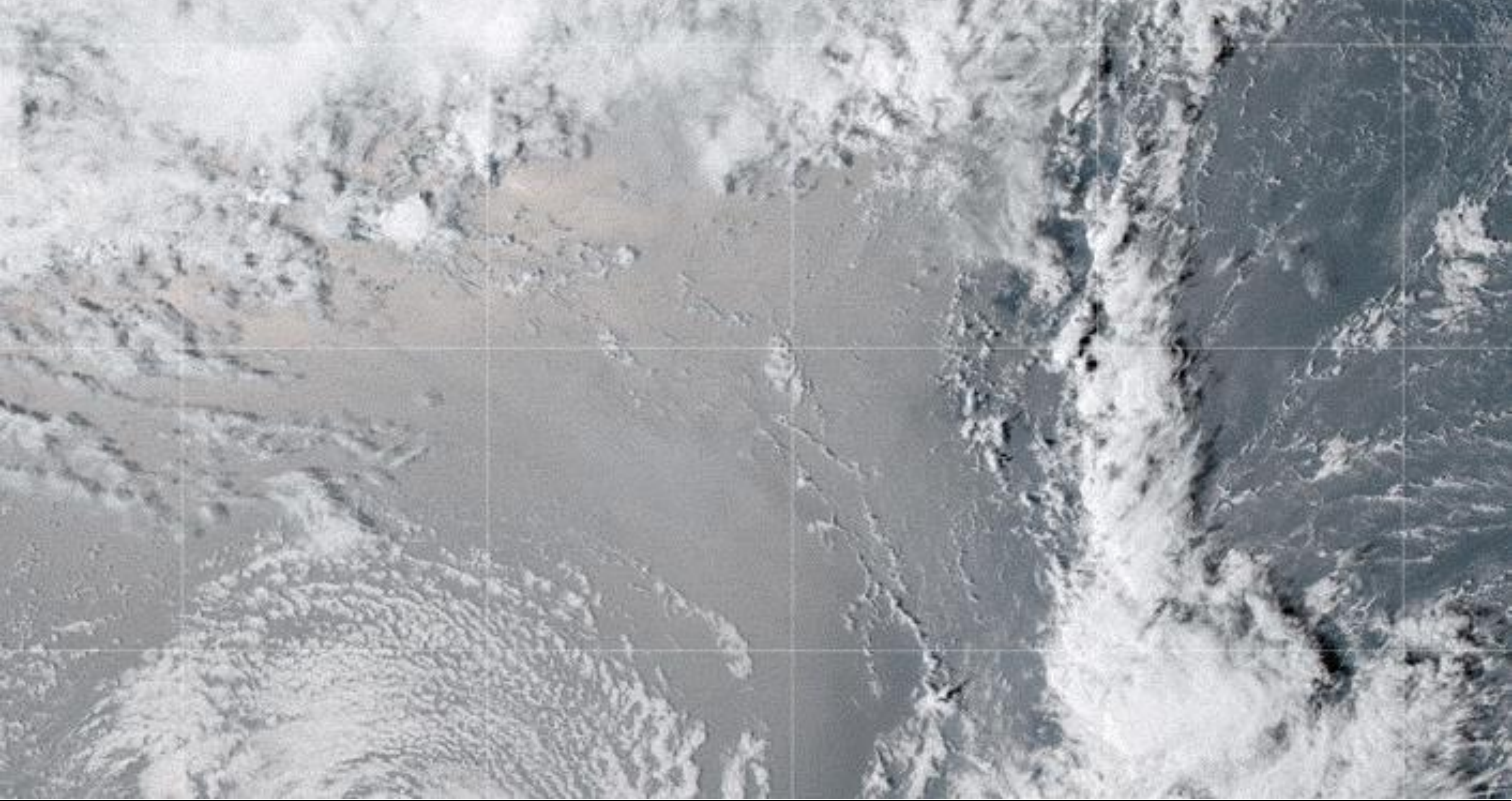
=> ~18 EJ

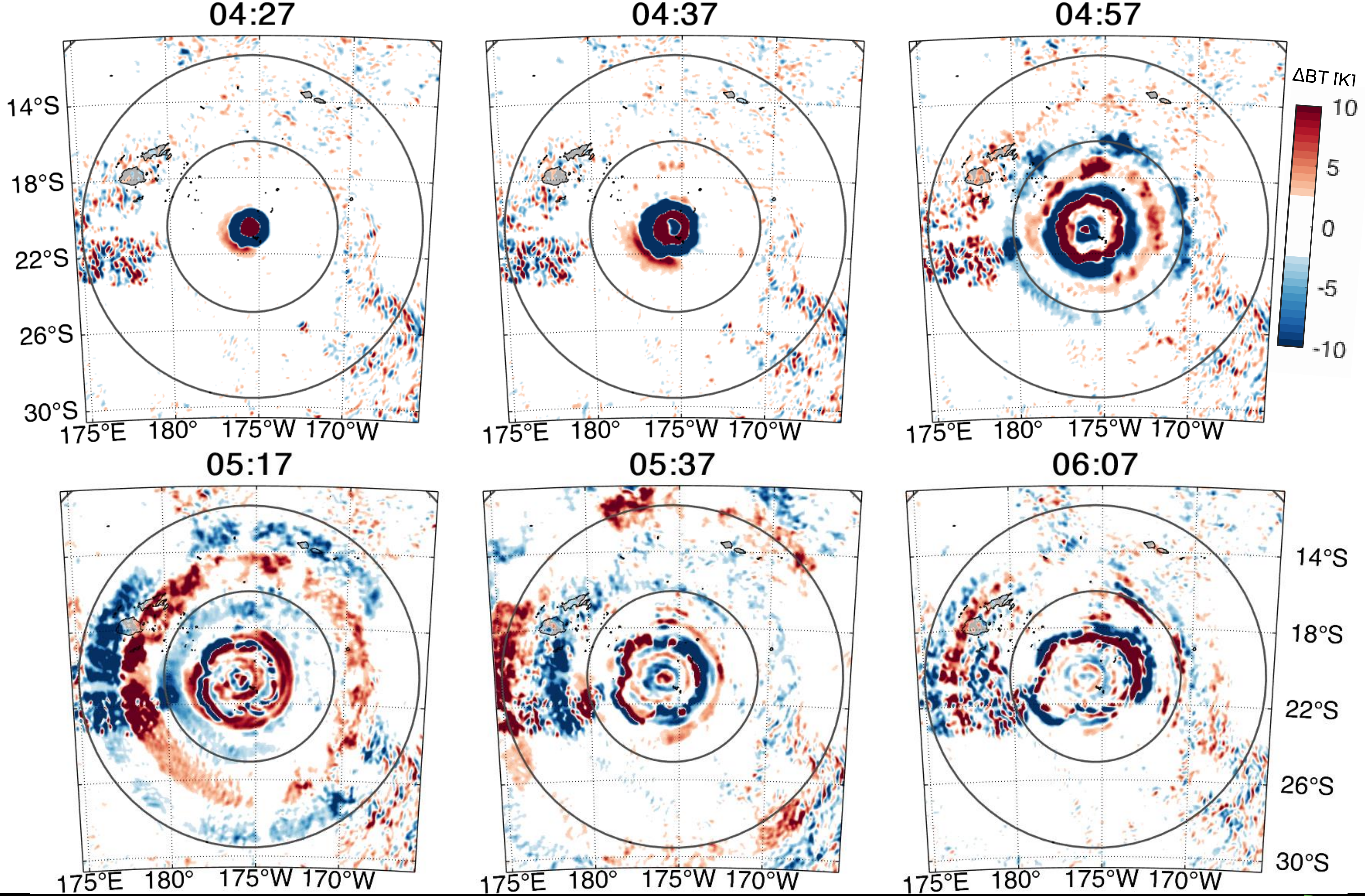
More than Pinatubo (1992)

Comparable to Krakatoa (1883)?

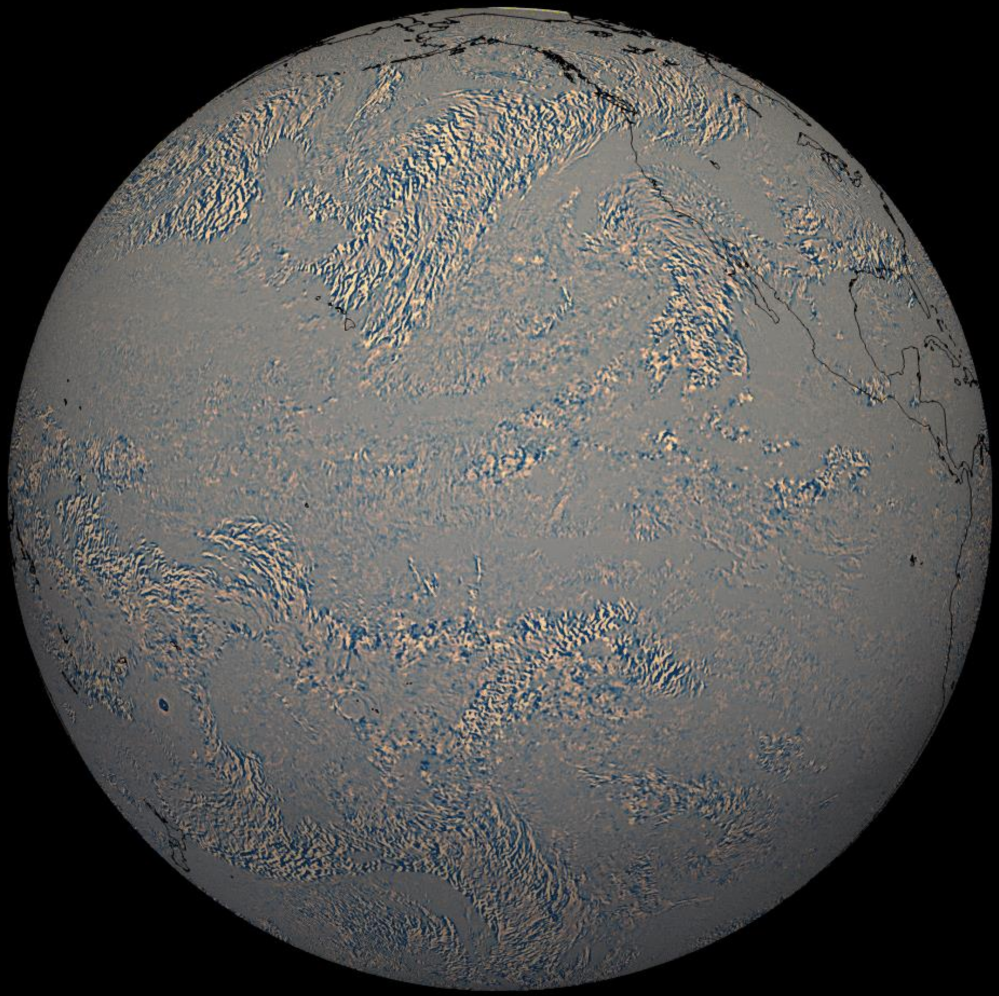

Lamb wave
Initial gravity waves

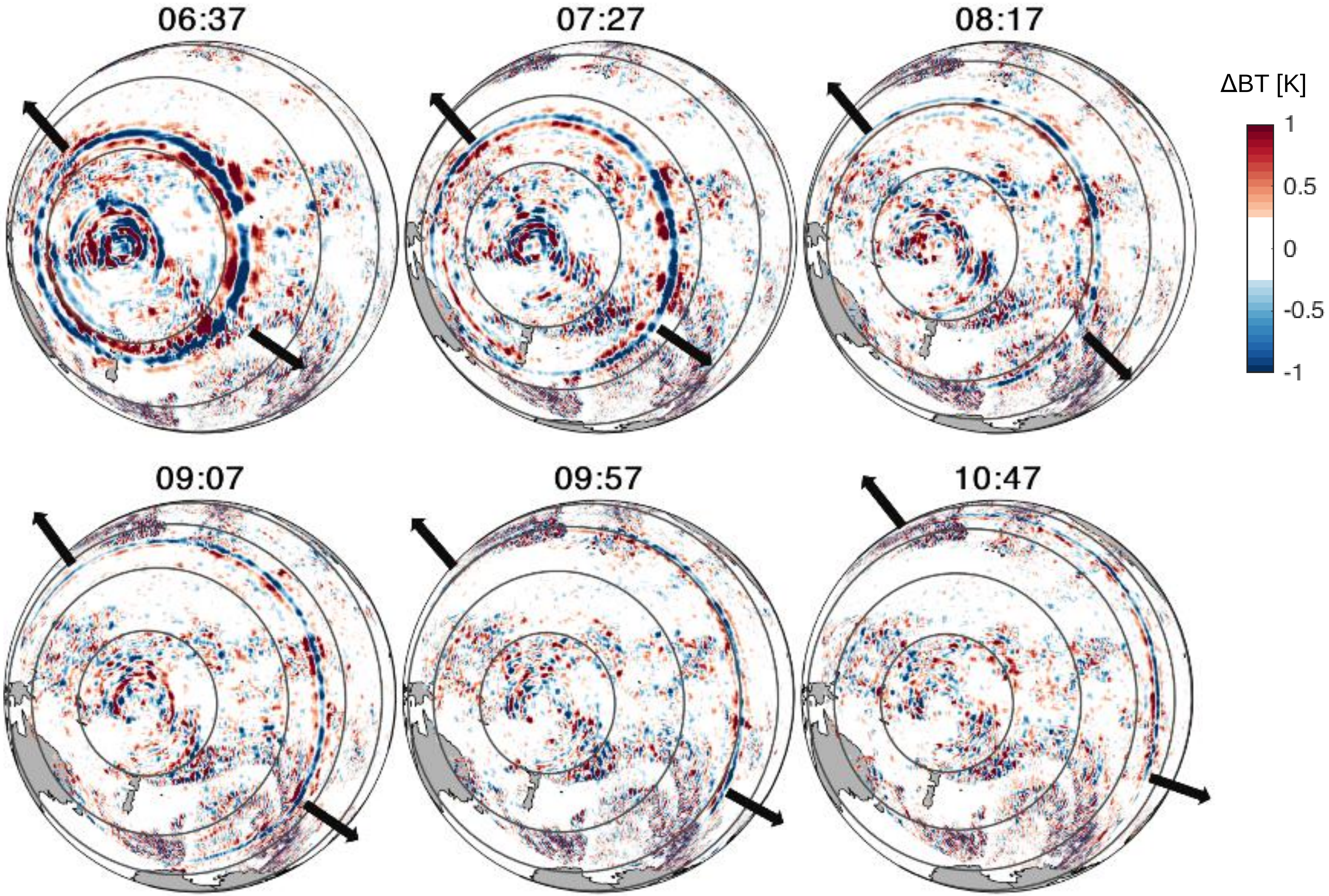

Lamb wave




04:27
04:37
04:57
05:17
05:37
06:07
ΔBT [K]
10
5
0
-5
-10
14°S
18°S
22°S
26°S
30°S
175°E
180°
175°W
170°W

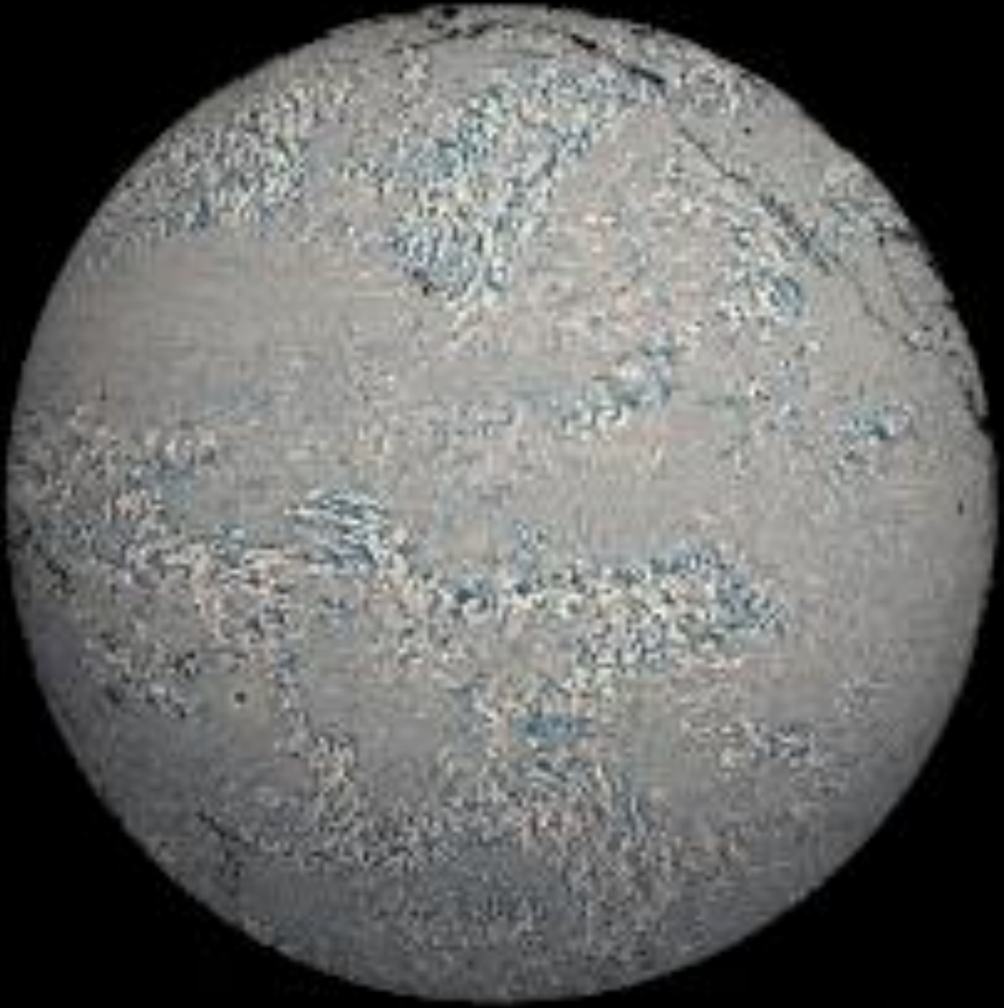
GOES-West



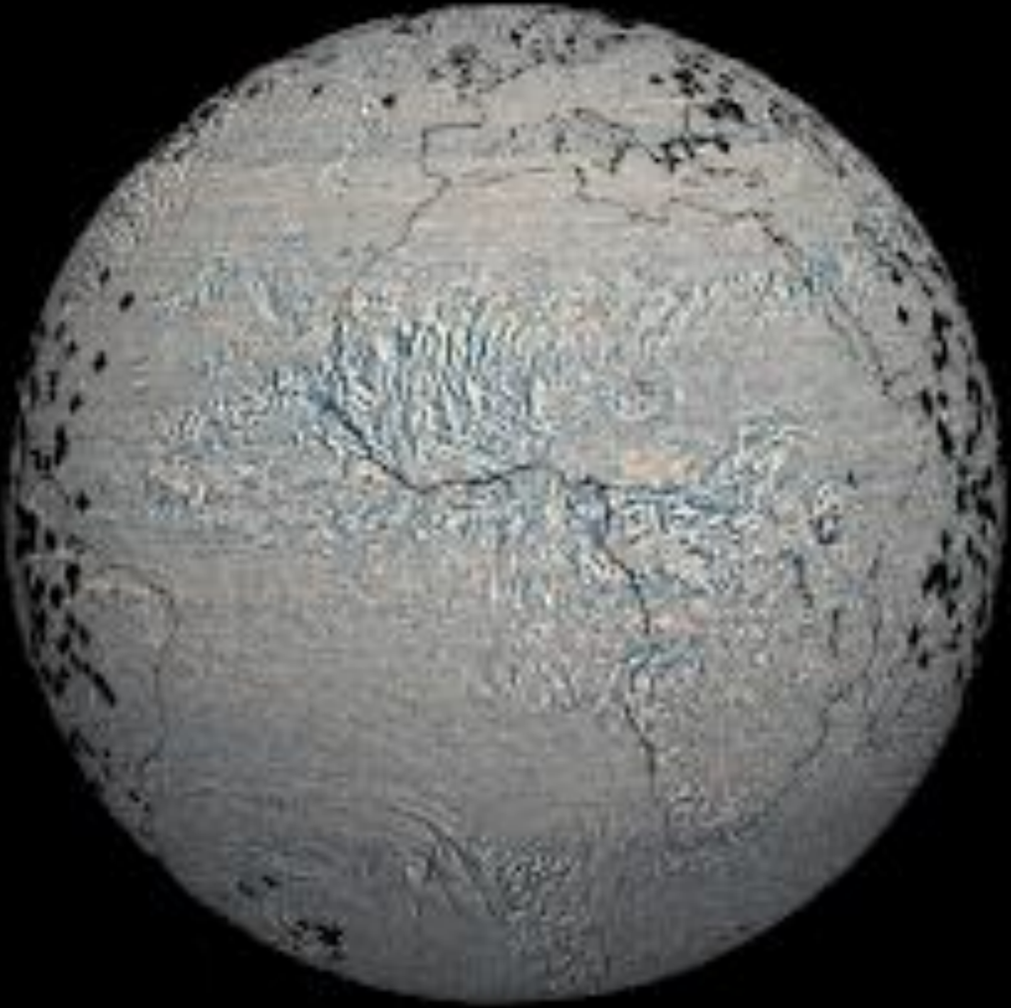


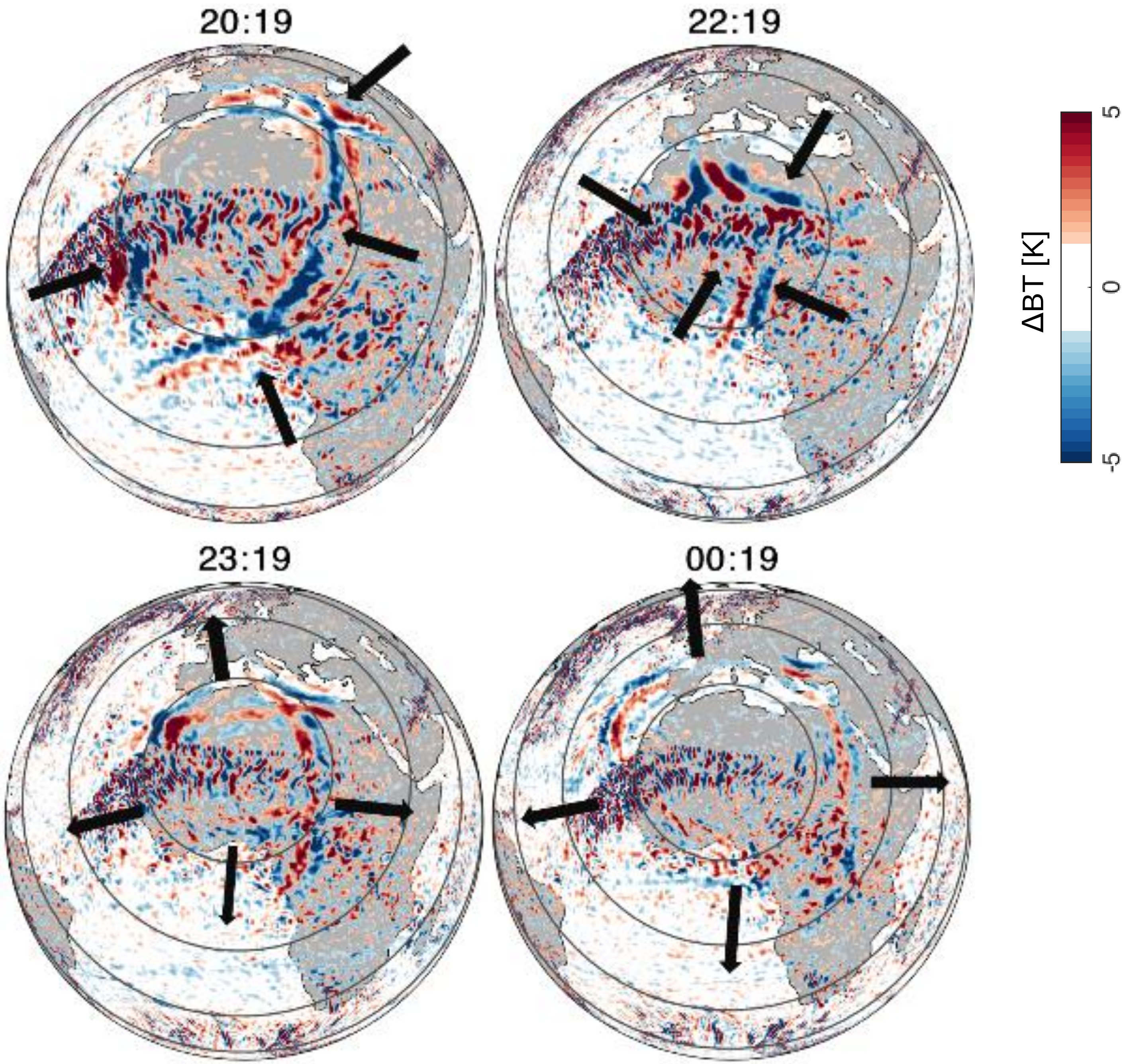
06:37
07:27
08:17
09:07
09:57
10:47
ΔBT [K]
1
0.5
0
-0.5
-1

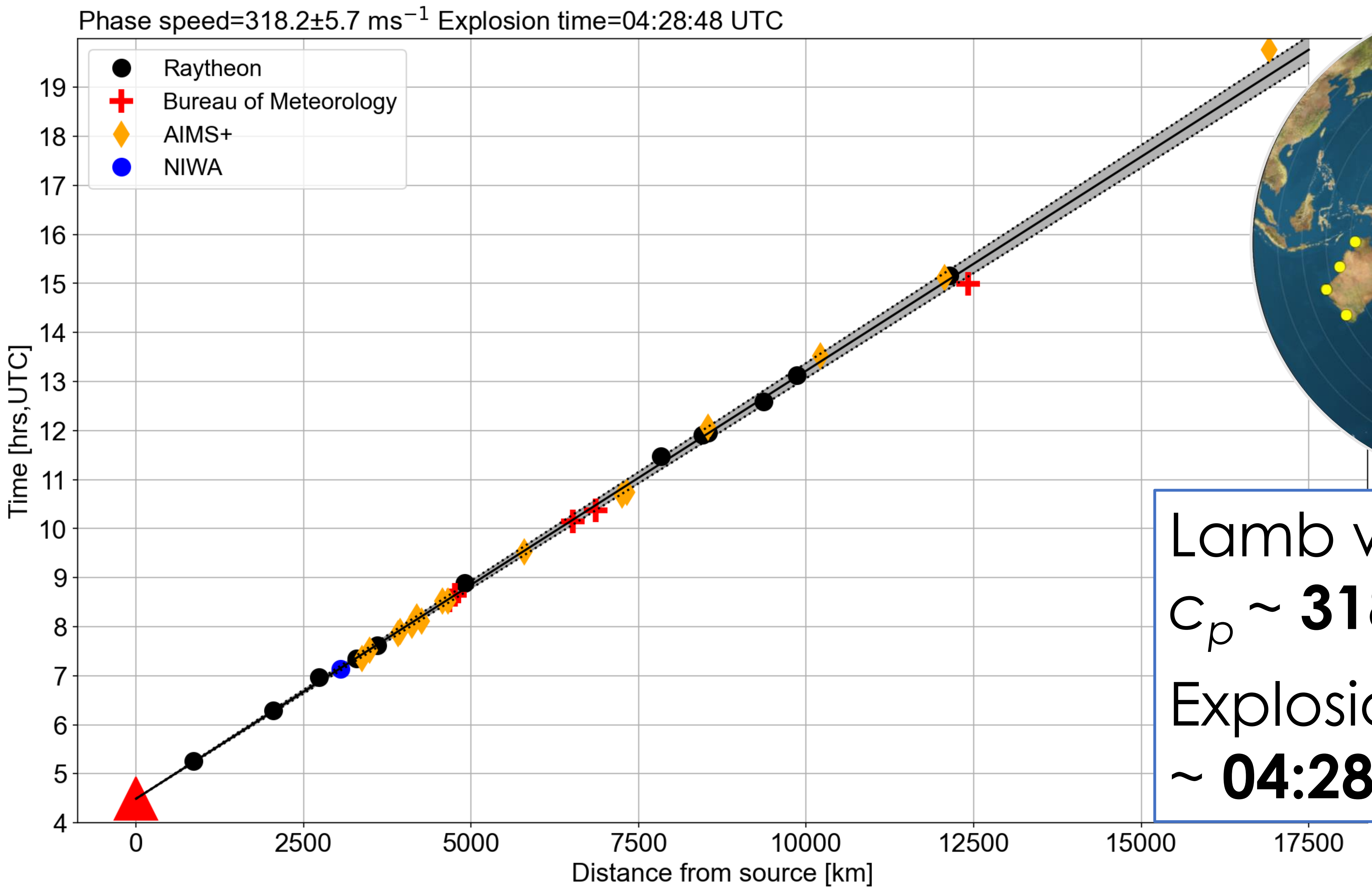
GOES-West

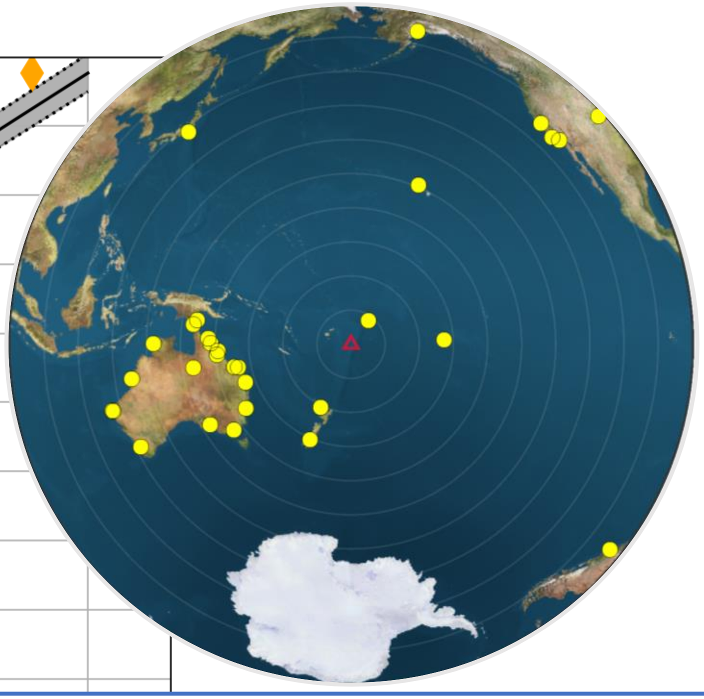


Meteosat-11




20:19
22:19
23:19
00:19
ΔBT [K]
5
0
-5





Lamb wave pulse:

c_p ~ **318 +/- 5.7m/s**

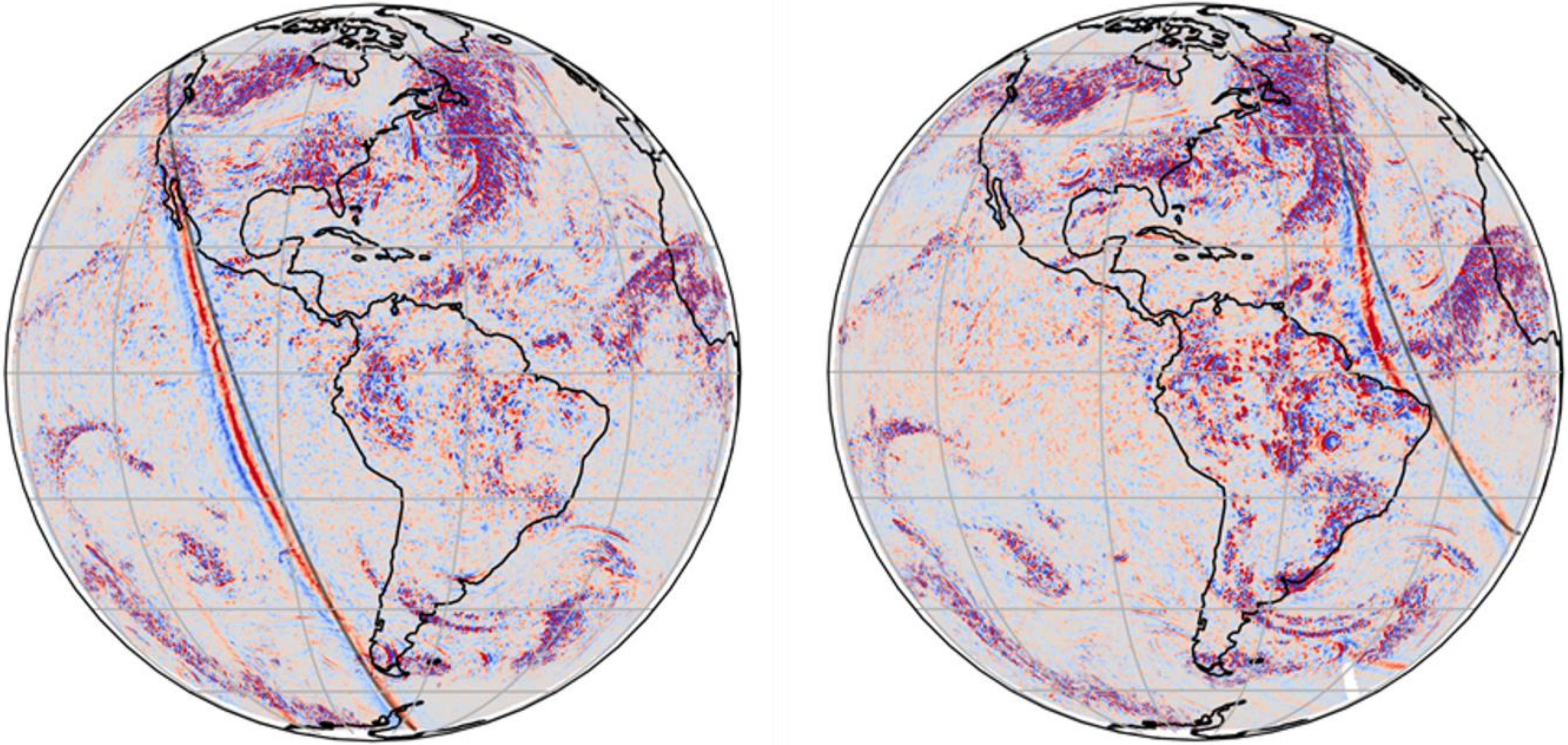
Explosion Time:

~ **04:28:48 UTC**

Pressure data repository: doi:10.5281/zenodo.6575810

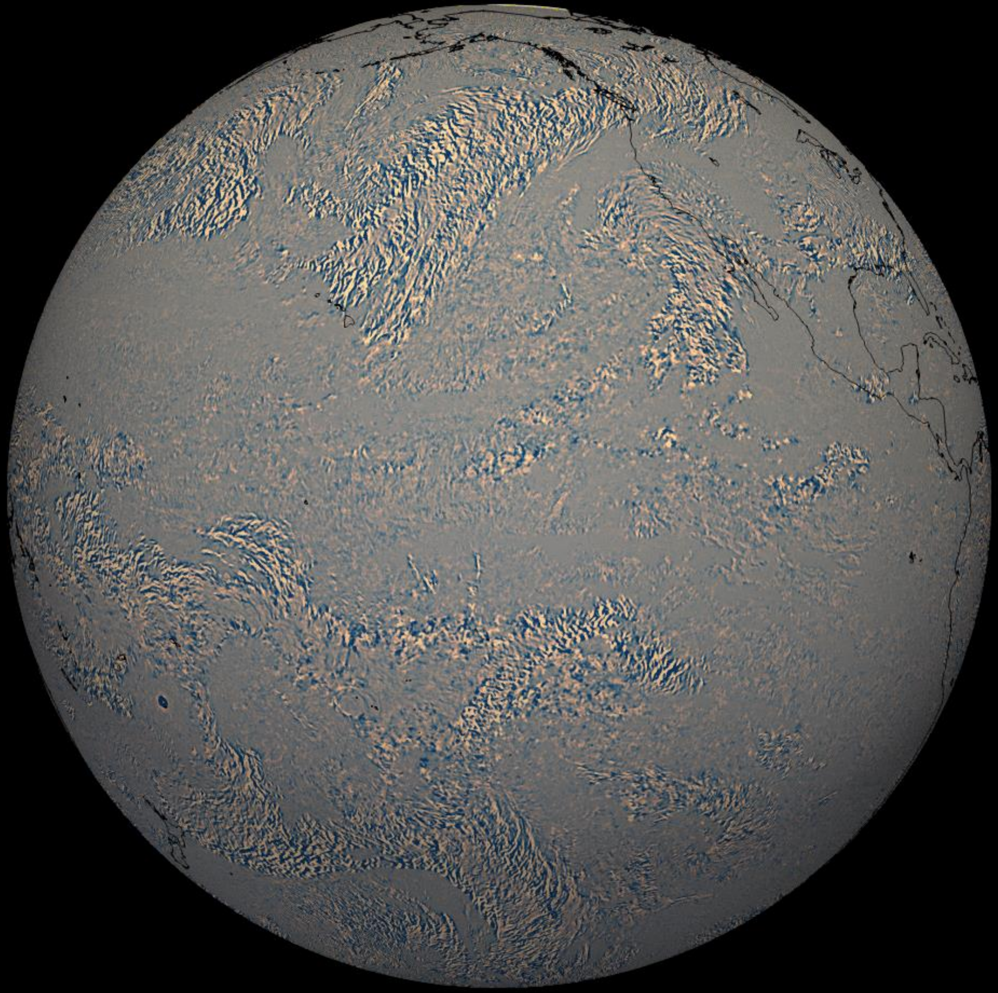
(a) GOES-16 Band 8: 15 Jan, 12 UTC

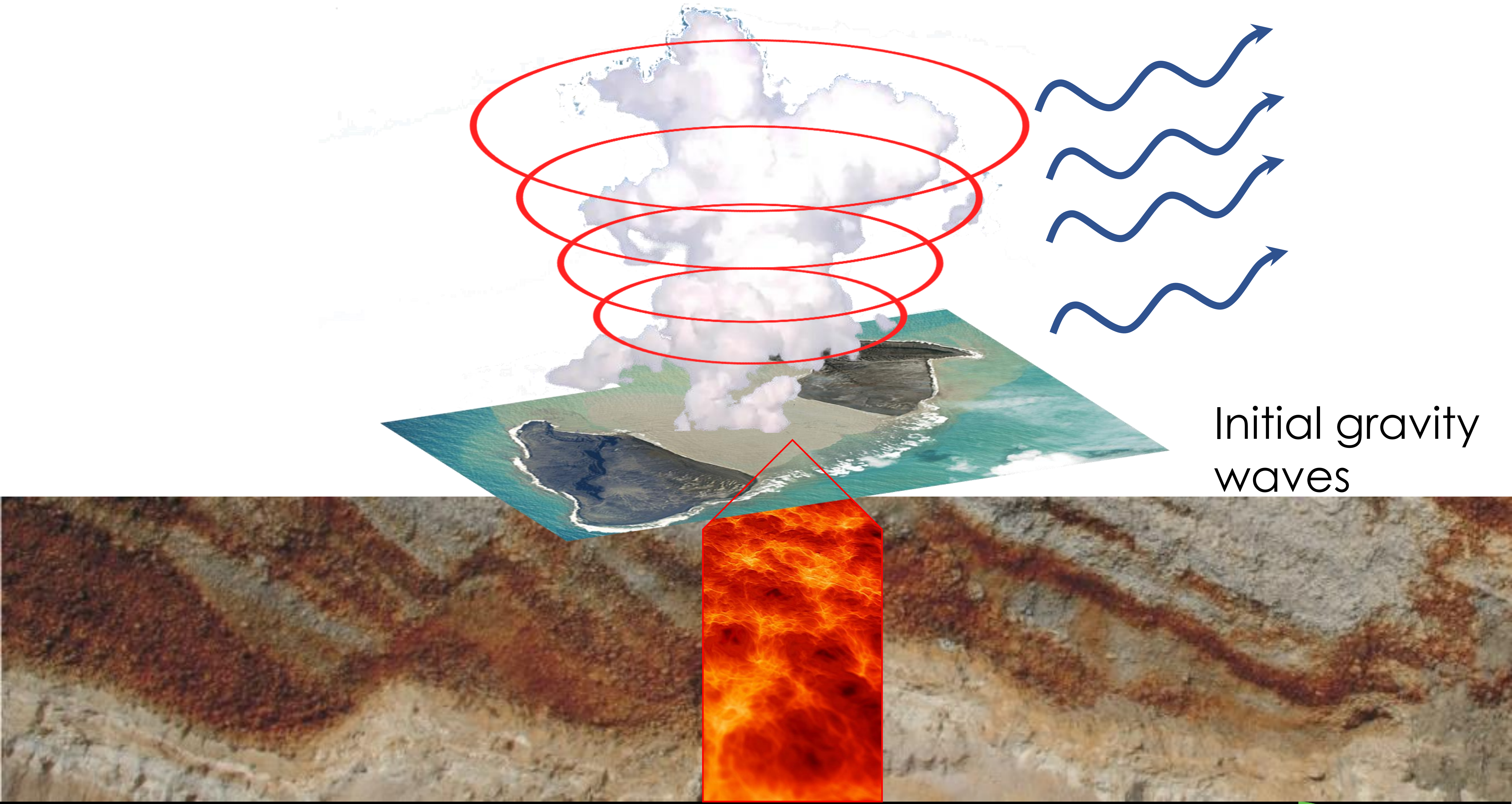
(b) GOES-16 Band 8: 15 Jan, 17:20 UTC

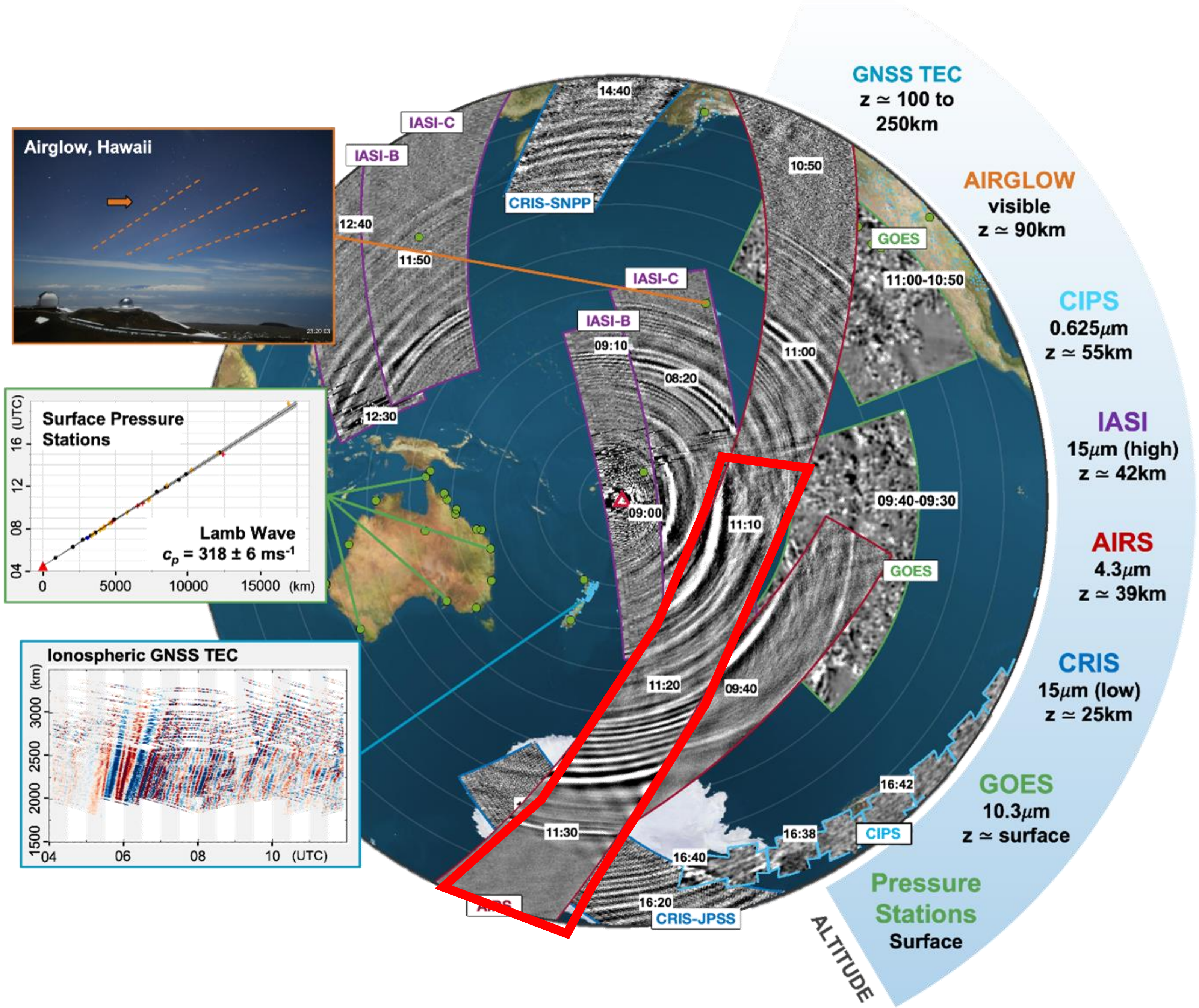


Conclusion 1:

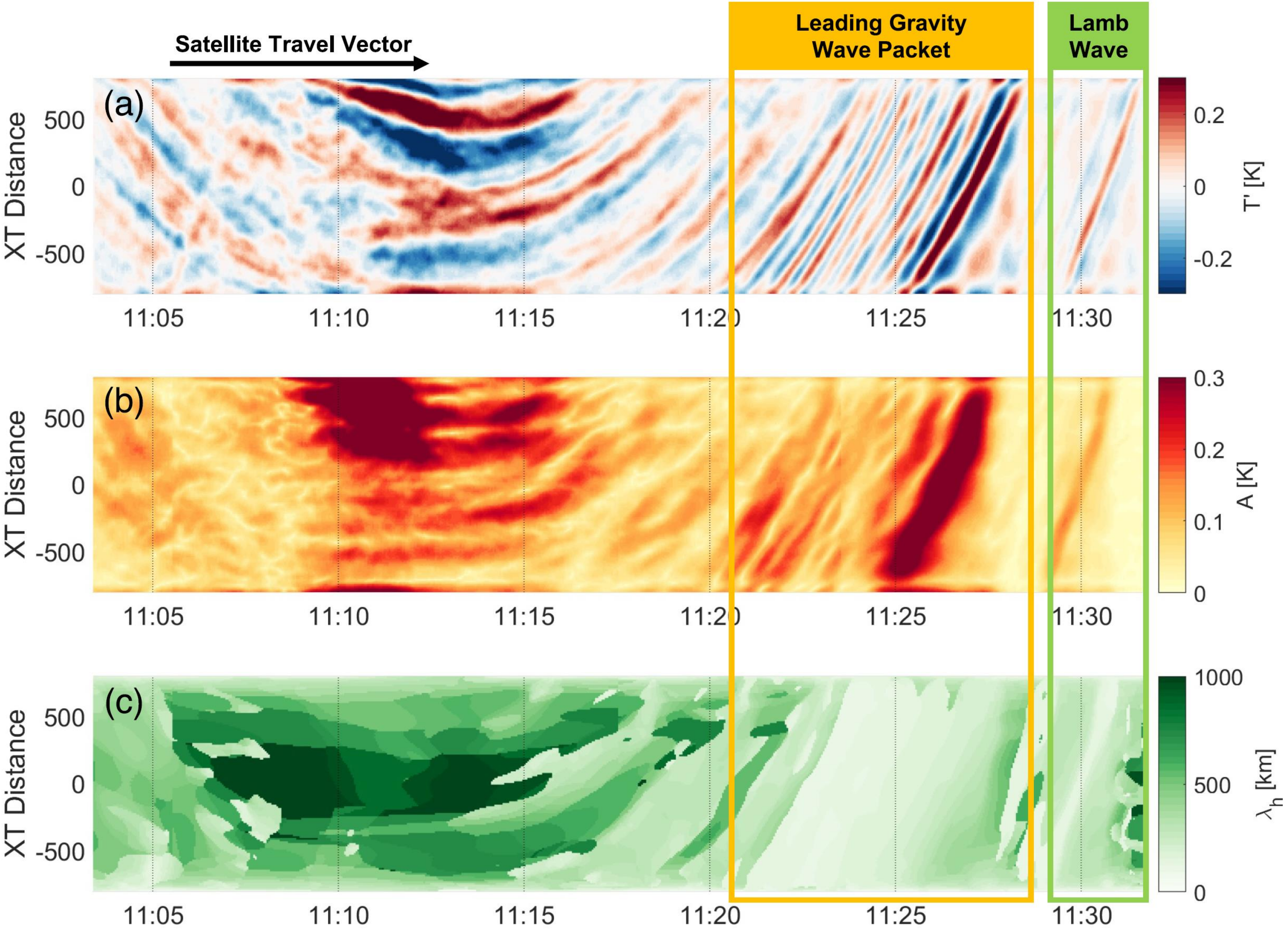
The leading Lamb wave travelled round the Earth multiple times at a speed of 318 m/s, and was affected by weather and surface



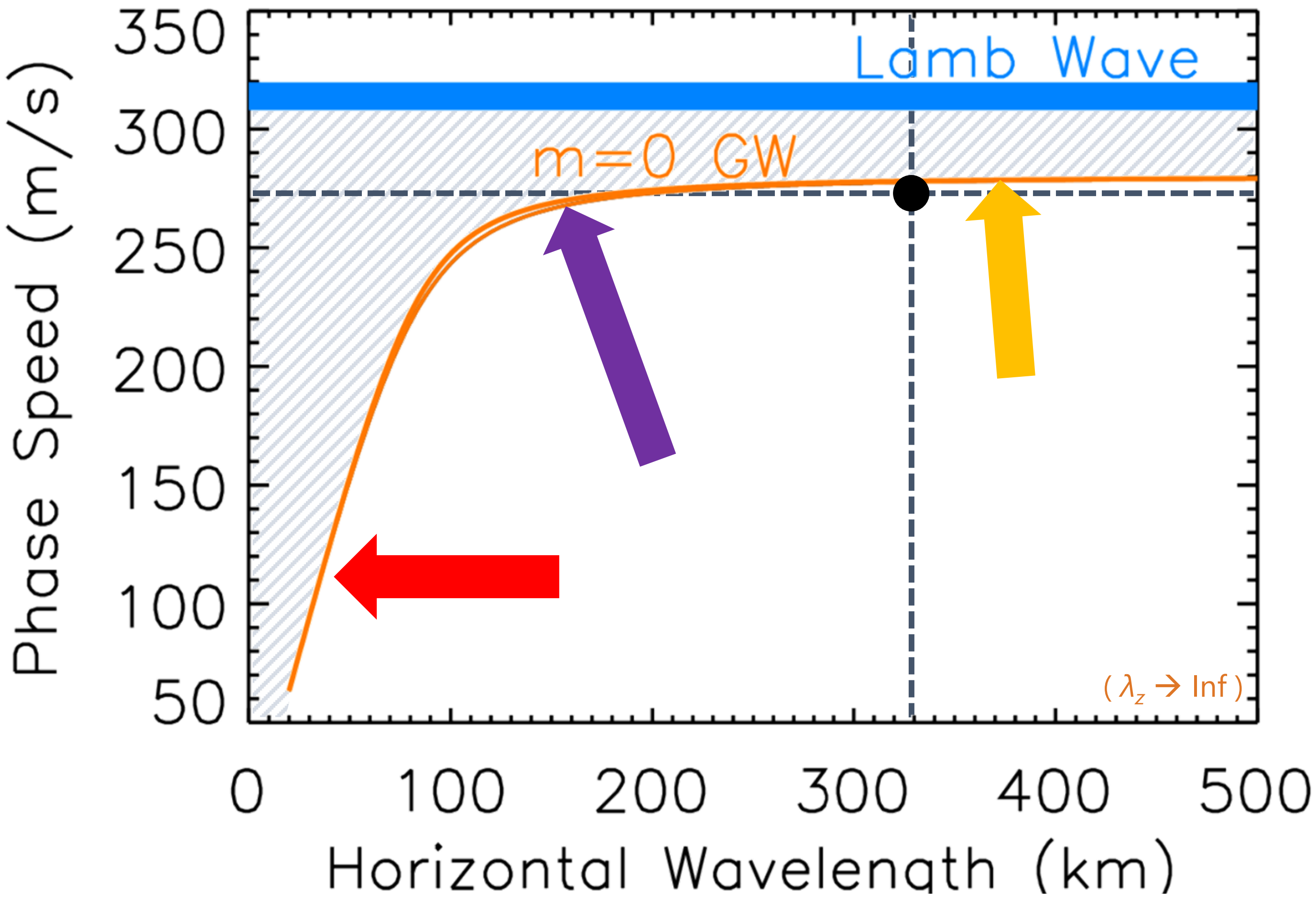

Initial gravity waves

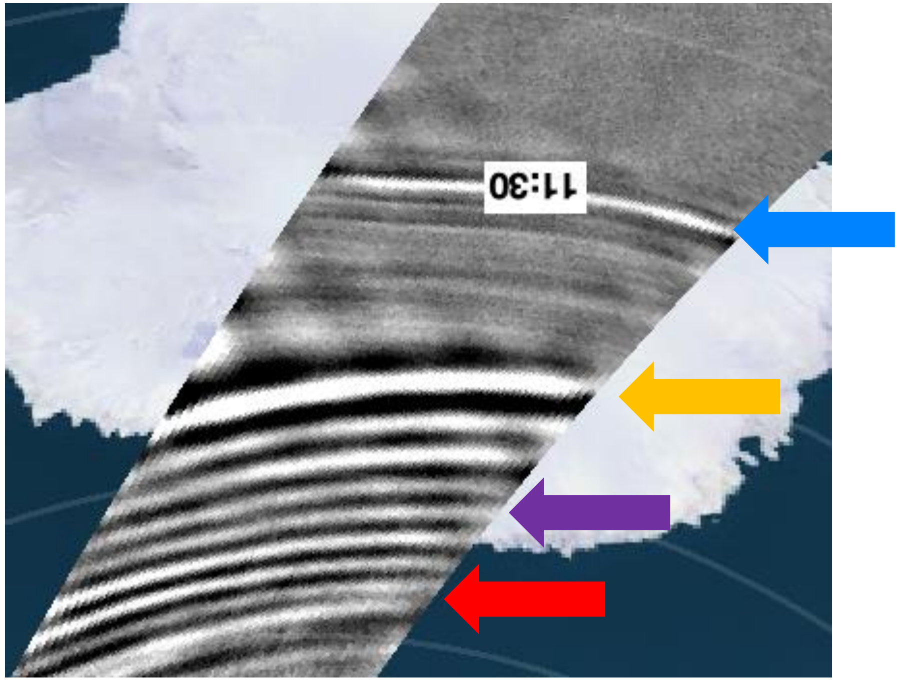


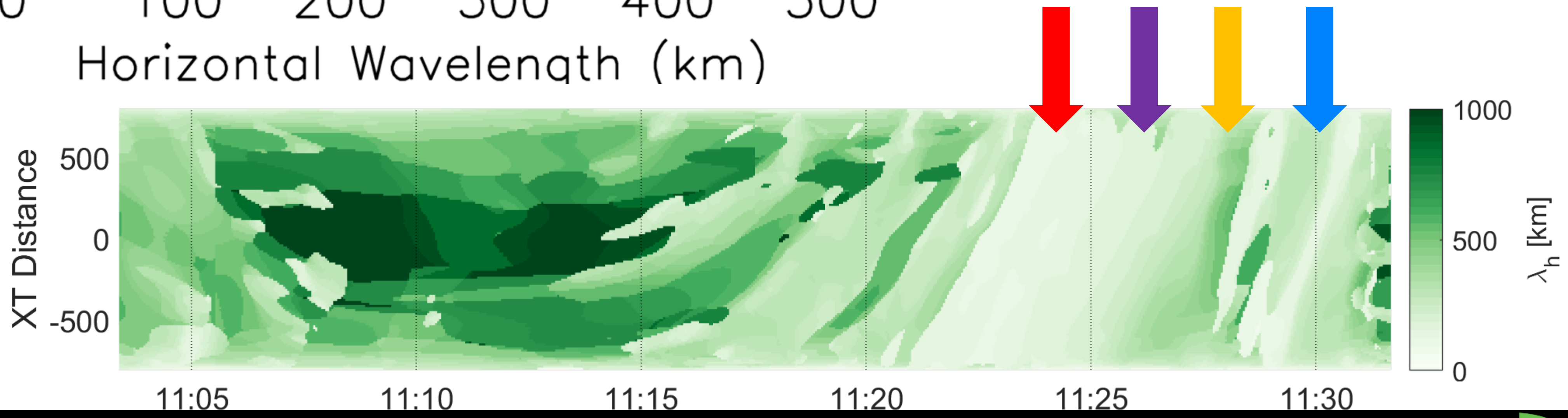
Airglow, Hawaii
Surface Pressure Stations
Lamb Wave
c_p = 318 ± 6 ms^{-1}
(UTC)
(km)
Ionospheric GNSS TEC
IASI-C
IASI-B
CRIS-SNPP
CRIS-JPSS
GOES
CIPS
AIRS
14:40
10:50
12:40
11:50
11:00-10:50
09:10
08:20
11:00
12:30
09:40-09:30
09:00
11:10
11:20
09:40
11:30
16:42
16:38
16:40
16:20
GNSS TEC
z ≃ 100 to 250km
AIRGLOW
visible
z ≃ 90km
CIPS
0.625µm
z ≃ 55km
IASI
15µm (high)
z ≃ 42km
AIRS
4.3µm
z ≃ 39km
CRIS
15µm (low)
z ≃ 25km
GOES
10.3µm
z ≃ surface
Pressure Stations
Surface
ALTITUDE

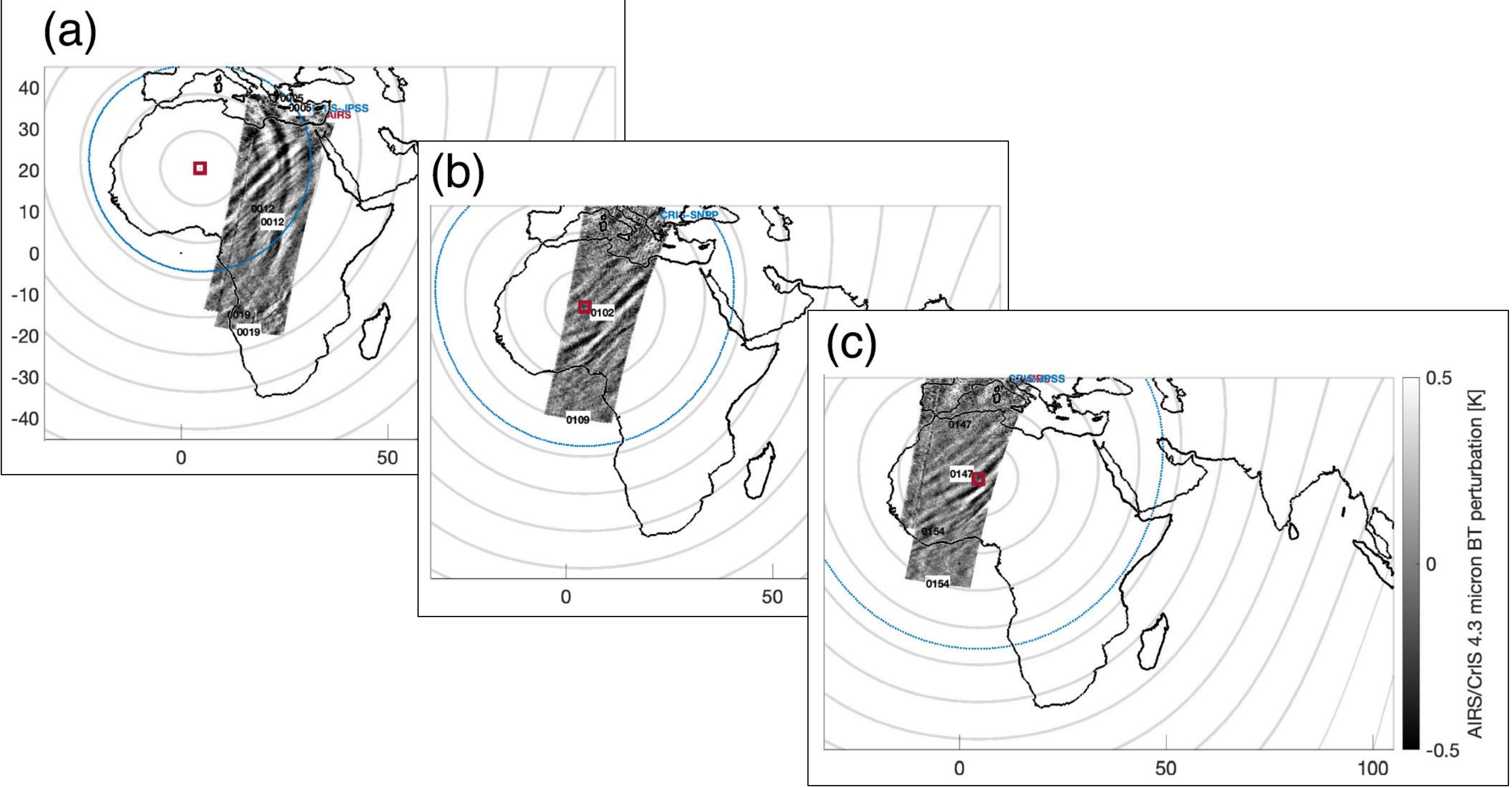


Satellite Travel Vector
Leading Gravity Wave Packet
Lamb Wave
(a)
(b)
(c)
XT Distance
500
0
-500
11:05
11:10
11:15
11:20
11:25
11:30
T' [K]
0.2
0
-0.2
A [K]
0.3
0.2
0.1
0
λ_h [km]
1000
500
0


Lamb Wave
m=0 GW
(λ_z → Inf)
Phase Speed (m/s)
350
300
250
200
150
100
50
0
100
200
300
400
500
Horizontal Wavelength (km)

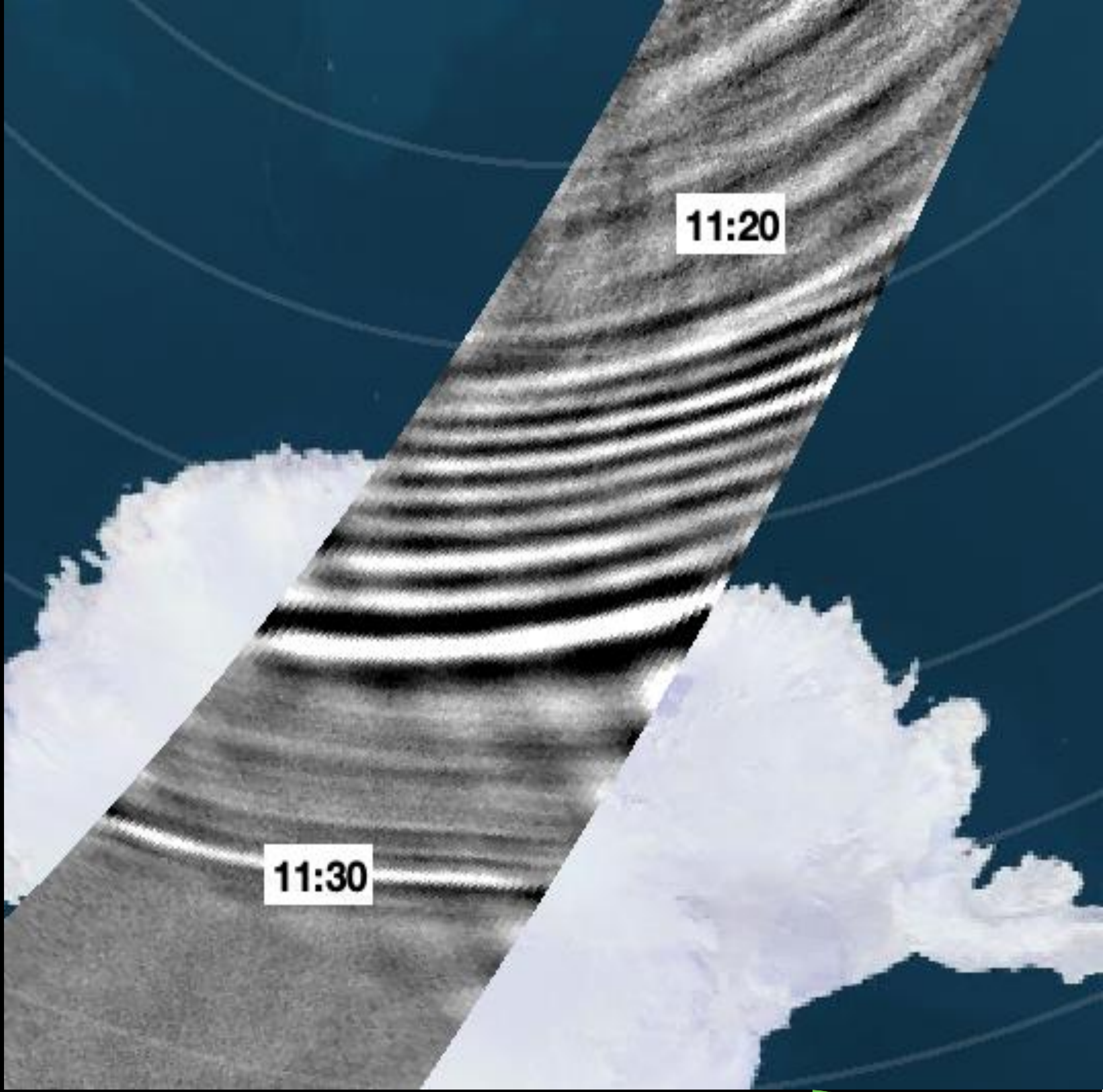


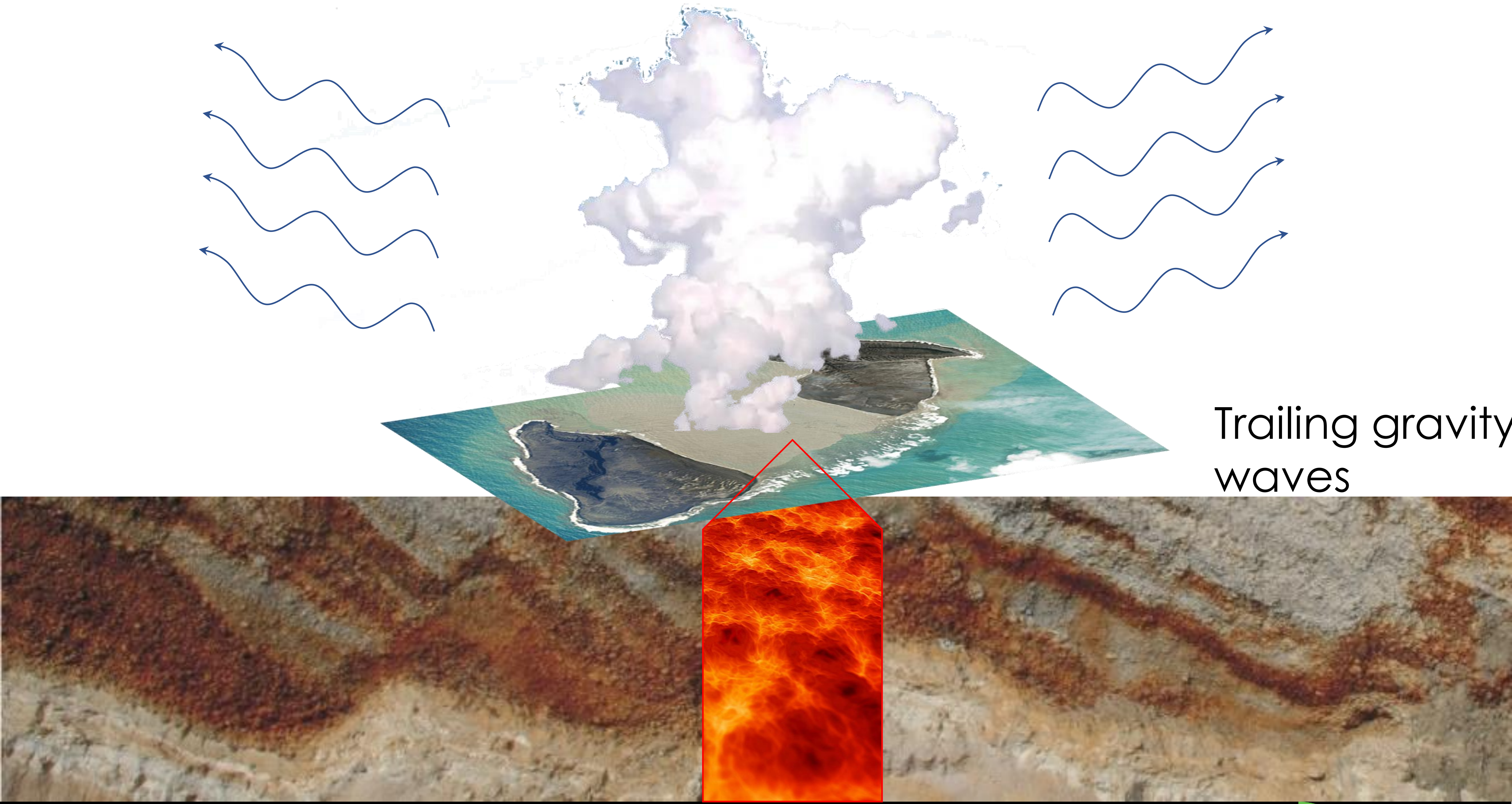

XT Distance
500
0
-500
11:05
11:10
11:15
11:20
11:25
11:30
1000
500
0
λ_h [km]

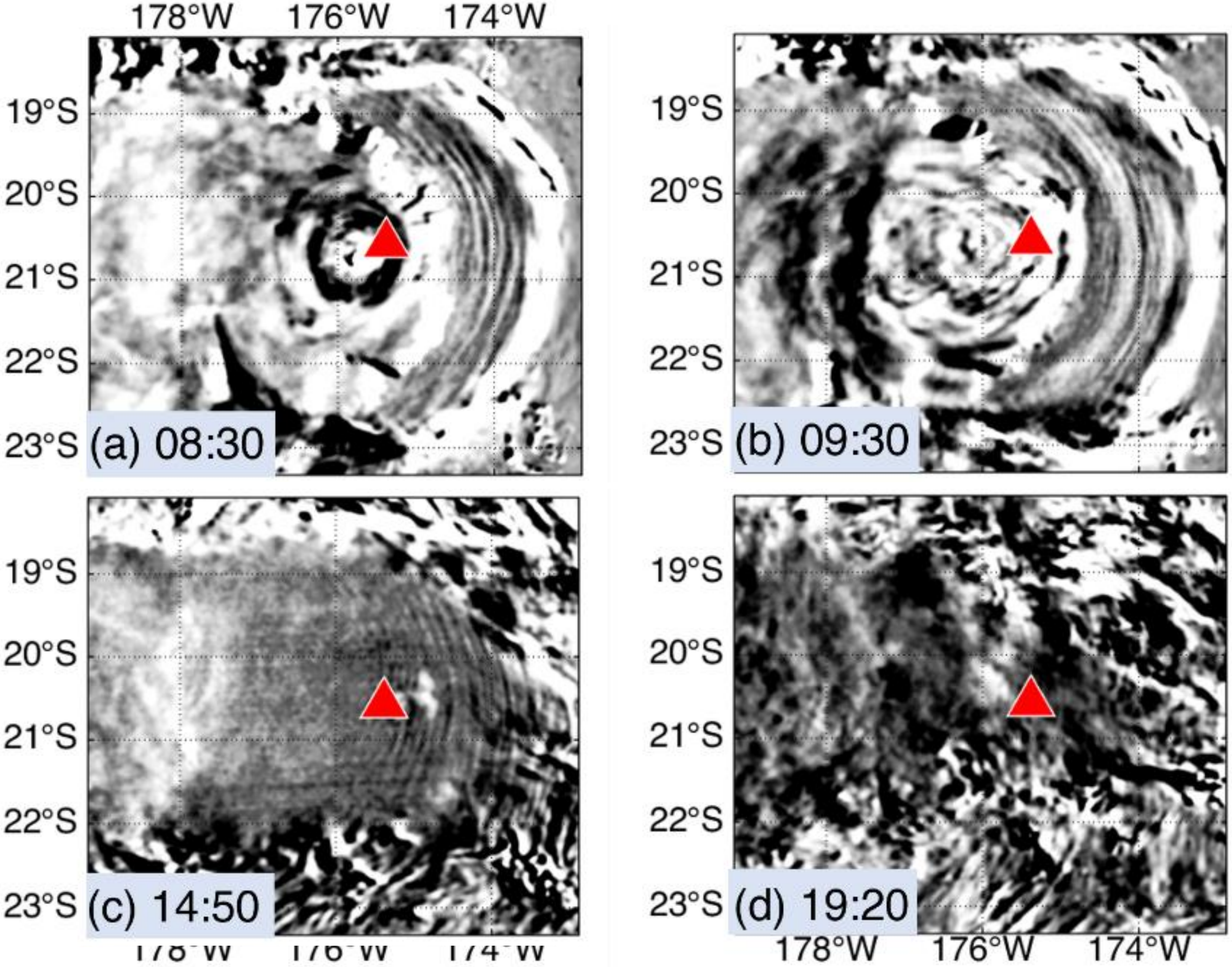

(a)
(b)
(c)
40
30
20
10
0
-10
-20
-30
-40
0
50
100
0005
CrIS-JPSS
AIRS
0012
0019
CRIS-SNPP
0102
0109
0147
0154
0.5
0
-0.5
AIRS/CrIS 4.3 micron BT perturbation [K]

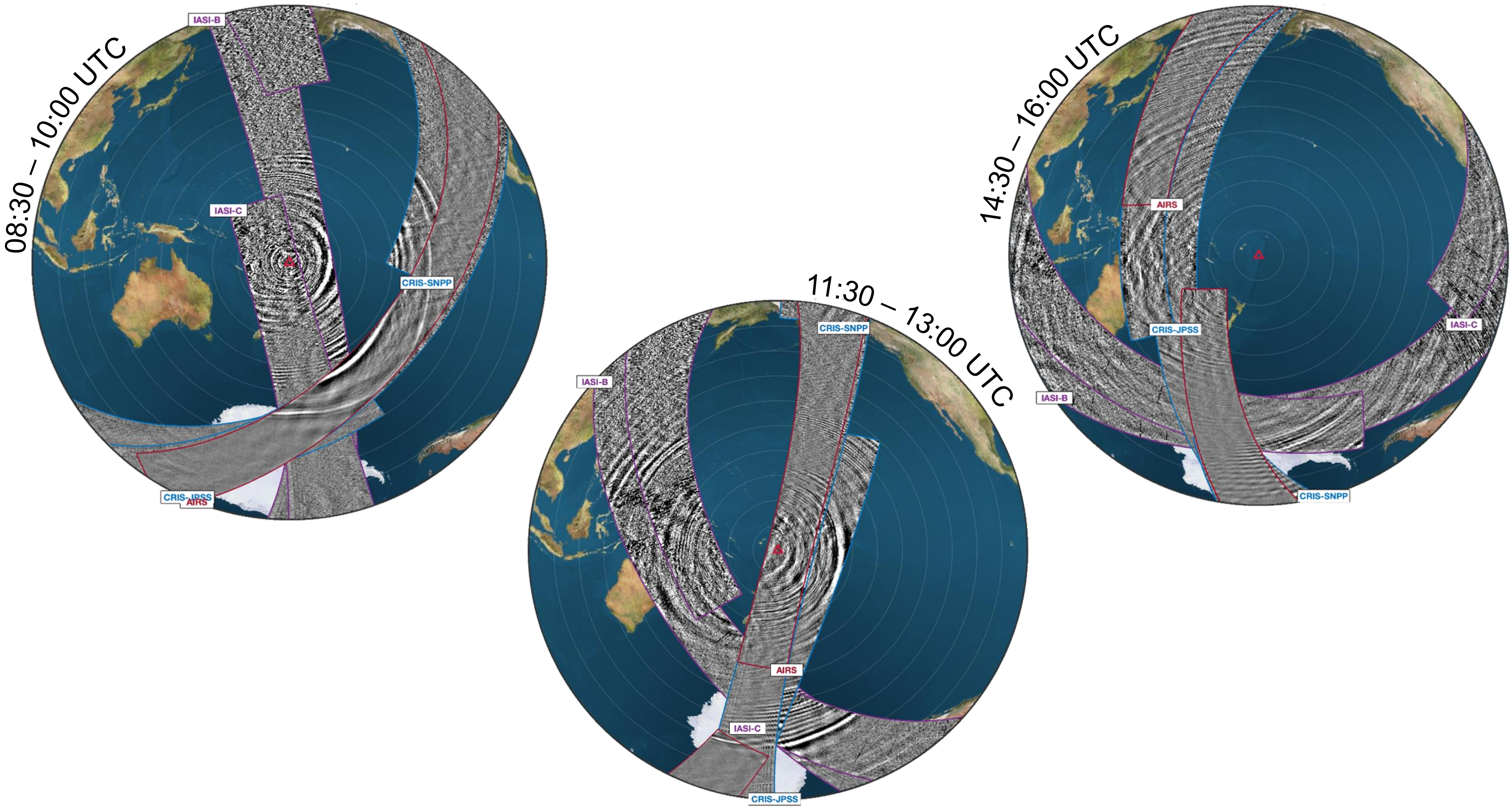
Conclusion 2:

The leading gravity waves travelled at the maximum possible speed around the Earth, splitting out across a range of phase speeds controlled by their wavelength structure.

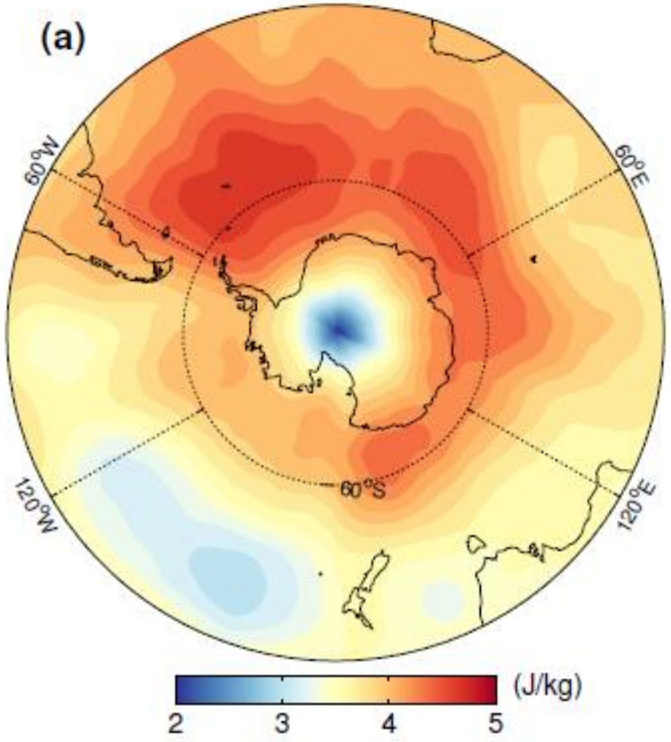


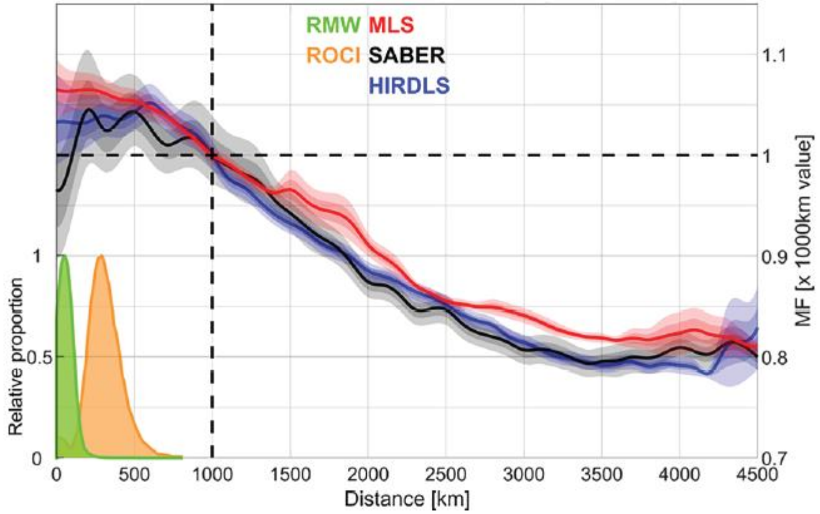

Trailing gravity
waves


178°W
176°W
174°W
19°S
20°S
21°S
22°S
23°S
(a) 08:30
(b) 09:30
(c) 14:50
(d) 19:20


08:30 – 10:00 UTC
IASI-B
IASI-C
CRIS-SNPP
CRIS-JPSS
AIRS
11:30 – 13:00 UTC
IASI-B
CRIS-SNPP
AIRS
IASI-C
CRIS-JPSS
14:30 – 16:00 UTC
AIRS
CRIS-JPSS
IASI-C
IASI-B
CRIS-SNPP

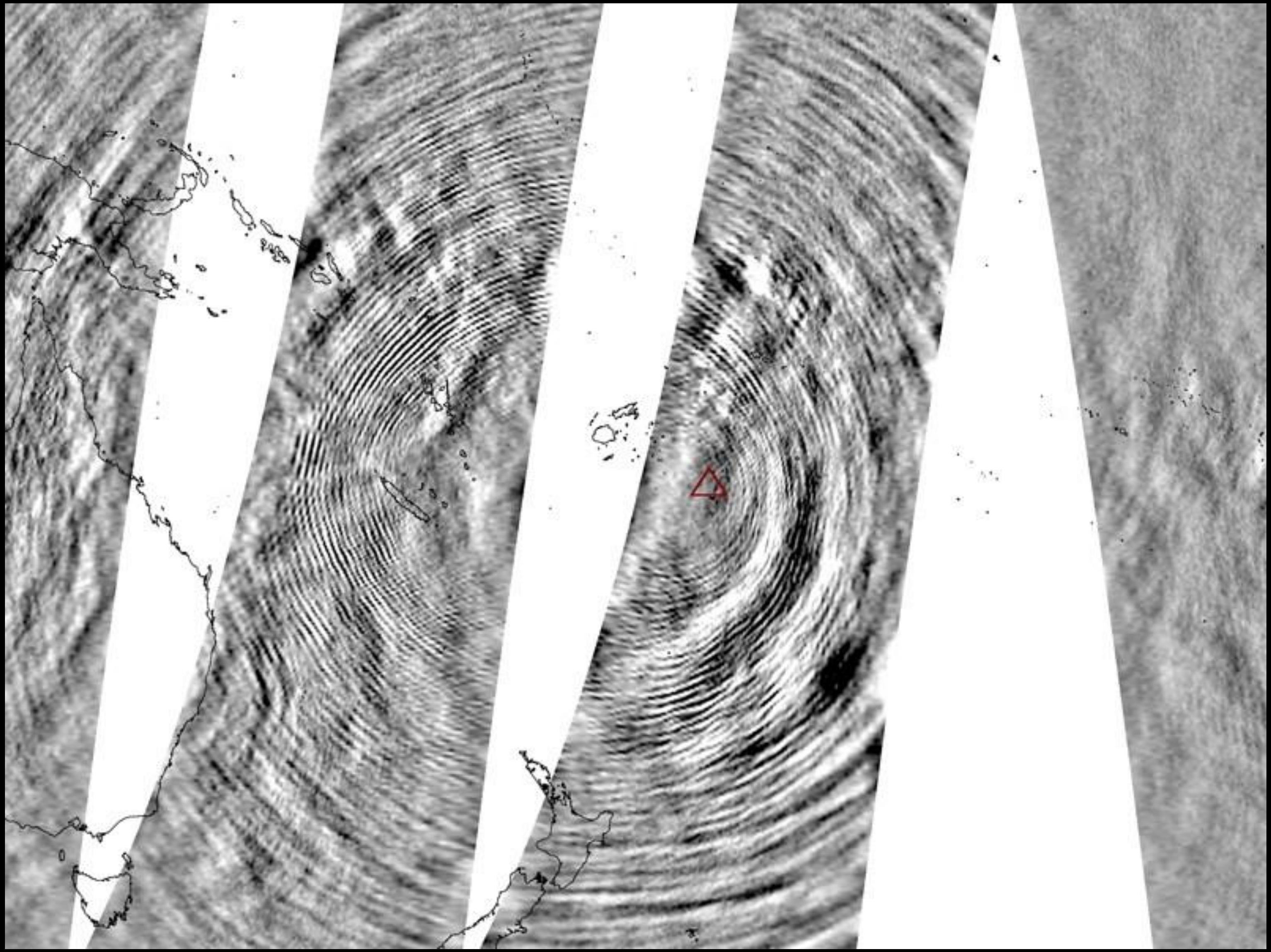
- Range of these GWs is ~9000km
- This is a **huge range** for stratospheric GWs:
  - Oro GWs waves theoretically don't travel
  - Even if refracted into the polar vortex, still <1/10 of area these covered
- Hurricane GWs propagate <~3500km at most (same is true for other convective waves) – also comparatively localised



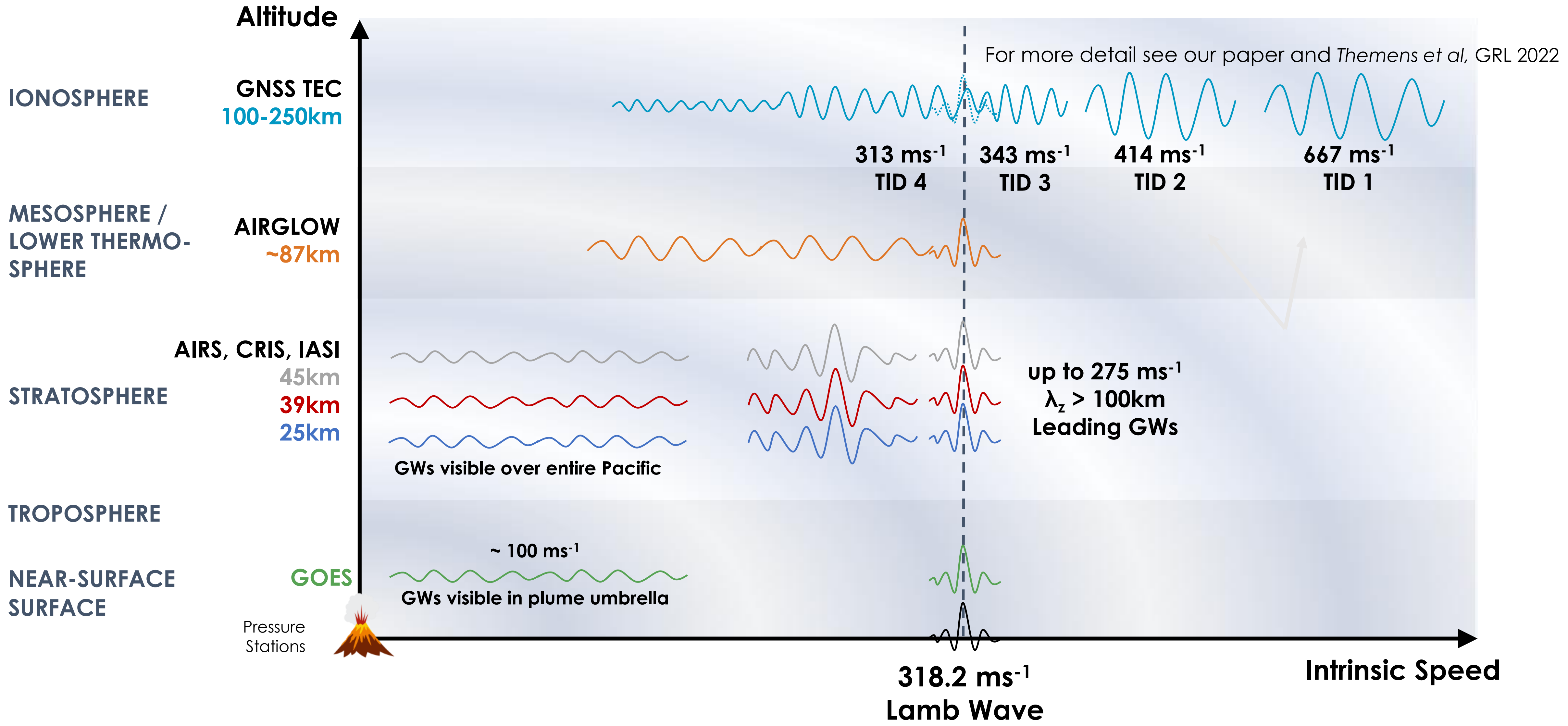


Conclusion 3:

The relatively minor 'trailing' gravity waves dominated the entire Pacific basin for most of a day, dominating a larger area than any previously-observed GW source.



Atmospheric Waves from the Tonga volcano: Surface to Spac



Conclusions

- Hunga Tonga explosive power unusually large – possible largest since Krakatoa (1883)
- Initial Lamb wave propagated around the Earth at ~318 m/s, hitting antipode after 17.5 hrs
- Initial gravity waves also propagated around the Earth, at ~240-275 m/s and splitting out by wavelength
- Subsequent "minor" gravity wave activity still largest ever recorded in stratosphere

Implications

- Fantastic natural experiment for understanding:
  - basic atmospheric state (via Lamb and GW propagation comparisons)
  - convective wave generation
  - how to separate 'source' terms from 'propagation' terms in GW studies

Would you like to know more?

- Paper accepted at *Nature*, out soon: preprint at doi:10.1002/essoar.10510674.2