Fine-vertical-scale Waves near the Tropical Tropopause: Observations and Impacts

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Jennifer Haase and Bing Cao (Scripps)

Motivation: *Short Vertical Wavelength (λ_Z) Tropical Waves*

…have important climate influences:

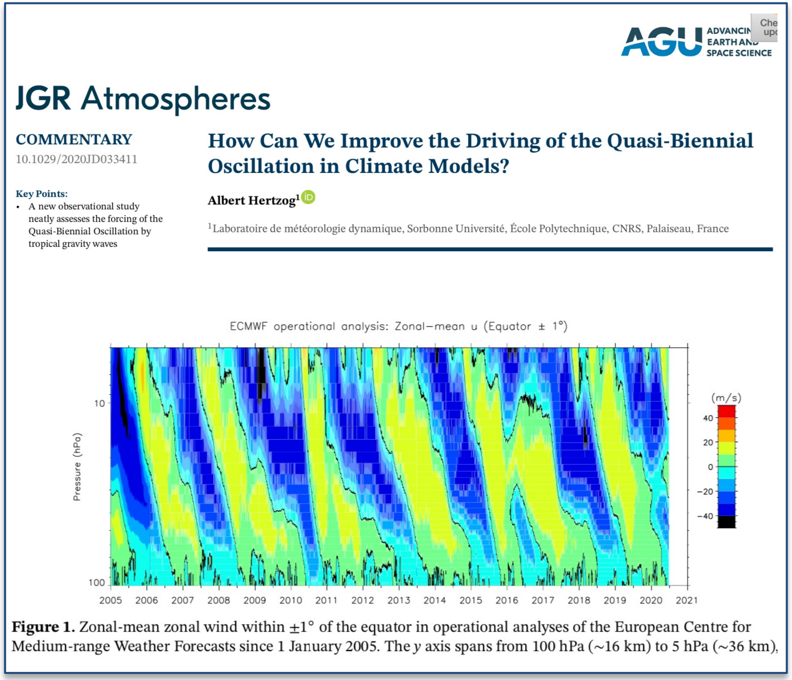
- Tropical waves drive the QBO through selective dissipation of waves below their critical levels (where $\lambda_Z \rightarrow 0$)
- Climate model QBOs are far too weak in the lower stratosphere, and as a result QBO teleconnections to surface climate are weaker than observed.

Recent observational studies emphasize:

- Dissipation closer to critical levels will give larger forces:

$$Force = -\frac{1}{\rho(z)}\frac{\delta Flux}{\delta z}$$

e.g. ***Vincent & Alexander [2020]***


JGR Atmospheres
COMMENTARY
10.1029/2020JD033411

Key Points:
- A new observational study neatly assesses the forcing of the Quasi-Biennial Oscillation by tropical gravity waves

How Can We Improve the Driving of the Quasi-Biennial Oscillation in Climate Models?

Albert Hertzog[1]
[1]Laboratoire de météorologie dynamique, Sorbonne Université, École Polytechnique, CNRS, Palaiseau, France

Figure 1. Zonal-mean zonal wind within ±1° of the equator in operational analyses of the European Centre for Medium-range Weather Forecasts since 1 January 2005. The *y* axis spans from 100 hPa (~16 km) to 5 hPa (~36 km),

Hertzog [2020]

Motivation: *Short Vertical Wavelength (λ_Z) Tropical Waves*

…have important climate influences:

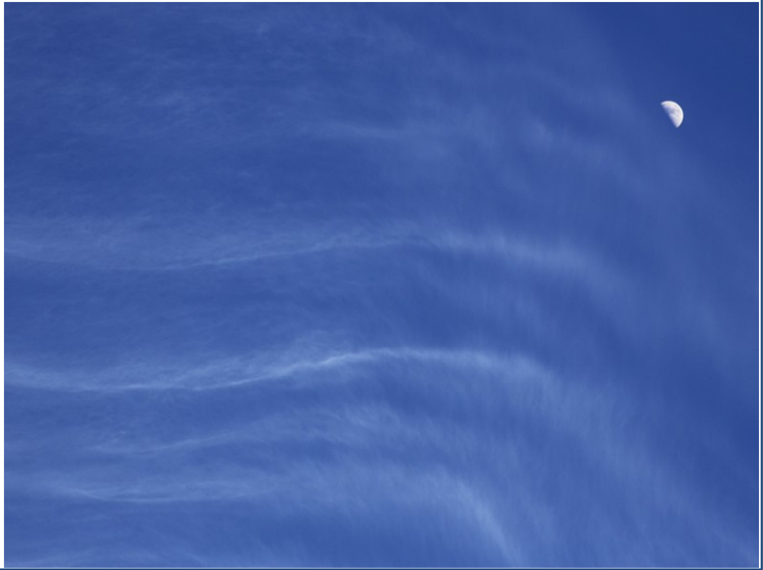
Waves modulate tropopause layer cirrus clouds and ice particle precipitation. *[Jensen et al. 2017]*

Short λ_Z waves enhance dehydration of stratospheric air with a cooling effect on the planet. *[Kim and Alexander 2016]*

Atmospheric Waves Help Cool Our Planet

A new method makes a direct estimate of the impact of atmospheric waves on water vapor concentrations in the stratosphere.

Source: Geophysical Research Letters



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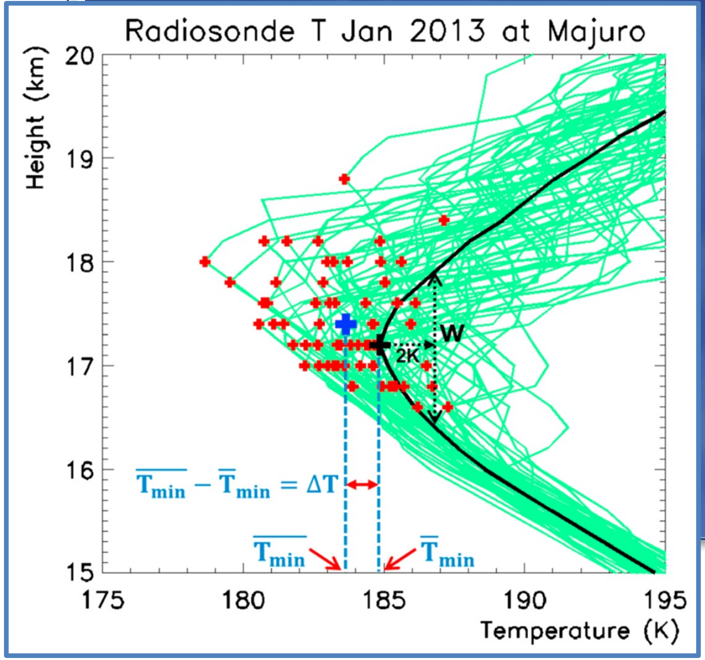
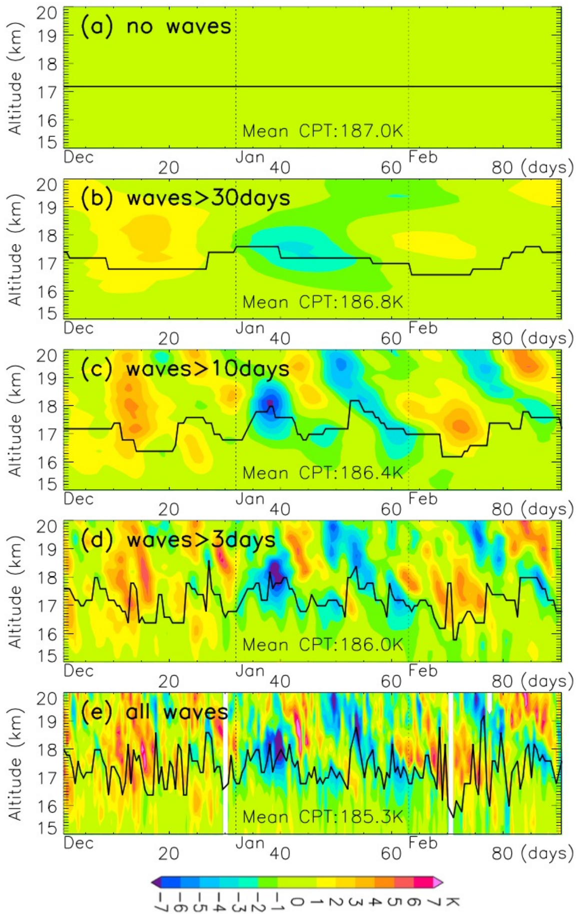
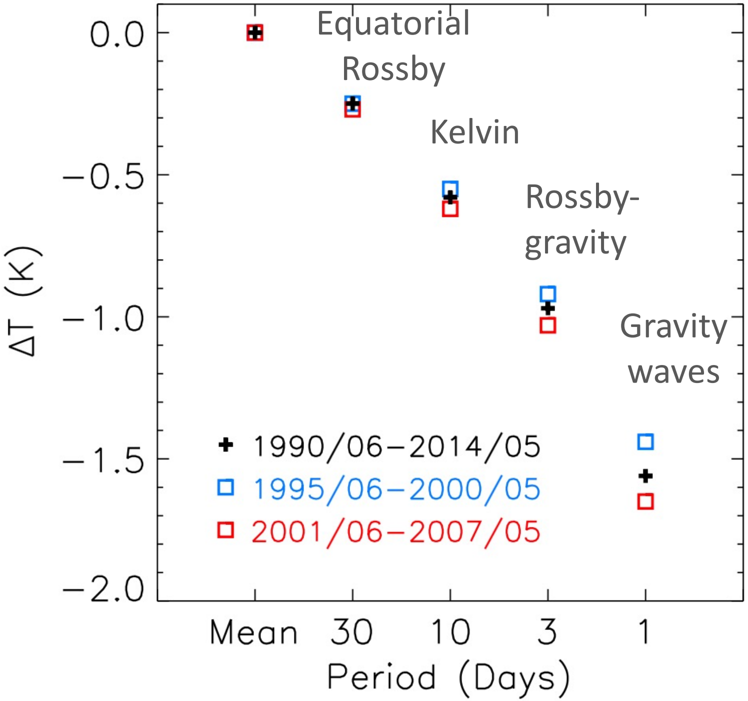
Waves enhance dehydration by lowering the cold point temperature of the tropical tropopause. [Kim and Alexander 2015]



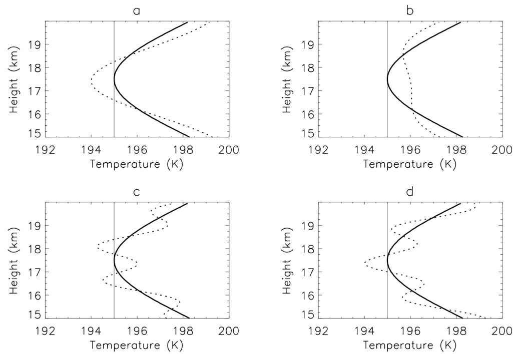
Tropical Waves in Radiosondes



What types of waves most affect Cold Point Temperature?



Answer:
The whole spectrum,
but short λ_Z are
more effective.



[Kim & Alexander, 2015]

Analyses of Tropical Gravity Waves

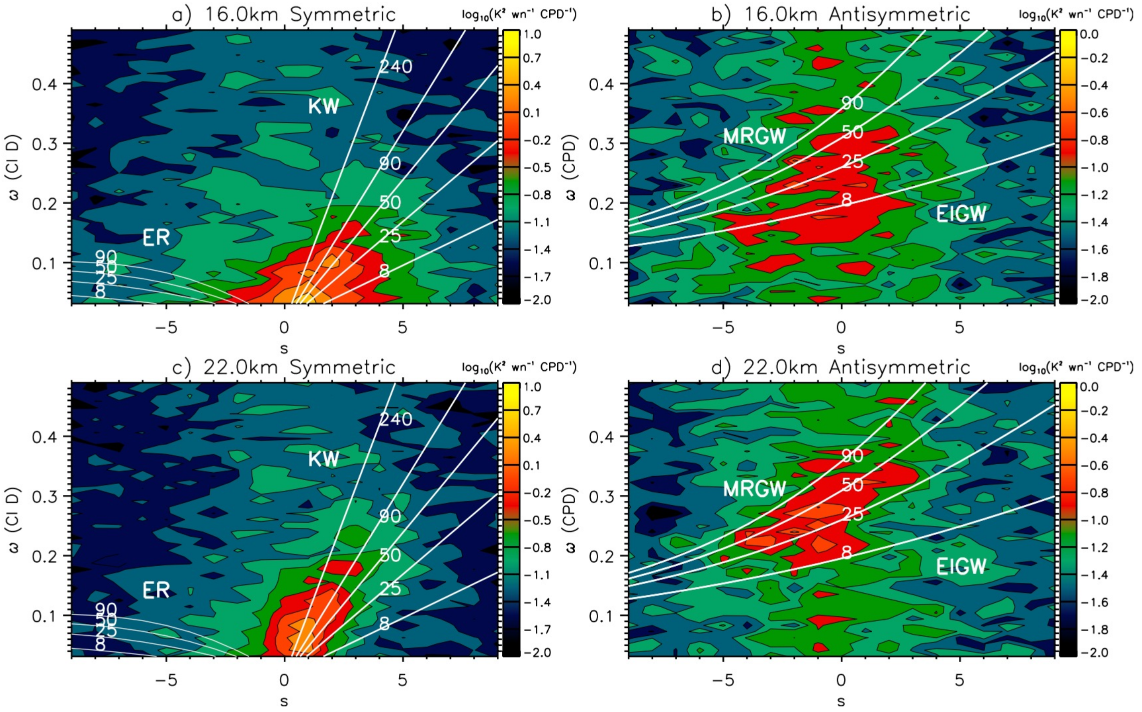
First step is always removing a "background" to isolate gravity wave perturbations
- Vertical filtering does not isolate gravity waves in the tropics!!!
- Time filtering can isolate low vs high frequencies (radiosondes)
- Combinations of time+space (satellite methods)

Some considerations:
- There is no clear scale break between large and small wave periods.
- Vertical scale does not discriminate between global-scale/low-frequency waves and small-scale/higher-frequency gravity waves.
- Dispersion equations relate spatial wavenumbers to *intrinsic frequency*
- There are differences between *intrinsic* (ω_i) and ground-based (ω_0) frequency, particularly in lower stratosphere

$$\omega_i = \omega_0 - \mathbf{U} \cdot \mathbf{k}$$

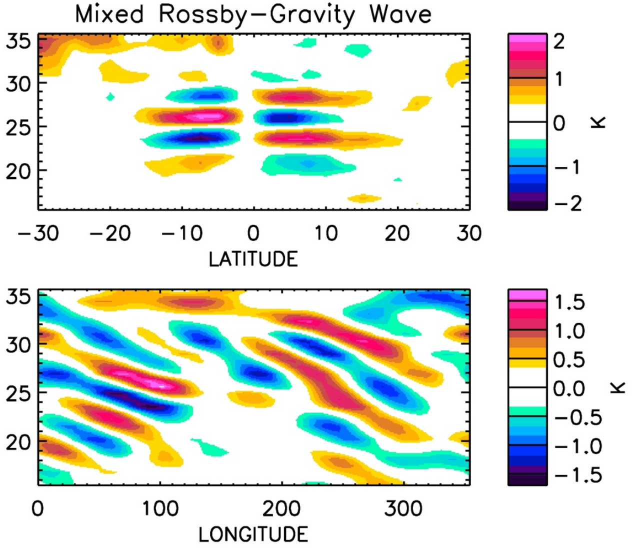
Satellite Examples of Space-Time Analysis

Wavenumber vs Frequency: COSMIC Temperatures



[S. P. Alexander et al. 2008]

Tropical Wave Modes (lat,z): HIRDLS Temperatures



Many occurrences of global scale waves with λ_z~4km (the minimum observable)

[Alexander & Ortland 2010]

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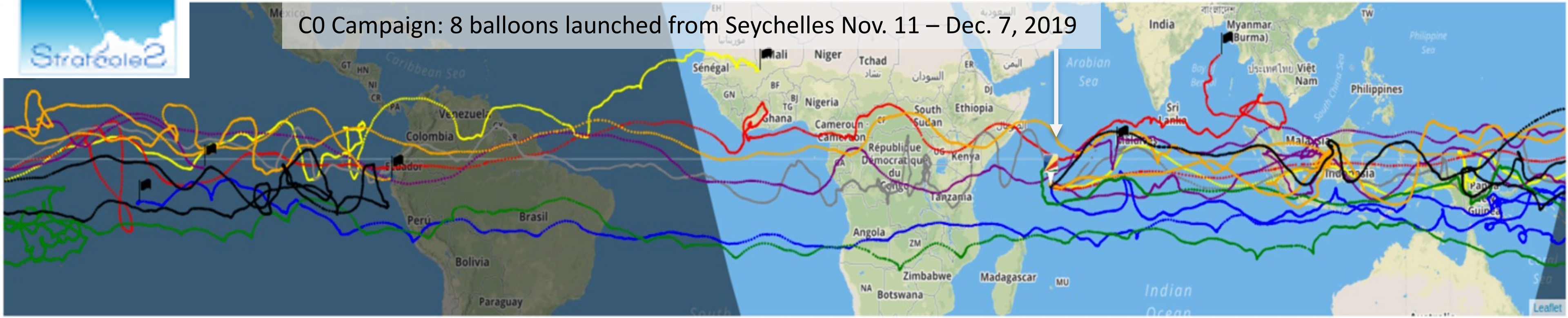
Strateole-2:

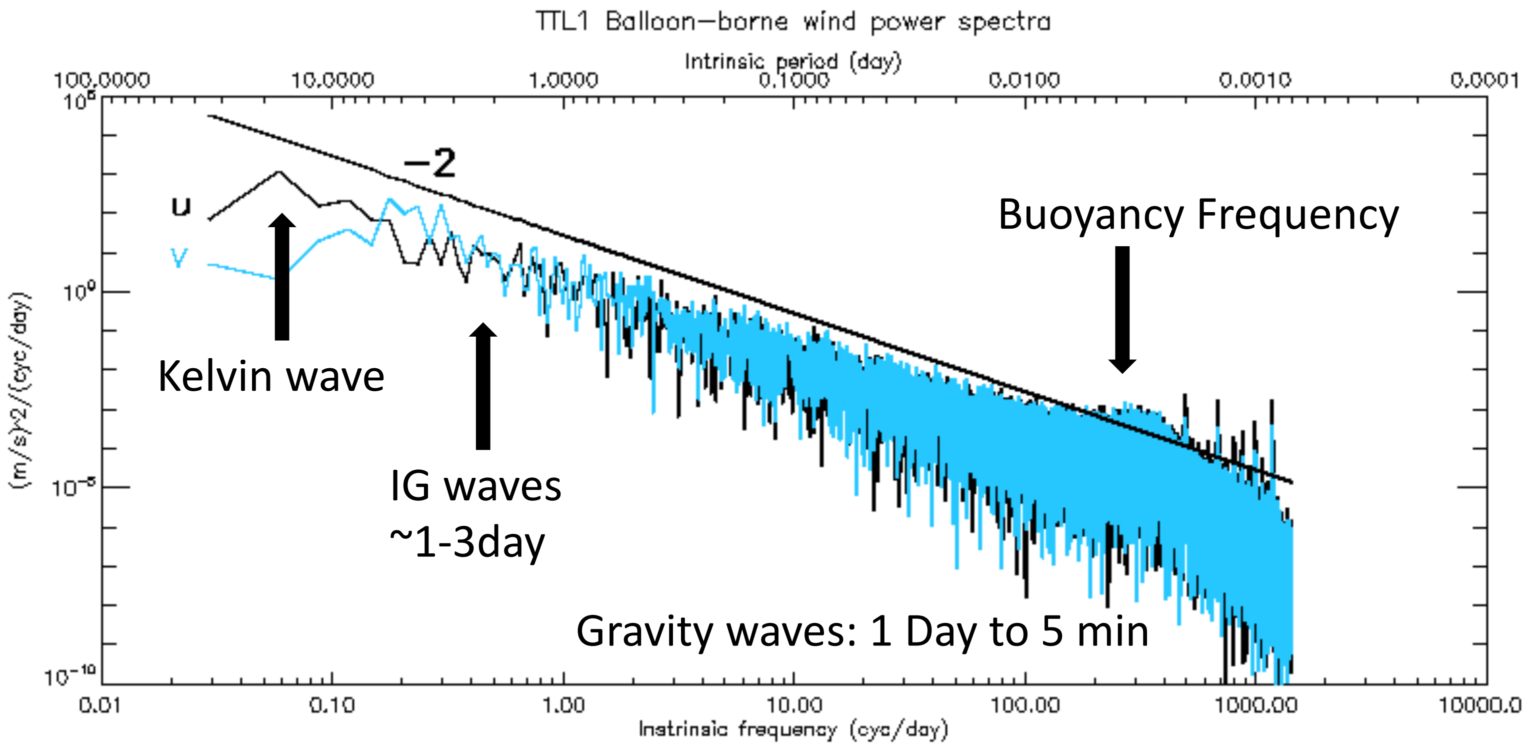
Exploring the tropical UTLS with long-duration balloons



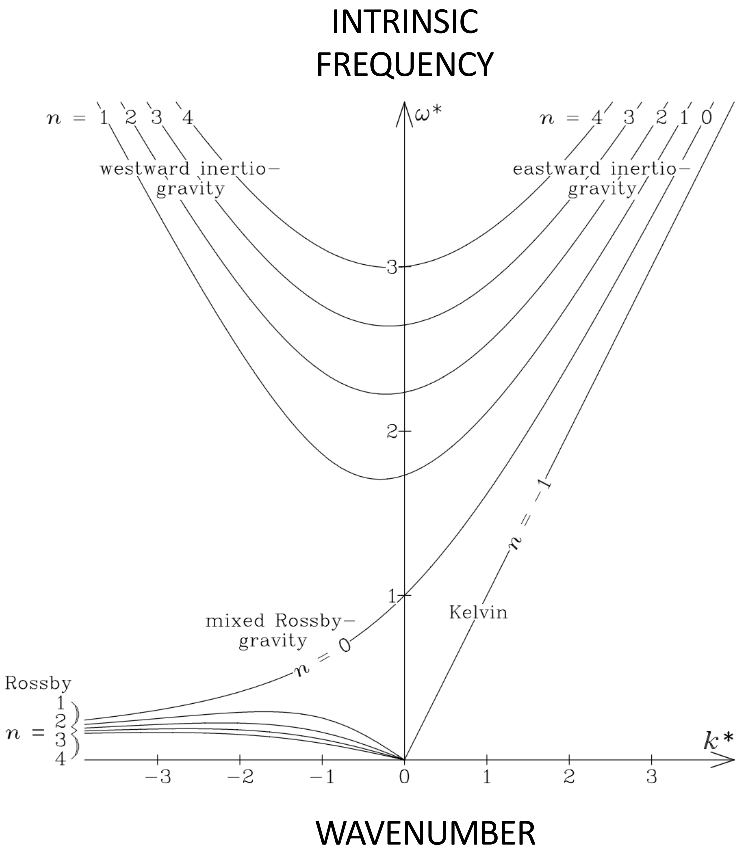
C0 Campaign: 8 balloons launched from Seychelles Nov. 11 – Dec. 7, 2019

- 30s measurement cadence observes the full tropical wave spectrum
- TSEN Instrument Measurements: u, v, T, z, p
- Radio-Occultation Sensor (ROC) on one balloon gave high resolution T(z)

Strateole2 Balloons: 30s Resolution & Multi-month Duration:
Full Tropical Wave Spectrum

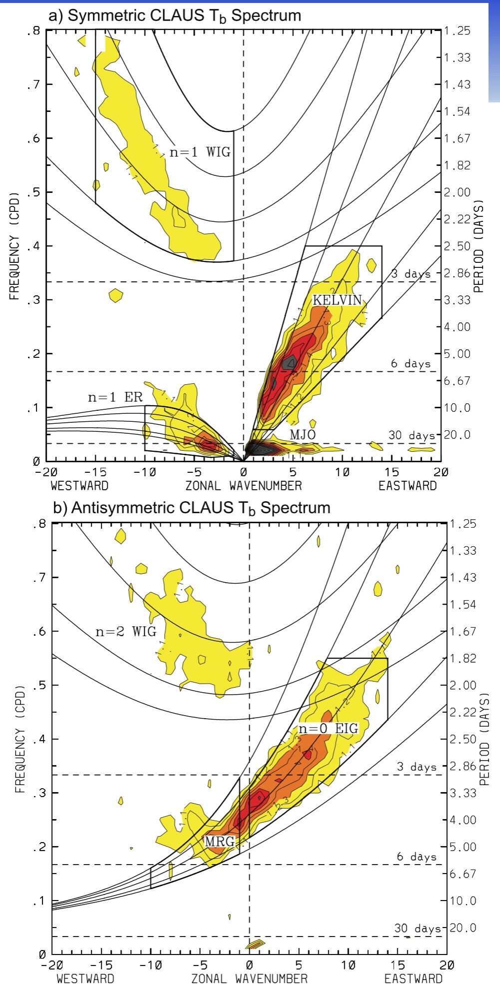


Tropical Wave Dispersion Relations



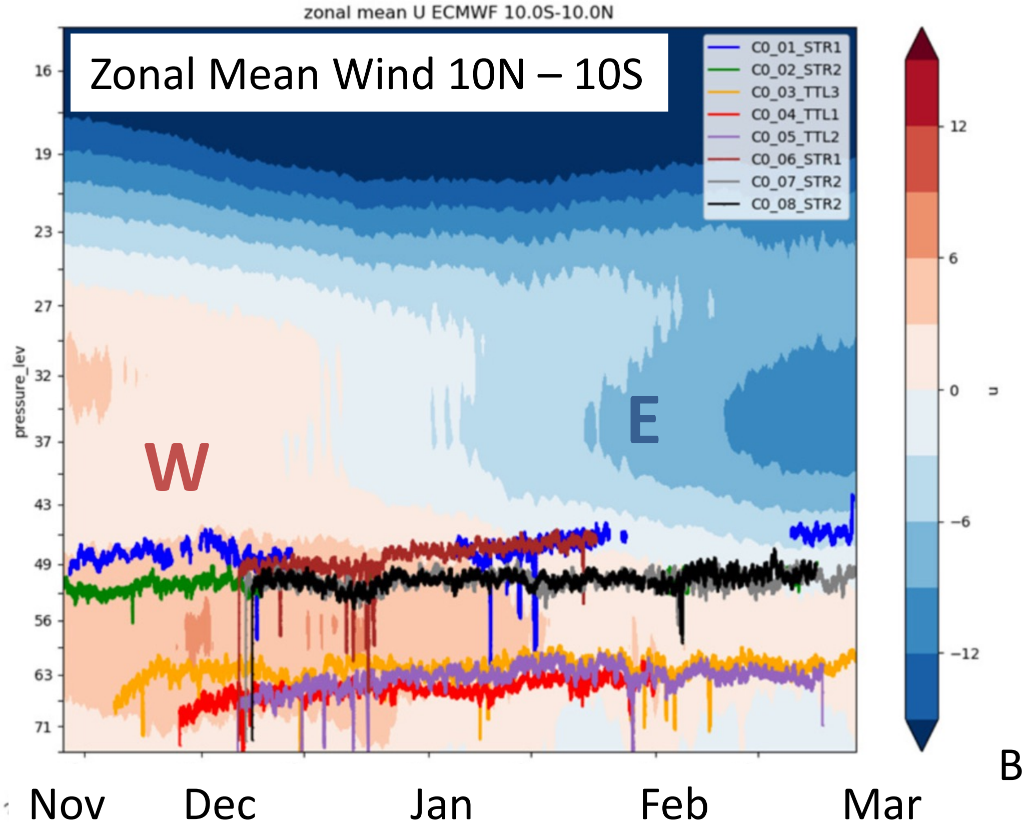
Wheeler & Kiladis [1999]:

- Cloud-top brightness temperatures
- Data analyzed for **ground-based** frequencies and tropospheric vertical wavelengths.
- Balloons rather uniquely observe intrinsic frequency!
- Family of curves for different λ_Z .



Figures from Kiladis et al. 2009

Balloon-borne Radio-Occultation (BRO) measurements 2019-2020 Strateole-2

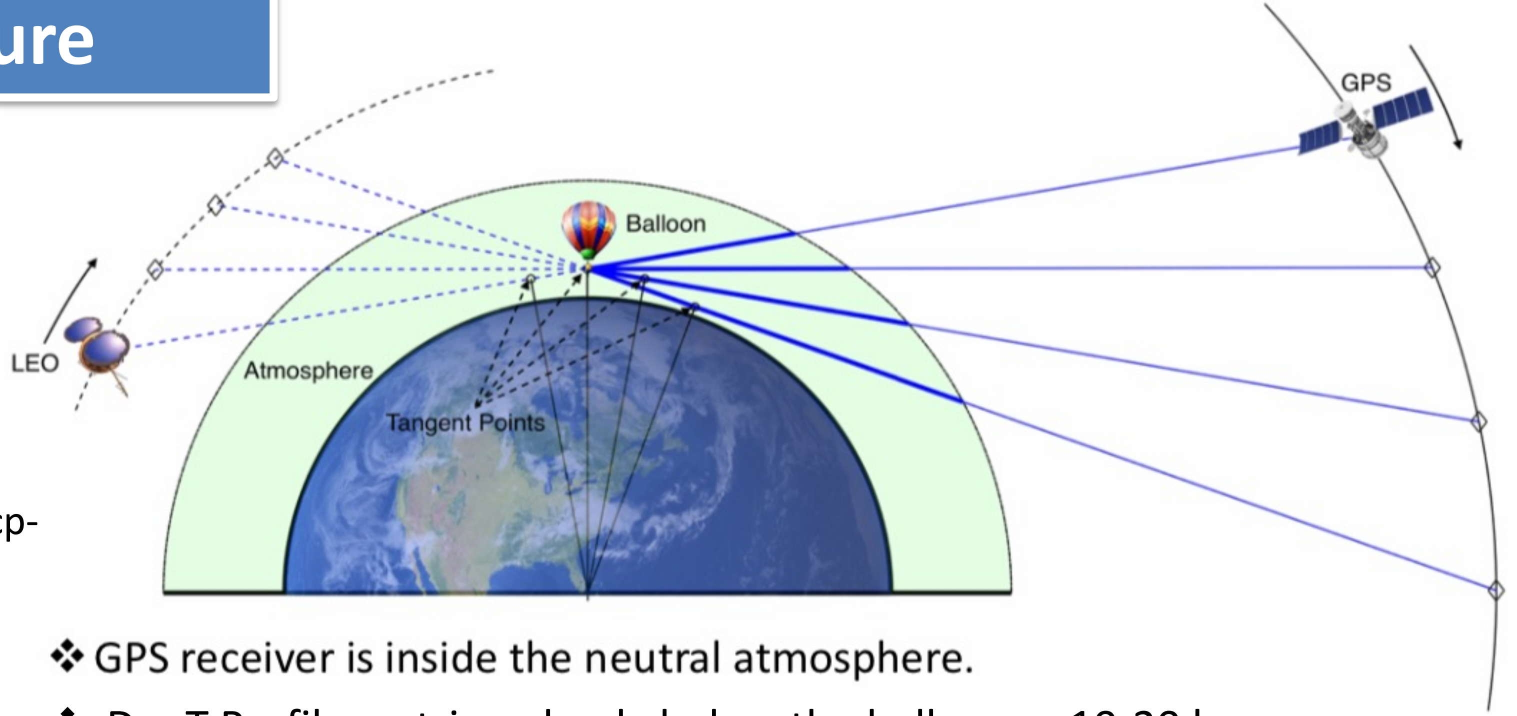


- Balloons drifted eastward with QBO flying at two levels: ~65 and ~50 hPa
- This talk: **STR1** balloon carrying "ROC" Radio-Occultation profiler observations of low-frequency tropical waves in the lower stratosphere.

Bramberger et al. [2022]

Measurements of Wave Vertical Structure

Balloon-borne RO

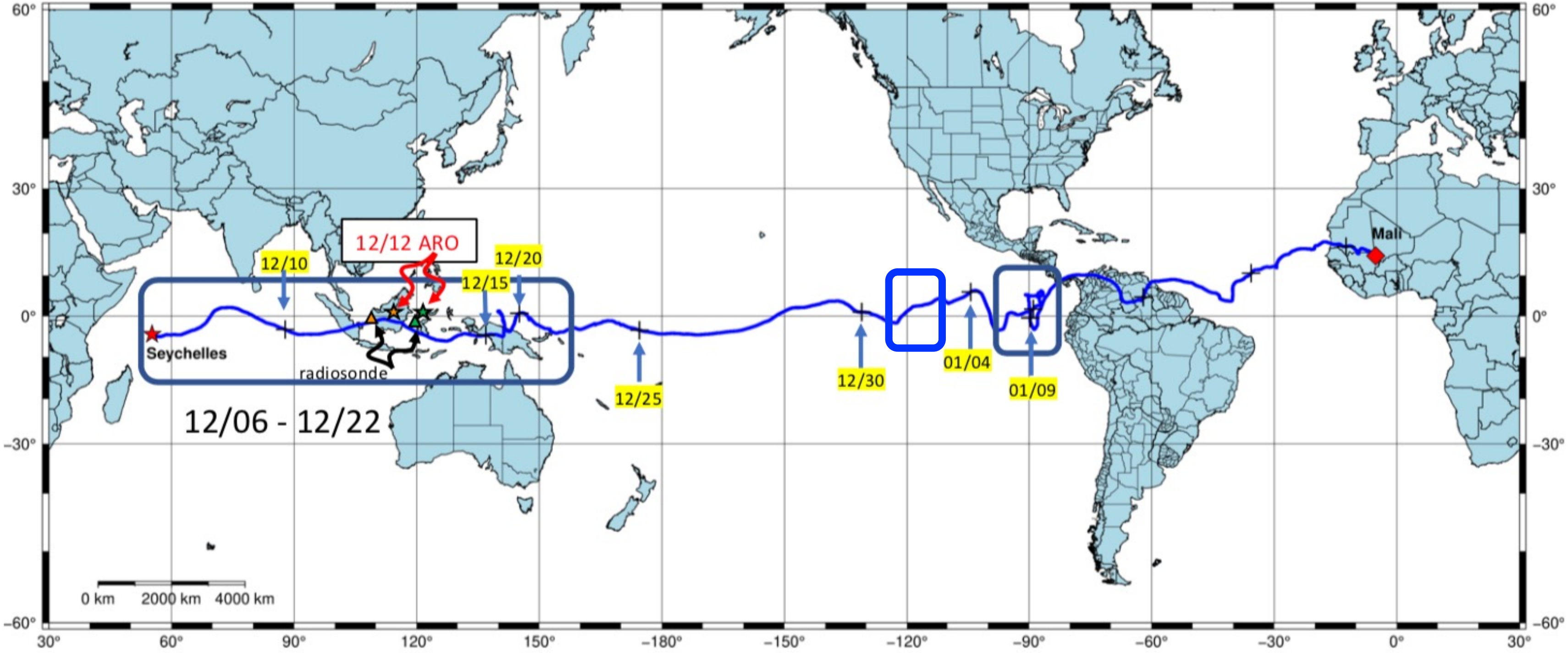


Cao et al. [2022]
ACP, DOI: 10.5194/acp-22-15379-2022

- ❖ GPS receiver is inside the neutral atmosphere.
- ❖ Dry T Profiles retrieved only below the balloon z~10-20 km
- ❖ Vertical resolution is a bit higher than COSMIC2 LEO satellite RO

Balloon-borne RO Temperature Profiles

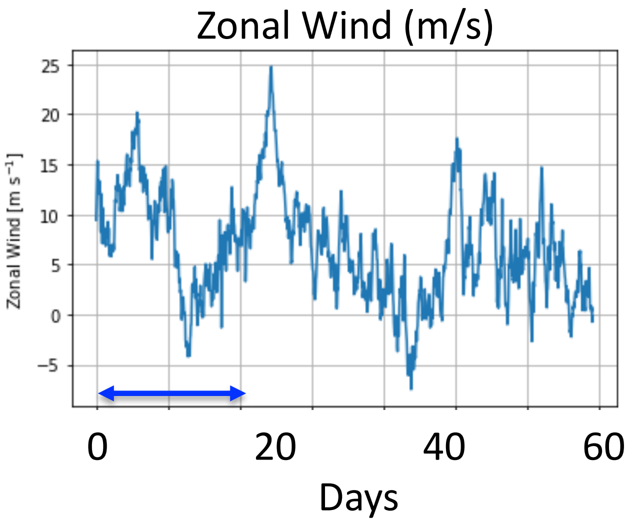
from the Strateole-2 Superpressure Balloon Flight 12/6/19-2/1/20

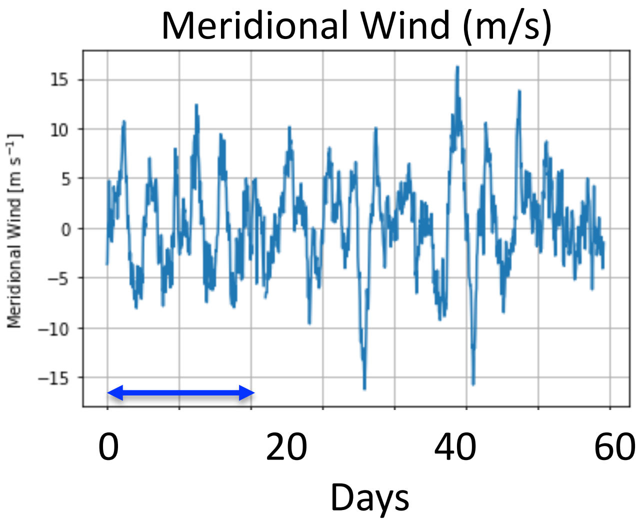


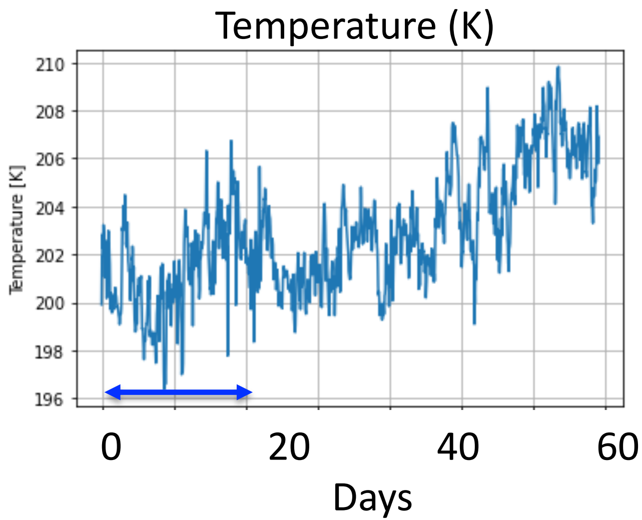
- Data recovered from Iridium link is mostly from the area in boxes, 17-day continuous part in Indian Ocean/SW Asia, some from East Pacific near South America.

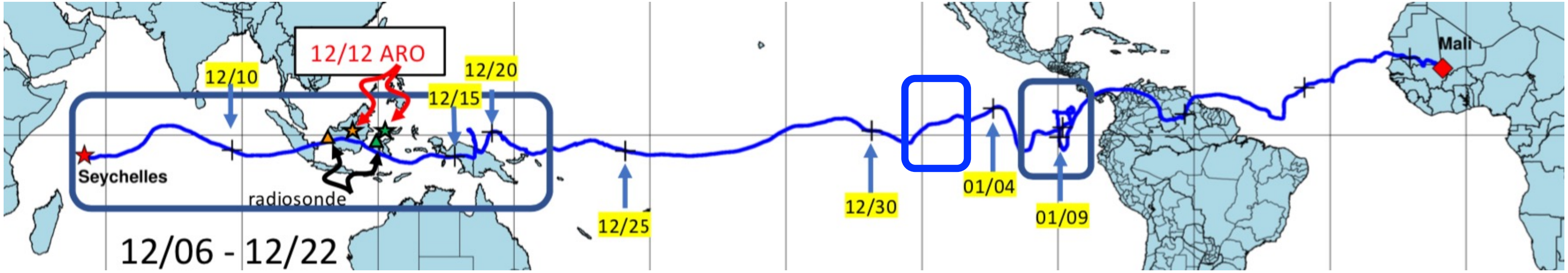
Balloon in situ measurements

30 sec sampling resolves gravity waves and equatorial wave modes



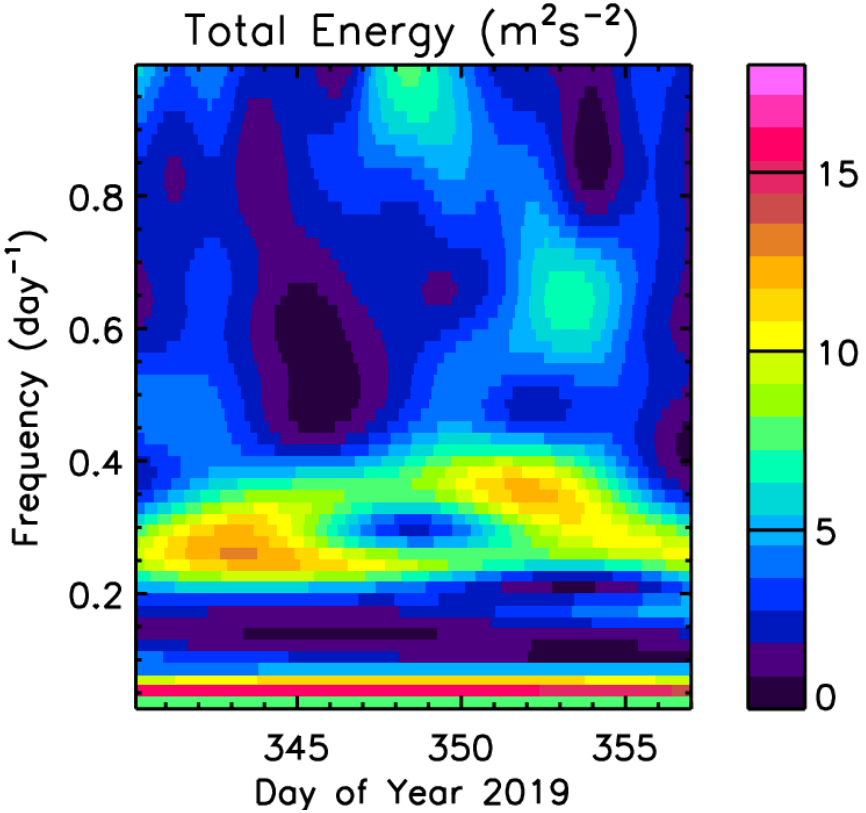


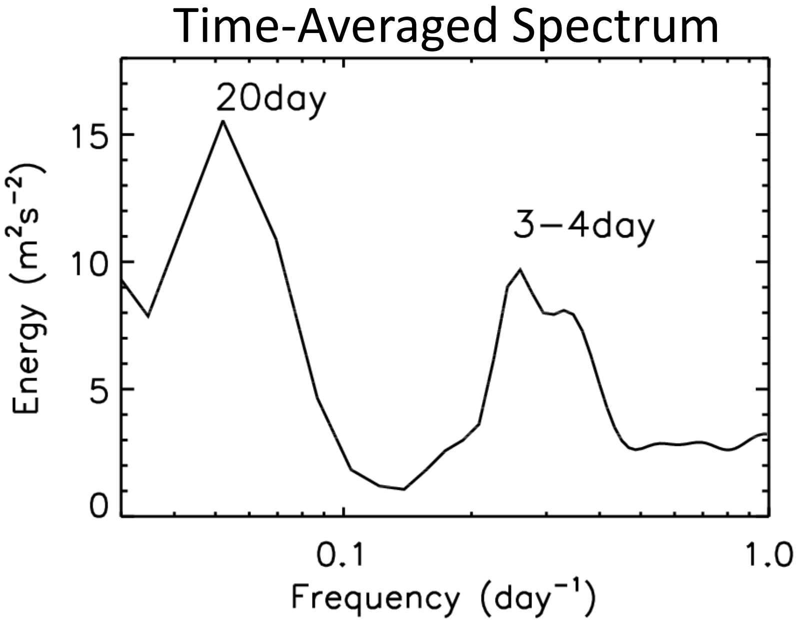




Flight Level S-Transform Total Energy Spectrum

20day Kelvin Wave and 3-4day Inertia-Gravity Wave

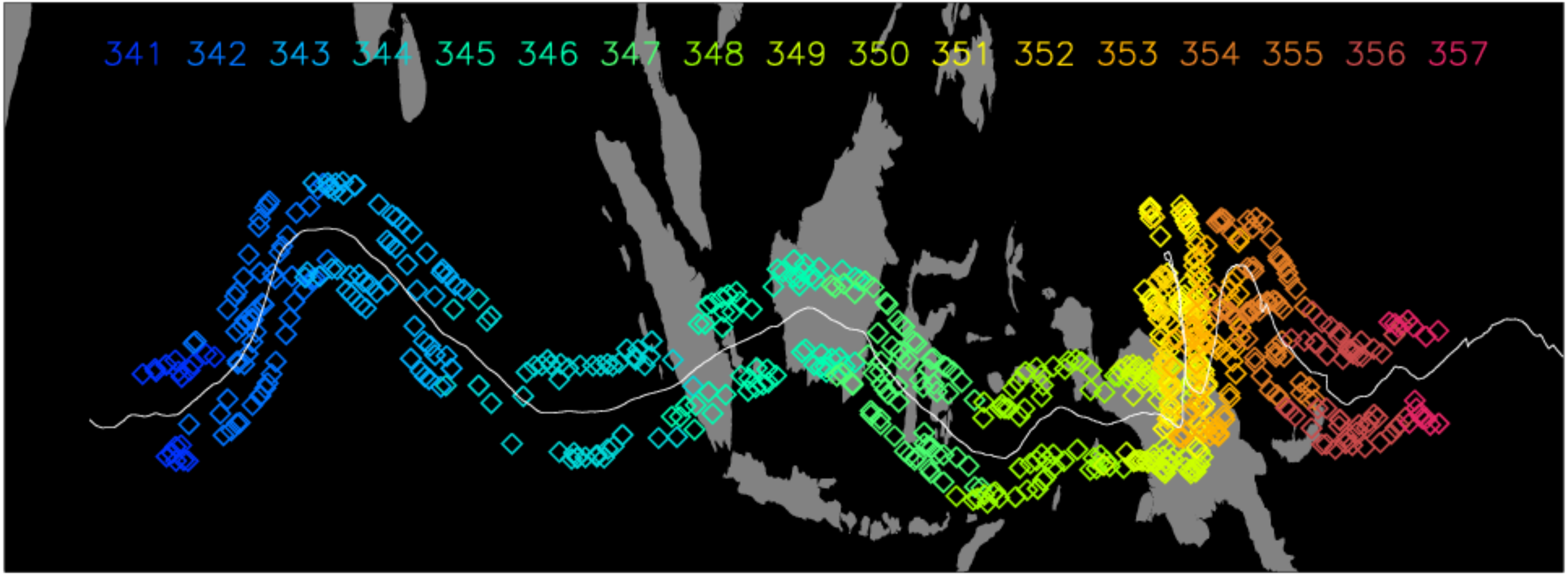




BRO Tropopause Tangent Points

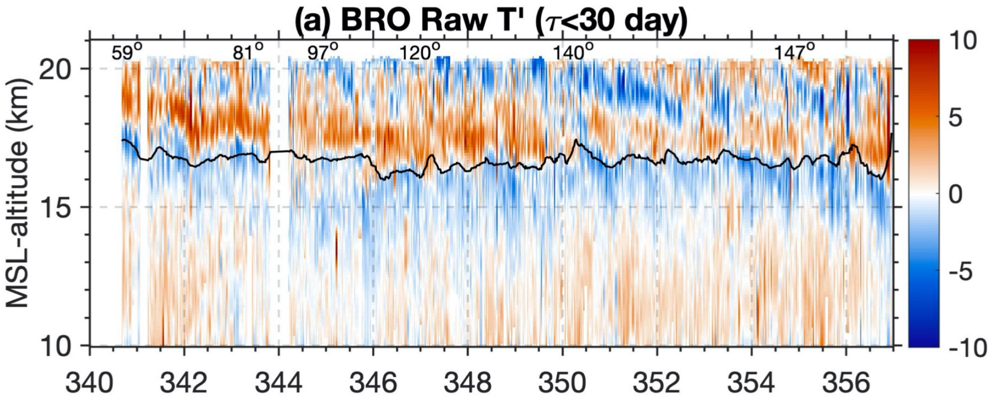
DOY: 340-357 = Dec 6-23, 2019

> 40 profiles/day

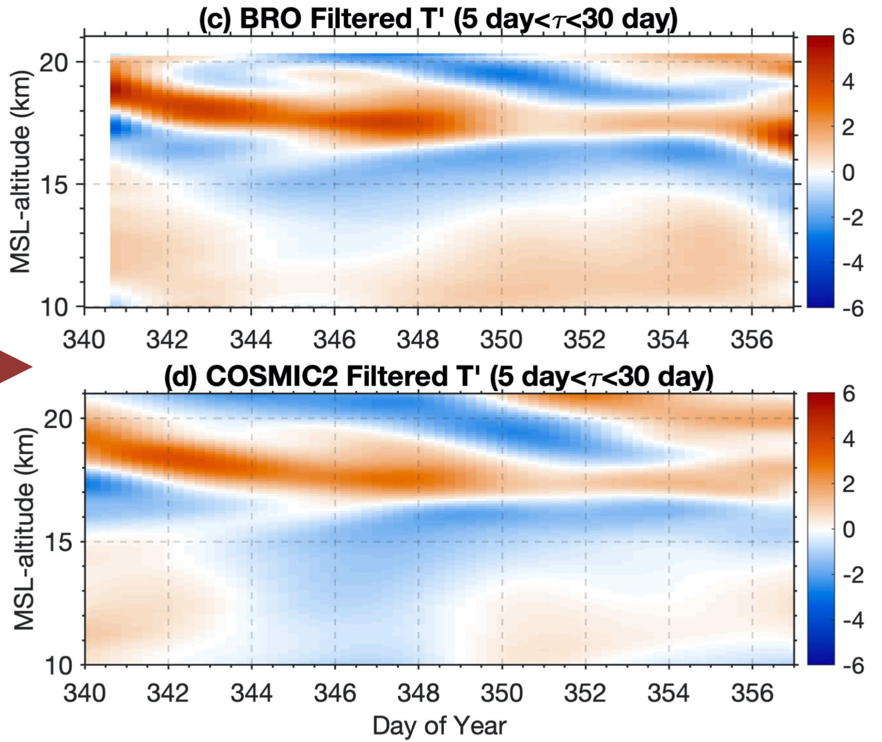


BRO Temperature Profiles 2019

Time-height series of BRO anomalies (K) with periods < 30 days



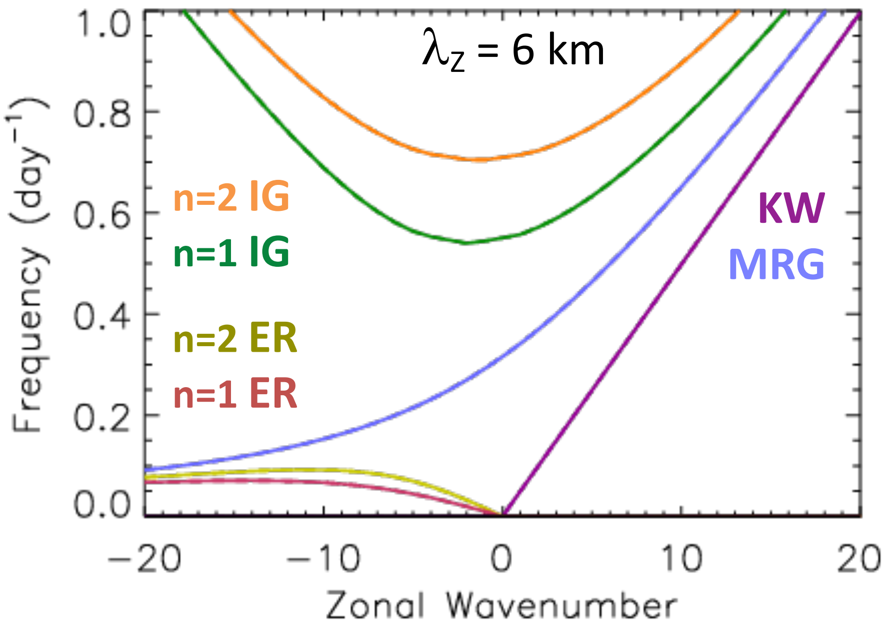
Define anomalies relative to balloon-following COSMIC2 space-time averages

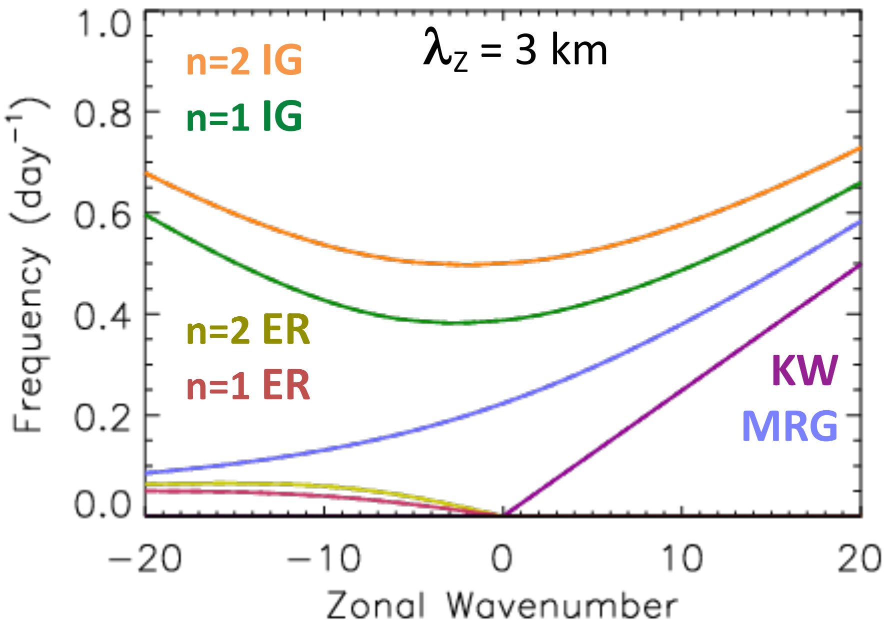


20-day period Kelvin Wave

- BRO shows blend of two KW signals:
  - λ_Z = 6km → WN 1
  - λ_Z = 3km → WN 2
- Very similar to COSMIC-2, but 3km wave is ~50% weaker amplitude–Better vertical resolution with BRO in the stratosphere.

Tropical Waves Dispersion Relation Curves





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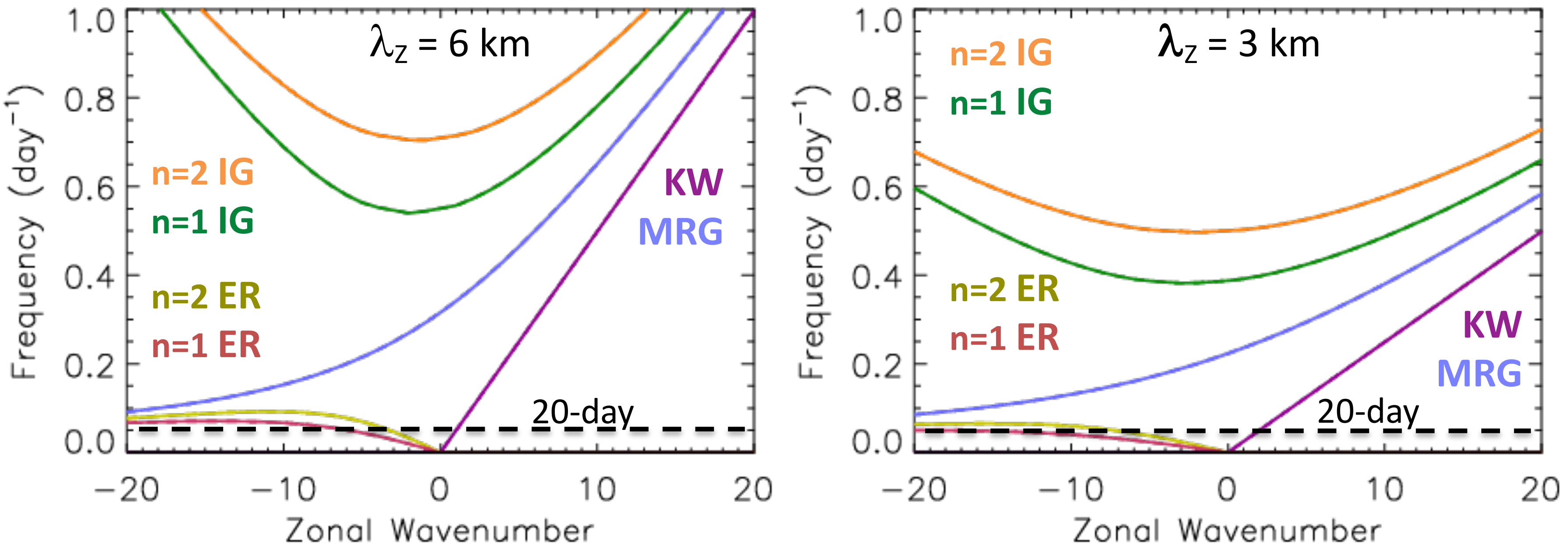

Additional information: v'=0; u' T' in quadrature
→ Identifies these two modes as Kelvin waves

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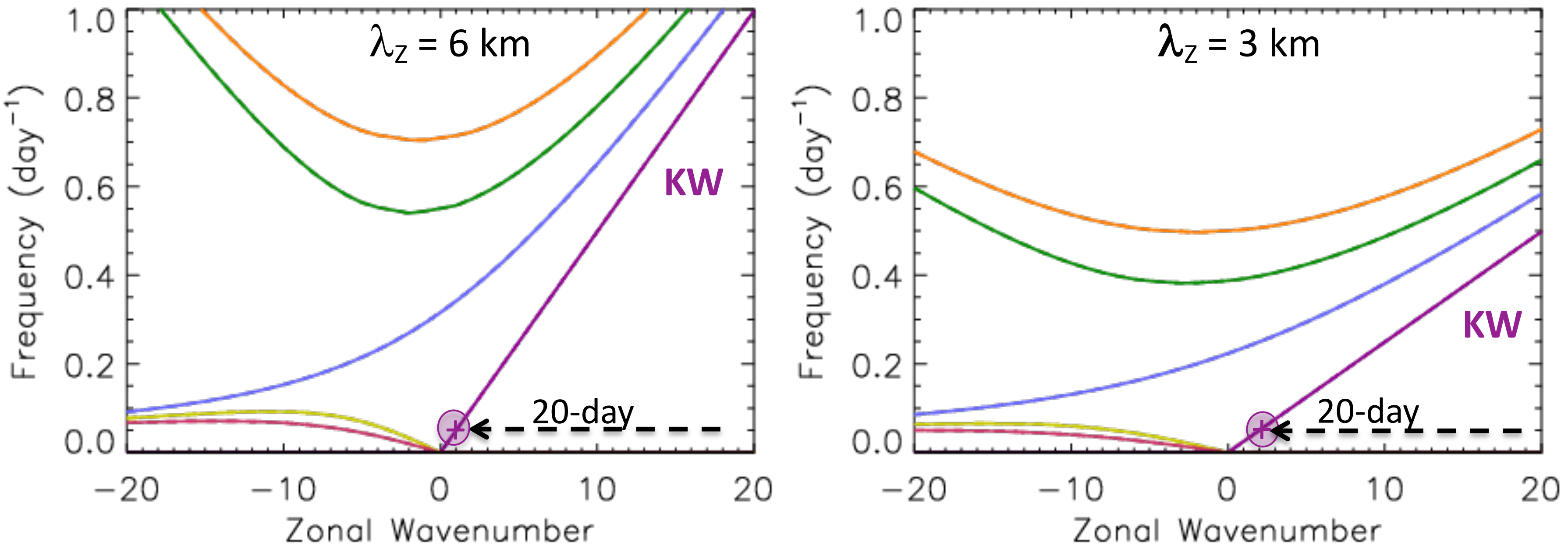
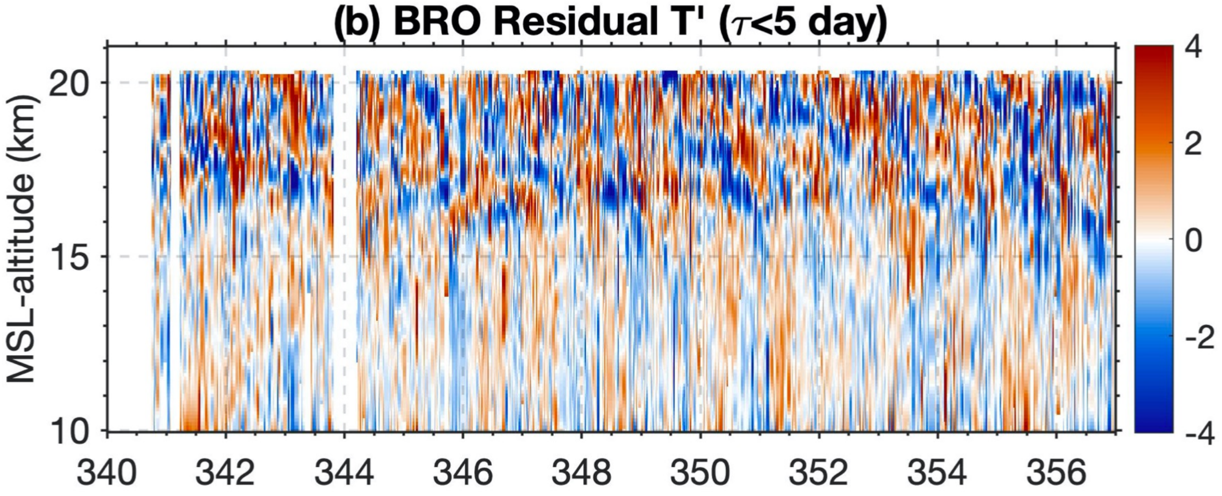


6 km wave is wavenumber=1 (λ_H = 40,000km)
3 km wave is wavenumber=2 (λ_H = 20,000km)

BRO Temperature Profiles 2019

Shorter period residuals



- Kelvin Wave removed as background shows many other wave signals present for future time-series and 3D analysis
- Other Strateole-2 low-frequency Inertia-Gravity Wave observations (Bramberger talk)

Key Points

- Tropical waves with extreme λ_H / λ_Z aspect ratios approaching values 10,000 : 1 are observed in the tropics (also Bramberger talk)
- Long λ_H , short λ_Z , longer period waves are likely important drivers of the QBO in the lowermost stratosphere where model QBOs are weak
- Vertical high-pass filtering followed by traditional radiosonde analysis methods would mischaracterize Kelvin waves as high-frequency zonally-propagating gravity waves
- Long-duration balloon observations combining measurements in the intrinsic reference frame with vertical profiling are a powerful tool for characterization of tropical waves and their climate impacts