Fine-scale Waves and Shallow Mixing Layers in the TTL and Lowermost Stratosphere

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Strateole 2

Strateole 2 – in a nutshell:

- 25 super-pressure balloons from Mahe, Seychelles Islands (4.7S, 55.5E)
- Flight altitude: 18 – 20km
- Data from:
  - November 2019 until late February 2020
  - October 2021 until January 2022
- Mean flight duration: ~3 months
- Insitu instrument: TSEN (temperature, pressure, wind)
- Other scientific instruments: Ozone, CO_2, water vapor and particles

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Strateole 2 – Balloon Flight Tracks

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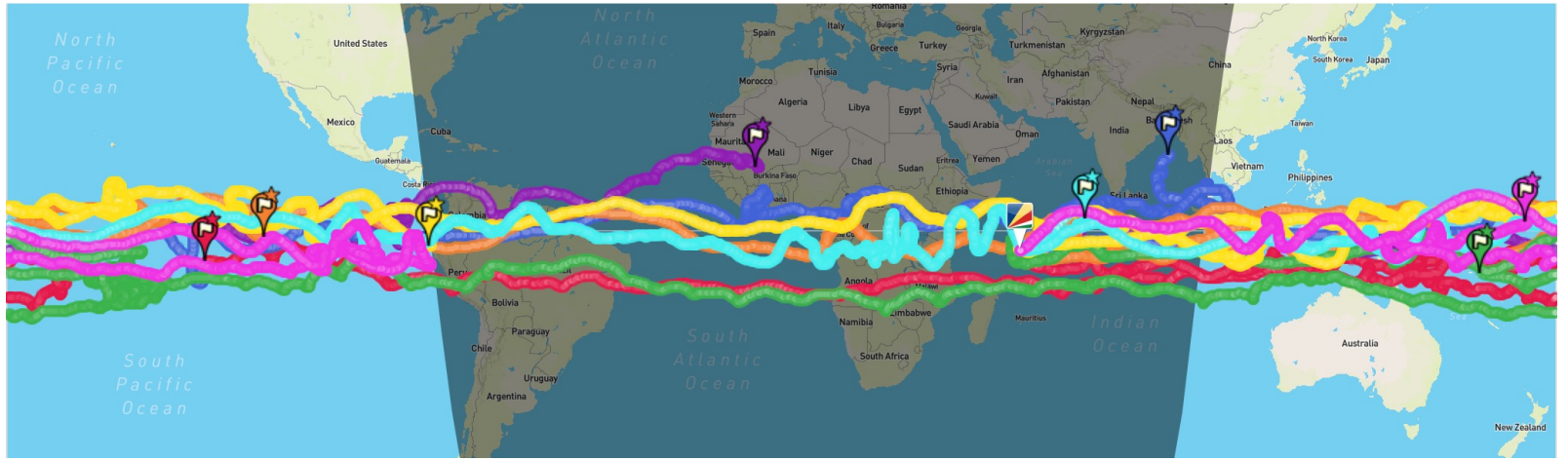
Strateole 2 – Balloon Flight Tracks

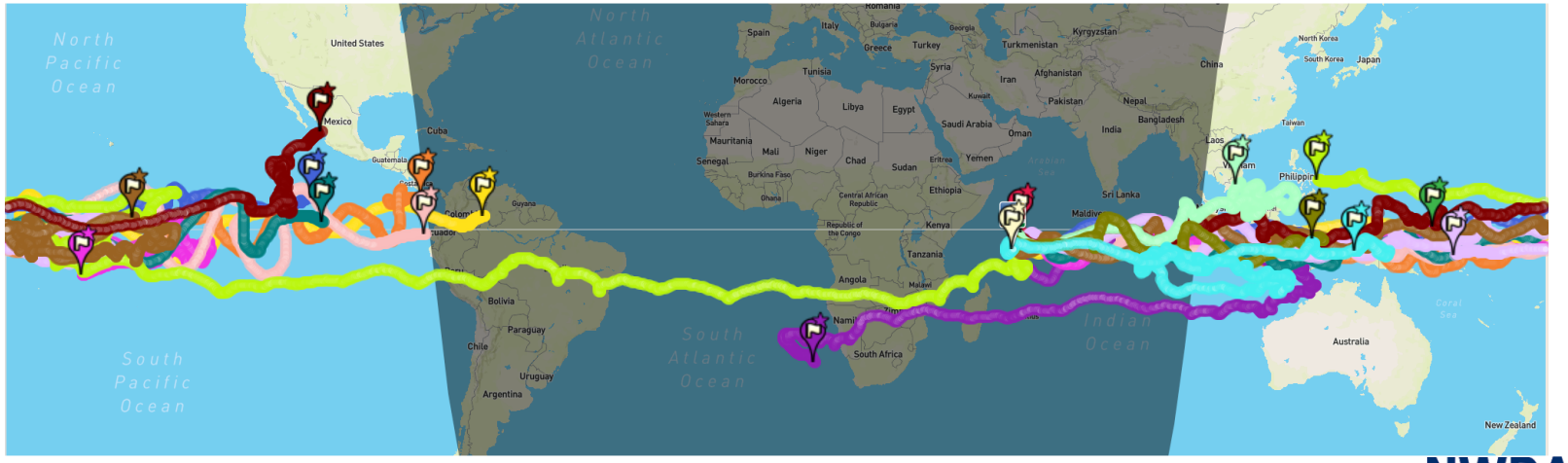
Test campaign in 2019 (8 flights)

- Nov 2019 – Feb 2020
- Quasi-Biennial Oscillation (QBO) westerly phase at 20 km



Science campaign in 2021 (17 flights)

- Oct 2021 – Jan 2022
- QBO transition westerly to easterly



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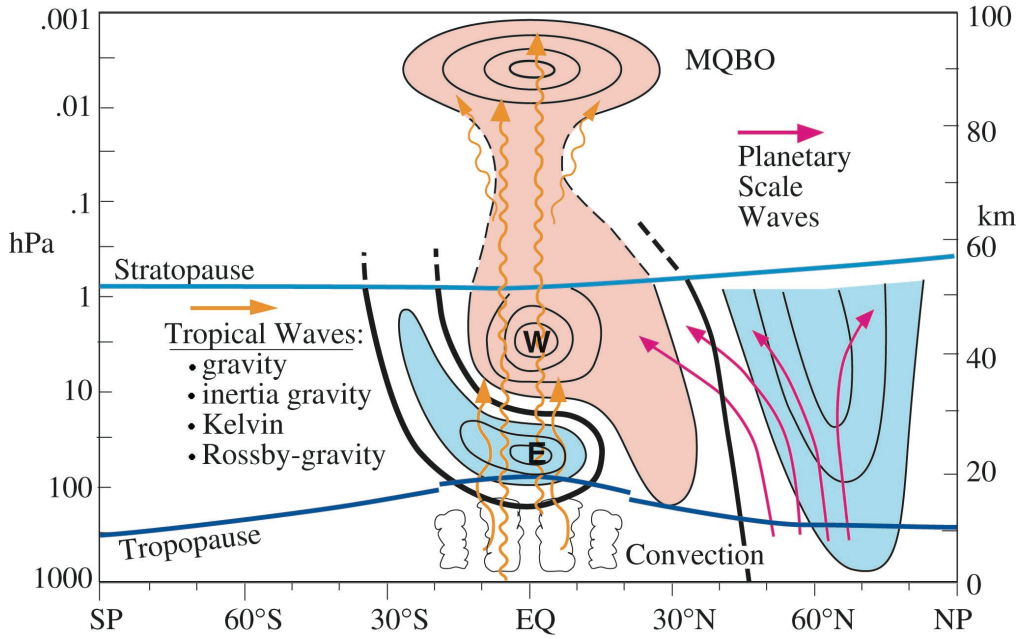
Background - QBO

QBO

-> modulates MJO intensity /duration
-> modulates polar stratospheric vortex
-> teleconnections to NH winter season weather
-> **important for S2S forecasts and interannual climate**



Baldwin et al. 2001

Challenges in representation of QBO in current GCMs:

- QBO is far too weak between 50hPa and 100hPa in most climate models (Bushell et al. 2020)
- Two disruptions in the cycle in the last 6 years suggest QBO may already be changing
- No consistency among GCMs on how QBO period will evolve in a warming climate

-> Representation of tropical waves and parameterization of gravity wave drag are large sources of uncertainty in modelling QBO (Holt et al. 2020, Richter et al. 2020)

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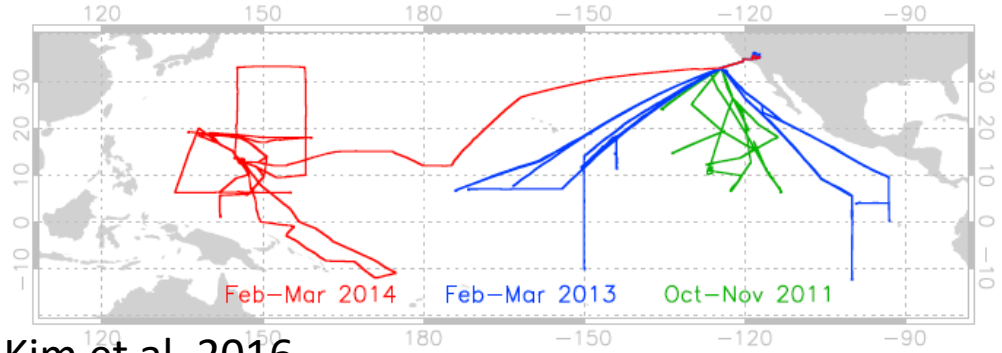
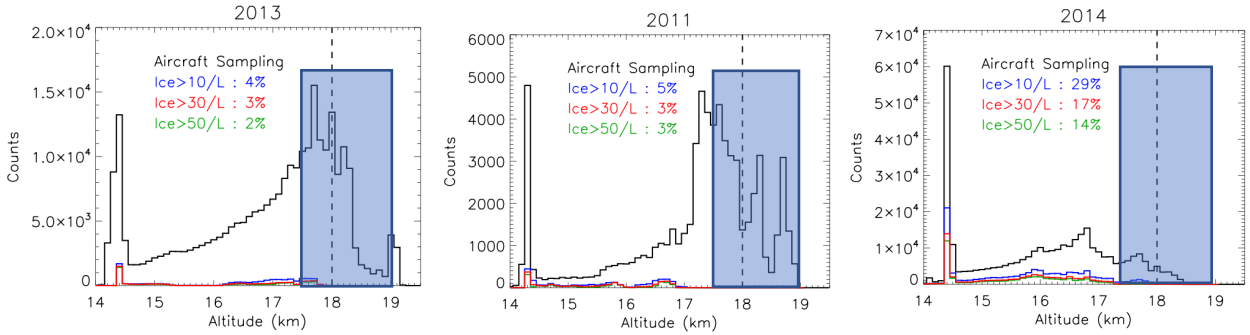
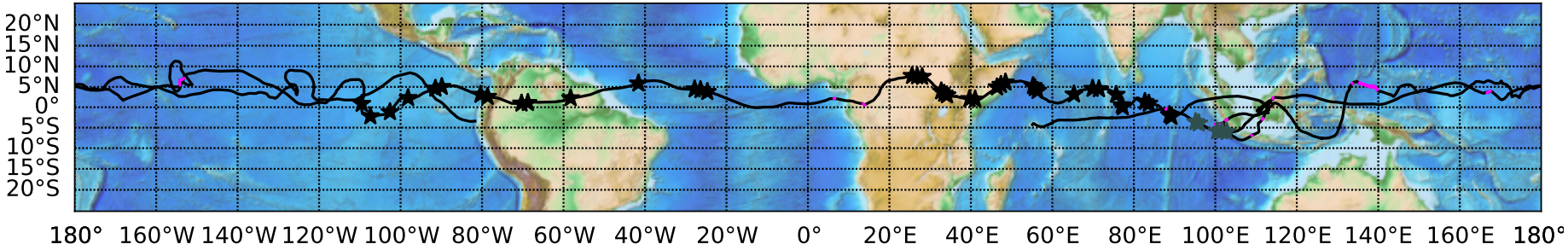
Background - ATTREX



Kim et al. 2016





- Data is focused over Pacific
- Sparse data above cold point
- It was not possible to characterize the type and scale of the waves generating the Cirrus clouds in Kim et al. 2016

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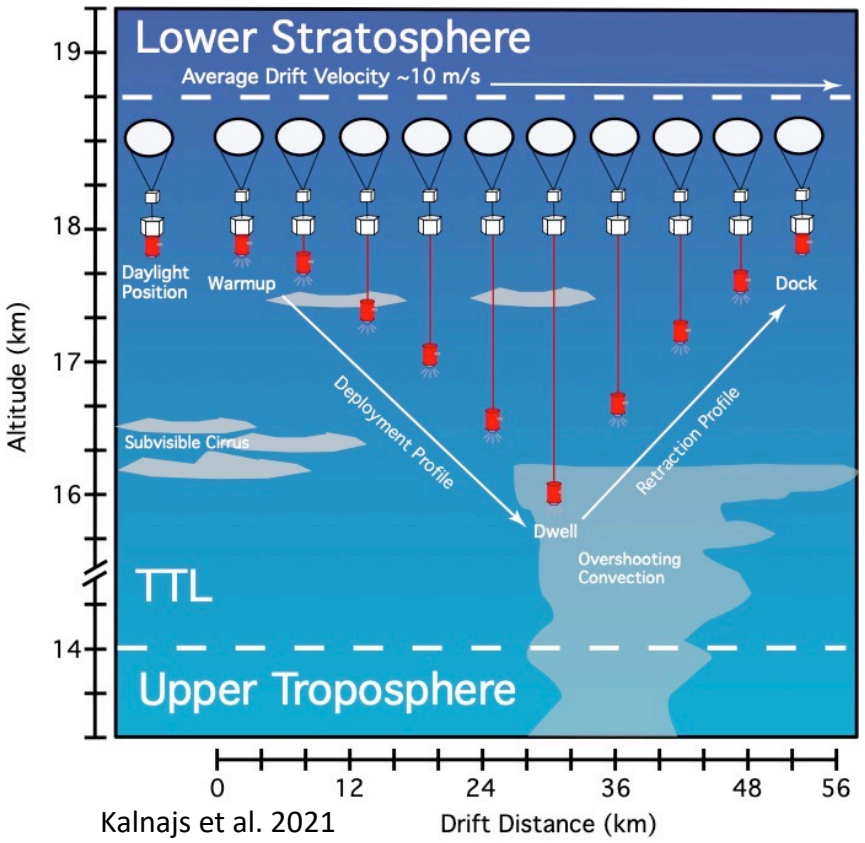
Strateole 2 - RACHuTS

- Profiles down to 2 km below the balloon of:
  - Temperature,
  - Water vapor and
  - Aerosol
- Part of the TTL3 configuration
- Unprecedented vert. resolution with one data point per meter
- 110 vertical profiles available from the test campaign



Kalnajs et al. 2021

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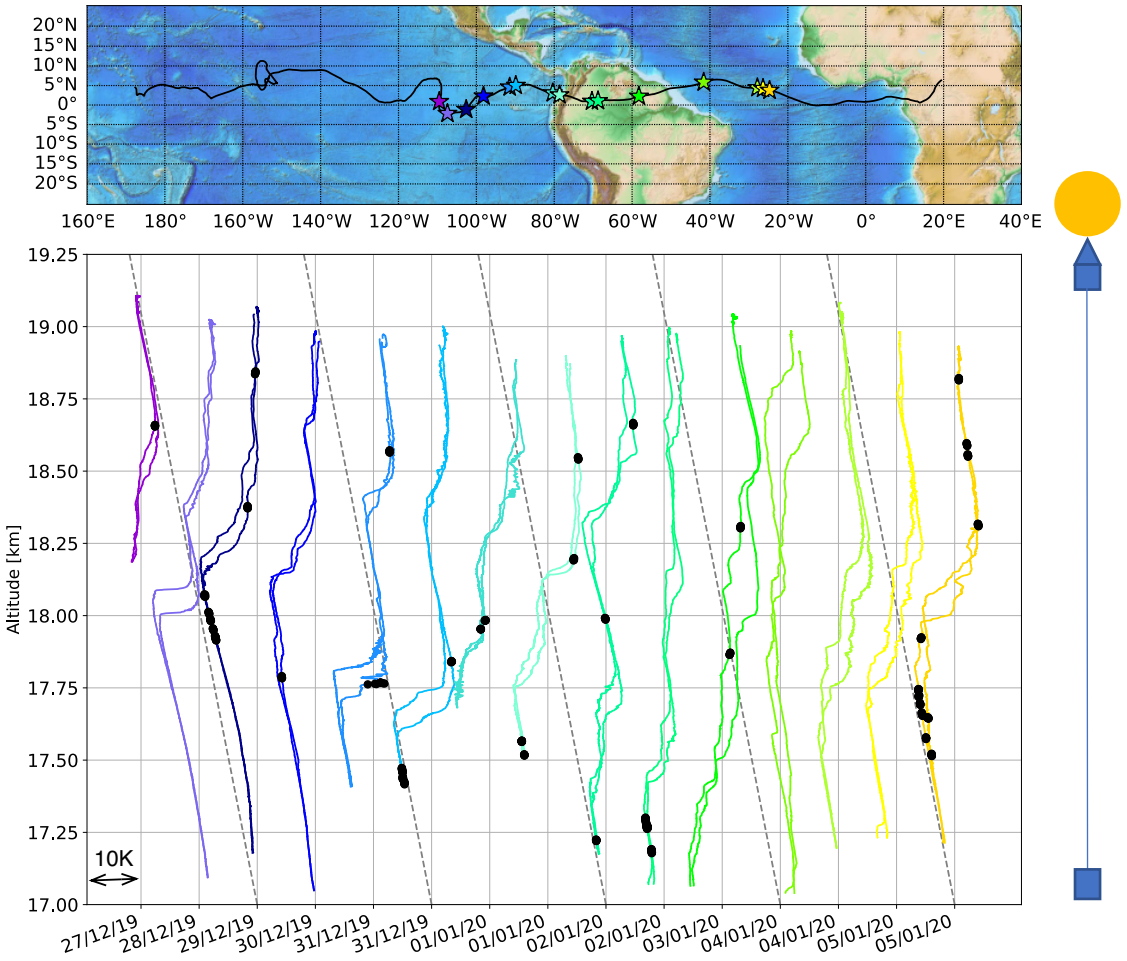
Wave Analysis – New Possibilities

RACHuTS T’ profiles



- We use COSMIC 2 profiles to determine background temperature (T) profiles
- Background = 30 day average within a 5˚x10˚ (lat x lon) box that is centered around each TSEN measurement point

Bramberger et al. 2021

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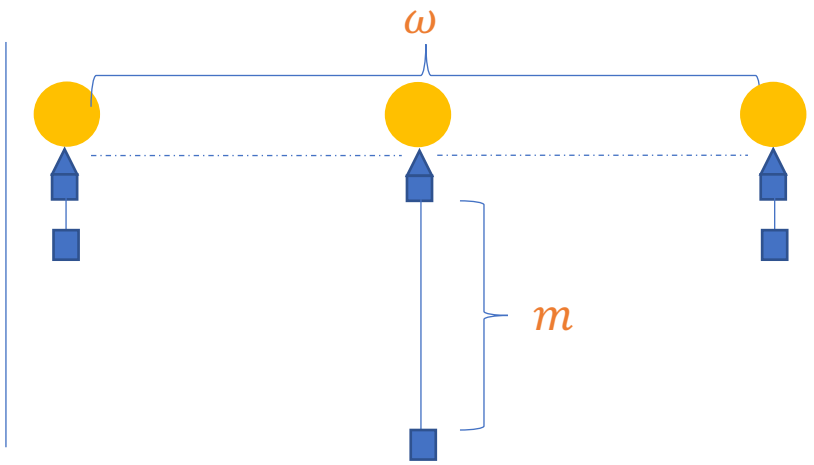
Wave Analysis – New Possibilities

Wave identification – different waves have different dispersion relations

Example for eastward propagating inertia gravity waves (EIG) on beta plane:

$$m = -\frac{N}{\omega^2}(\beta + \omega k)$$

Vertical wavenumber; Stability; Intrinsic frequency; Zonal wavenumber



Combination of TSEN and RACHuTS: ω from TSEN measurements
m from RACHuTS observations

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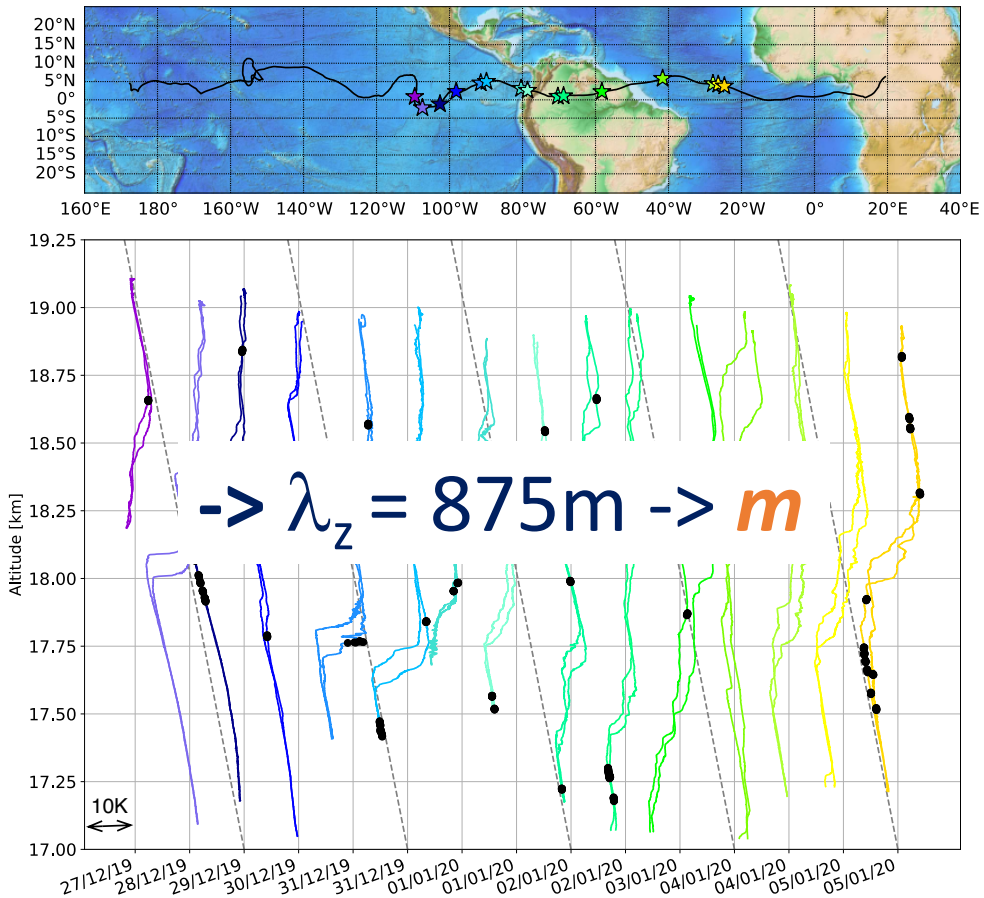
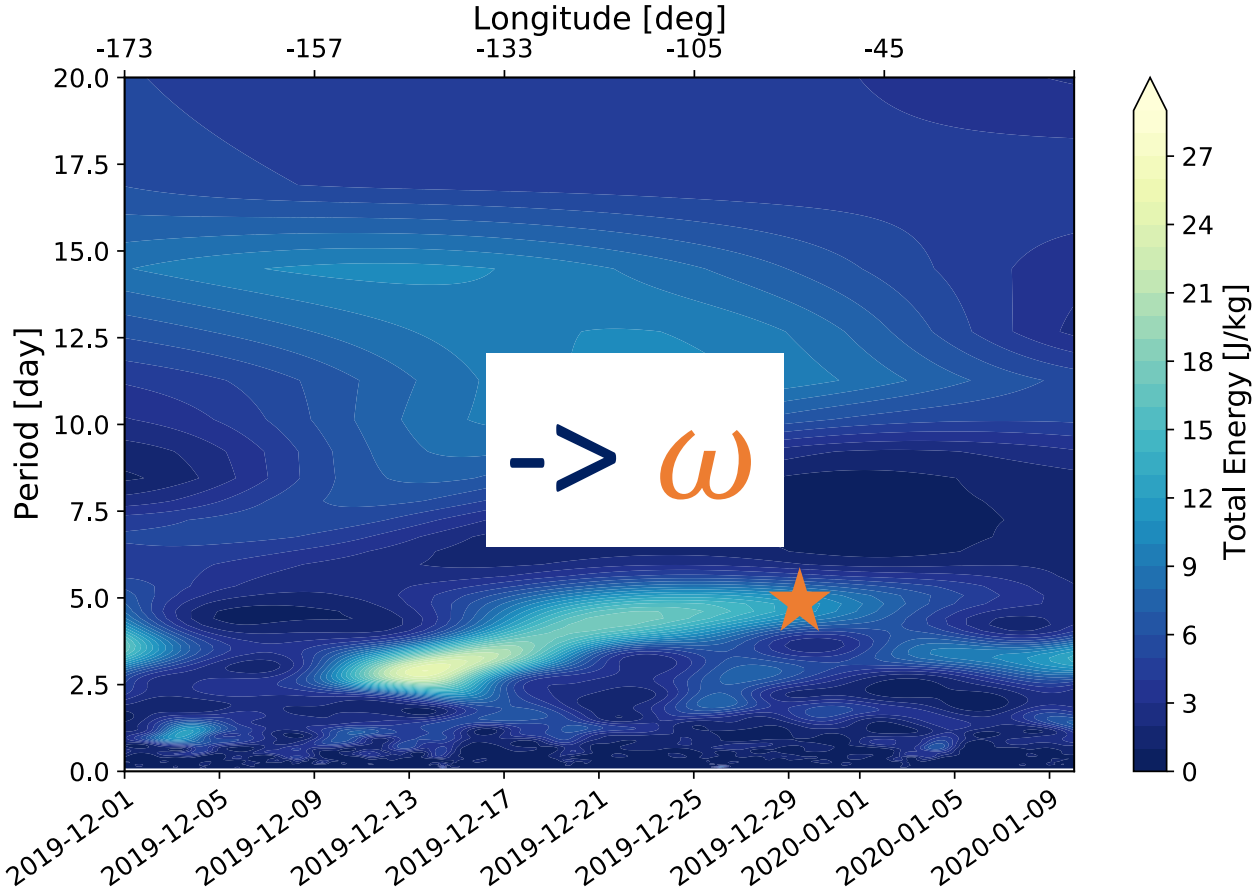
Wave Analysis – New Possibilities

RACHuTS



TSEN – Total Energy: $E_{tot} = \frac{1}{2}(u'^2 + v'^2) + \frac{1}{2}\left(\frac{g^2}{N^2}\frac{T'^2}{\overline{T}^2}\right)$



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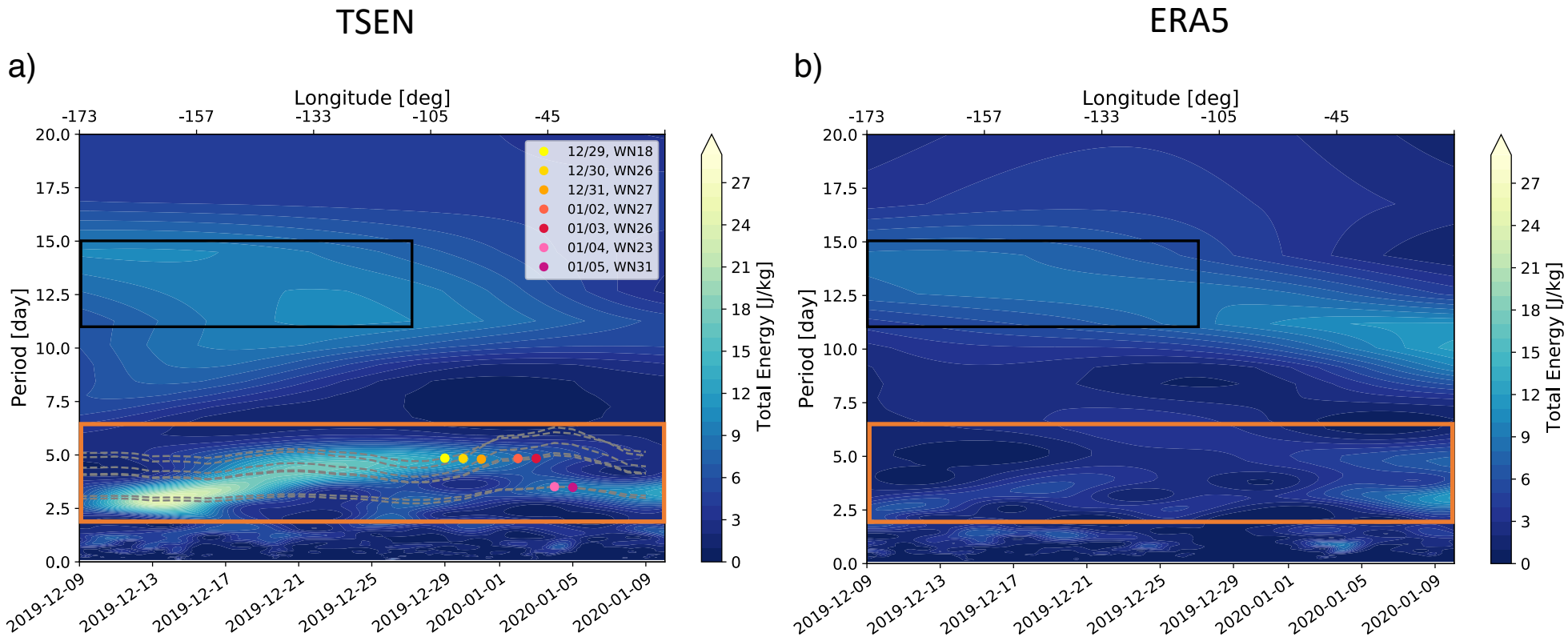
Wave Analysis – Comparison to ERA5



Observed waves under-represented in ERA5 reanalyses

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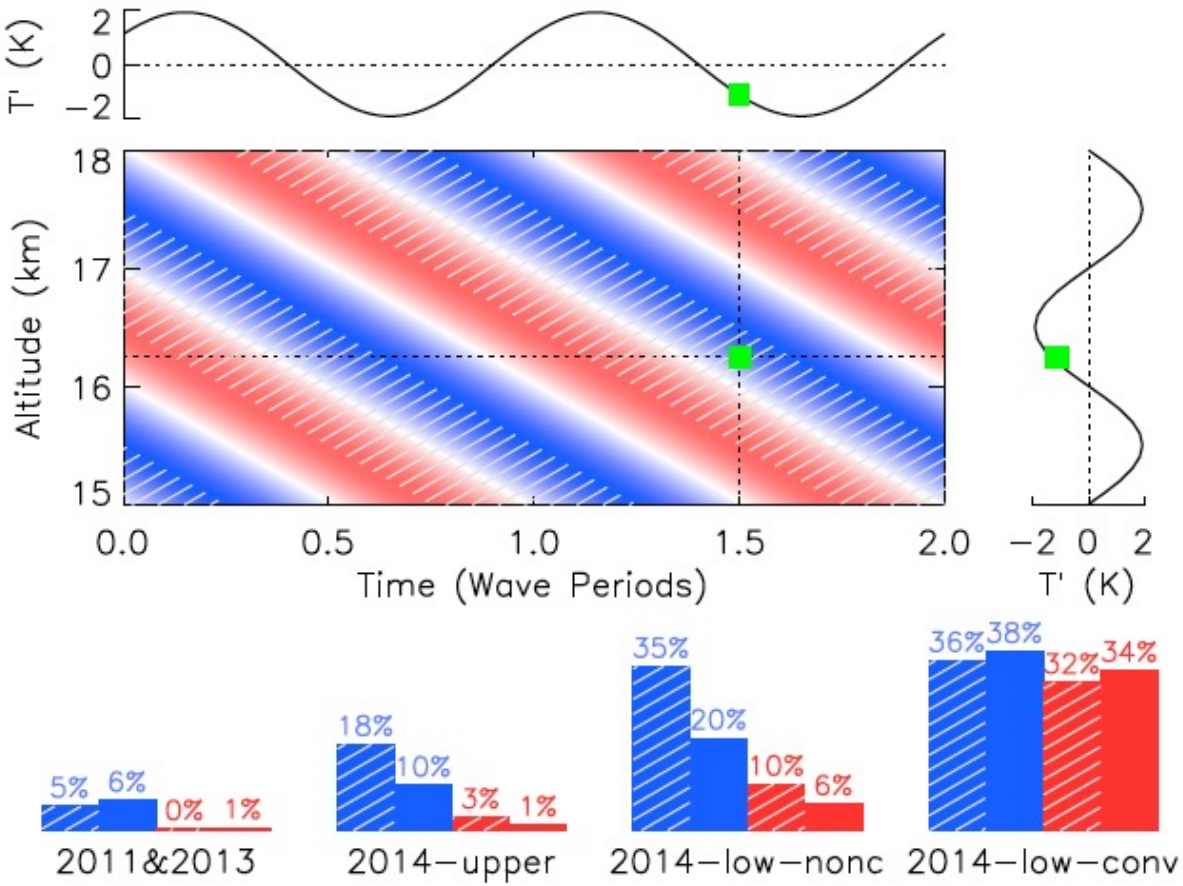
Active Cooling of Waves



Kim et al. 2016

Wave induced dT/dz <0 → dT/dt <0 → waves actively cool atmosphere

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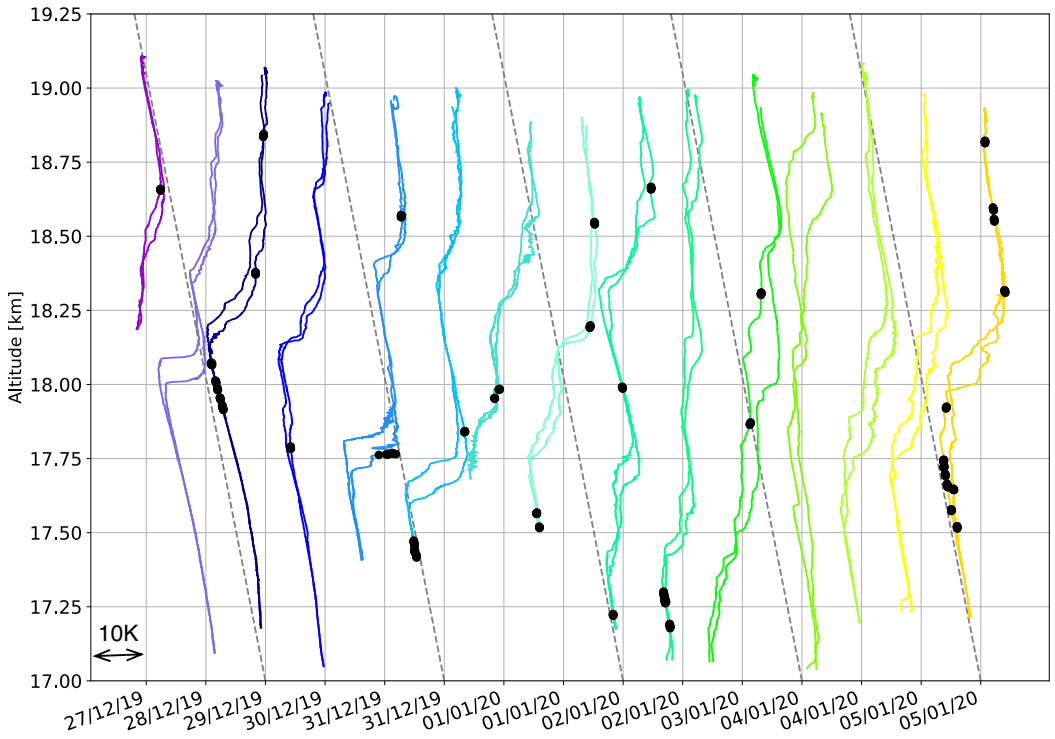
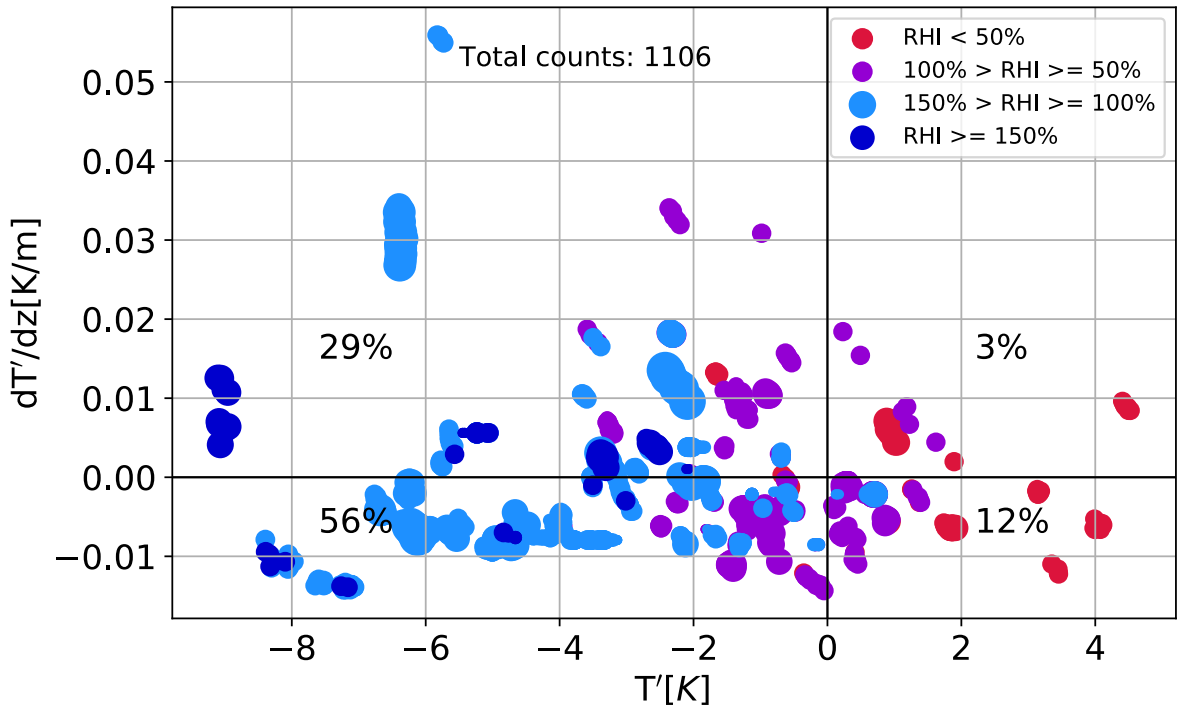
Cirrus cloud occurrence in Relation to Wave Activity





97% of all ice occurrences (particles >= 3 µm) are related to wave activity

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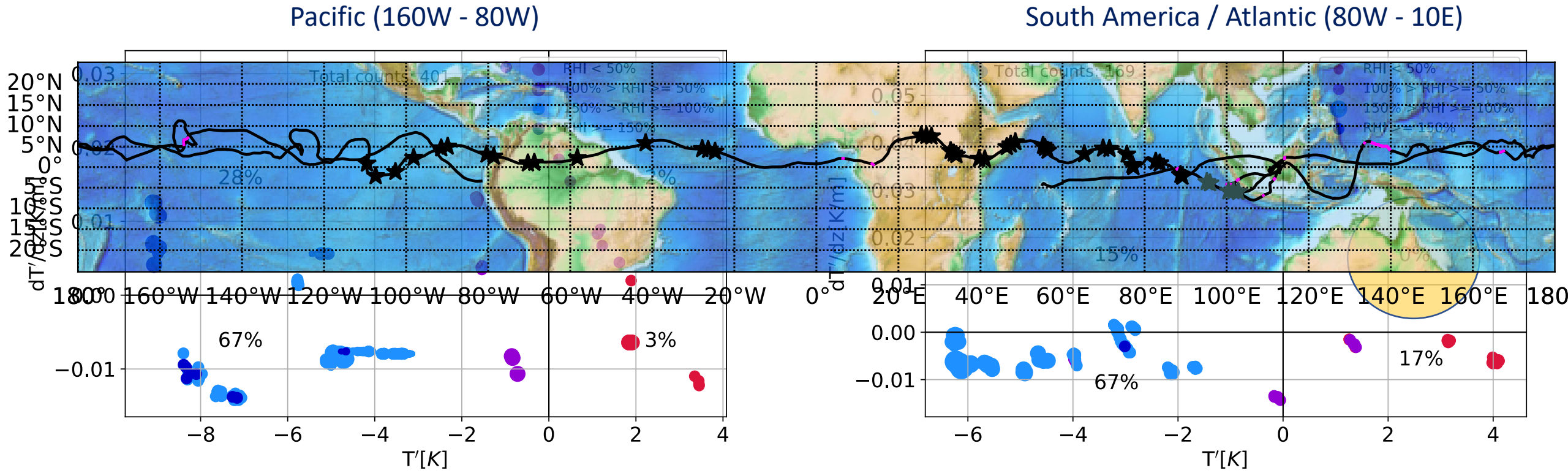
Cirrus cloud occurrence in Relation to Wave Activity



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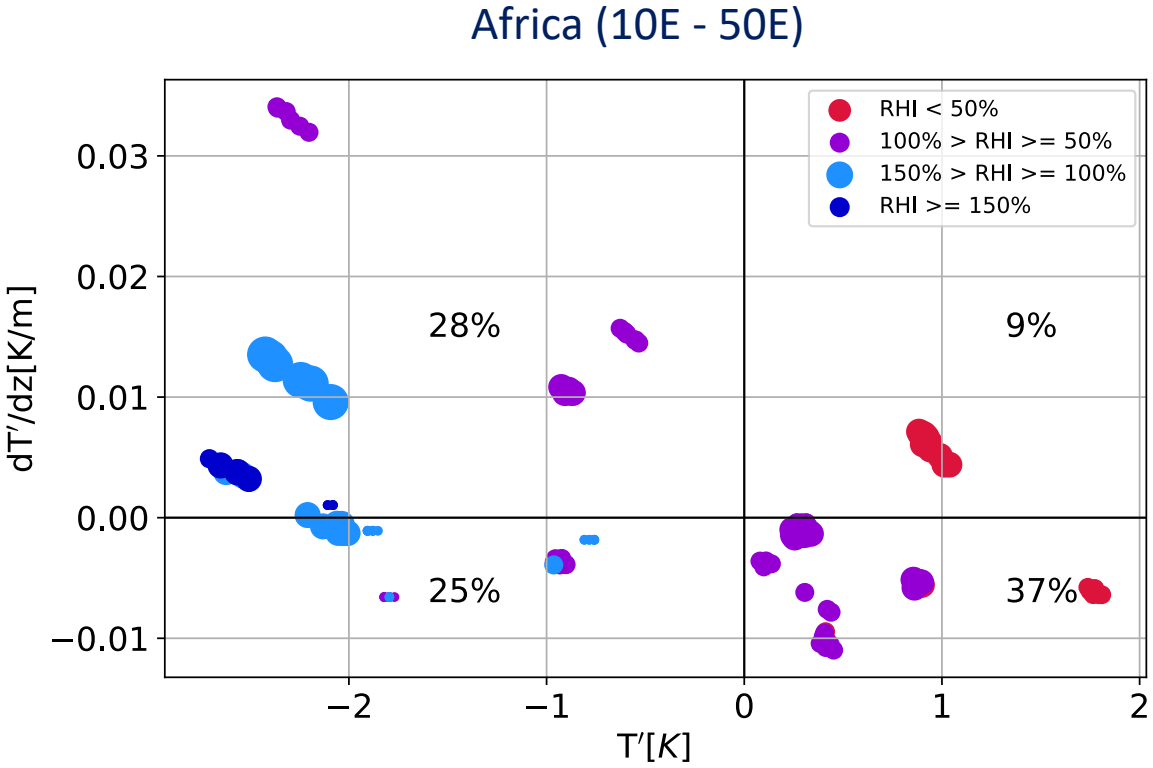

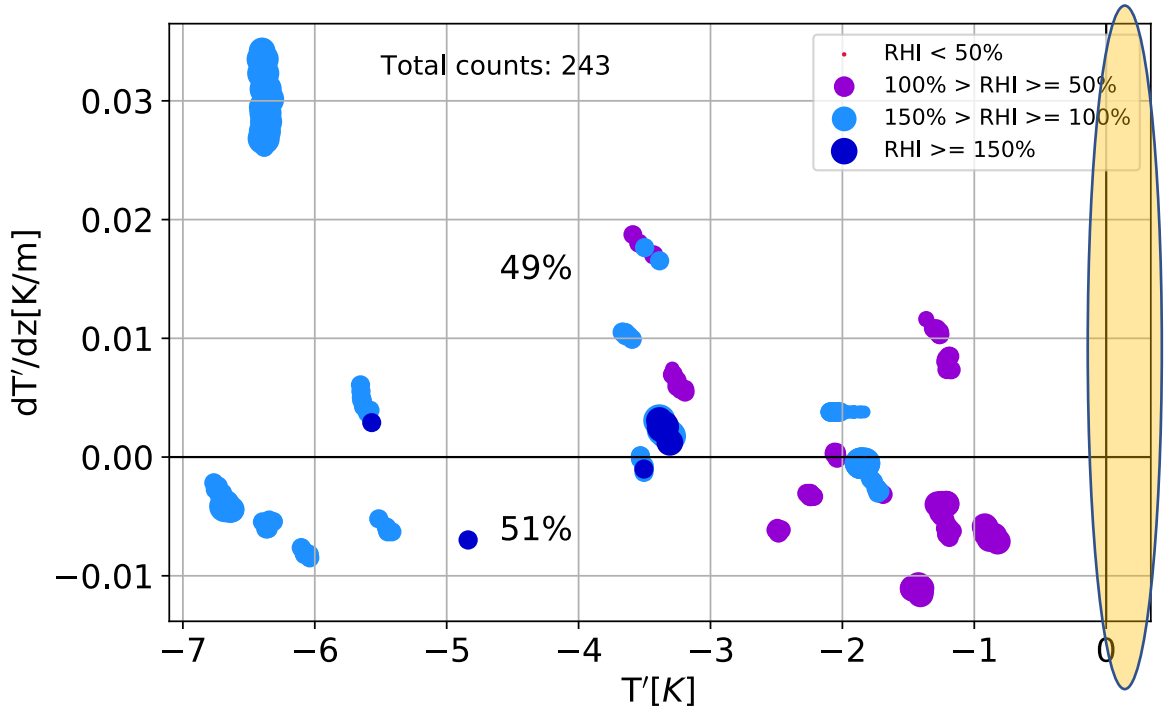

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Take aways

- EIG waves with WN 18 – 31 with short vertical wavelengths
- These waves have barely been observed before
- Estimated forcing about 0.3 - 0.5 m/s/day comparable to total wave forcing to drive QBO
- Large scale waves with short vertical wavelengths not resolved in modern GCMs or re-analyses as e.g. ERA-I, ERA5
- Detection of sub-visible cirrus clouds
- Most of cloud occurrence associated with large-scale waves (EIGW)

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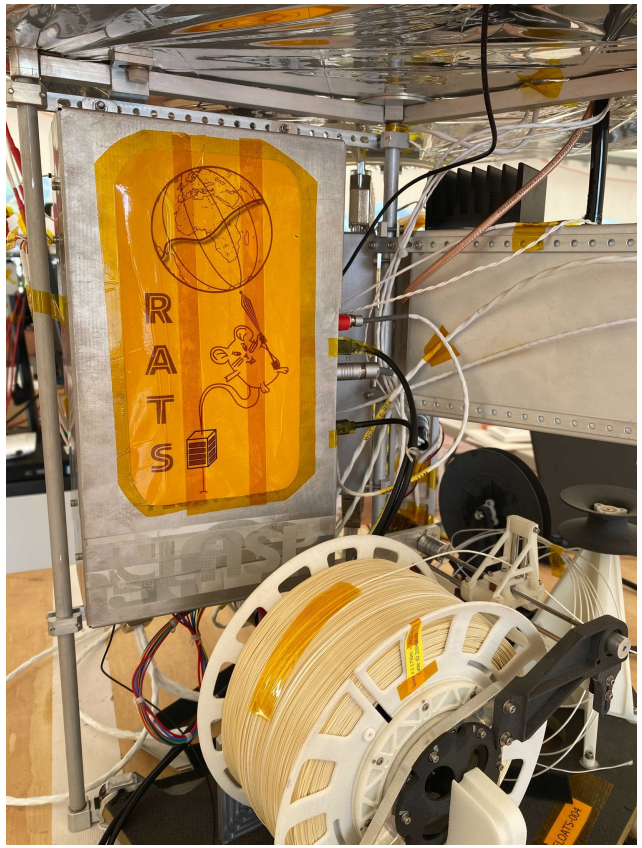
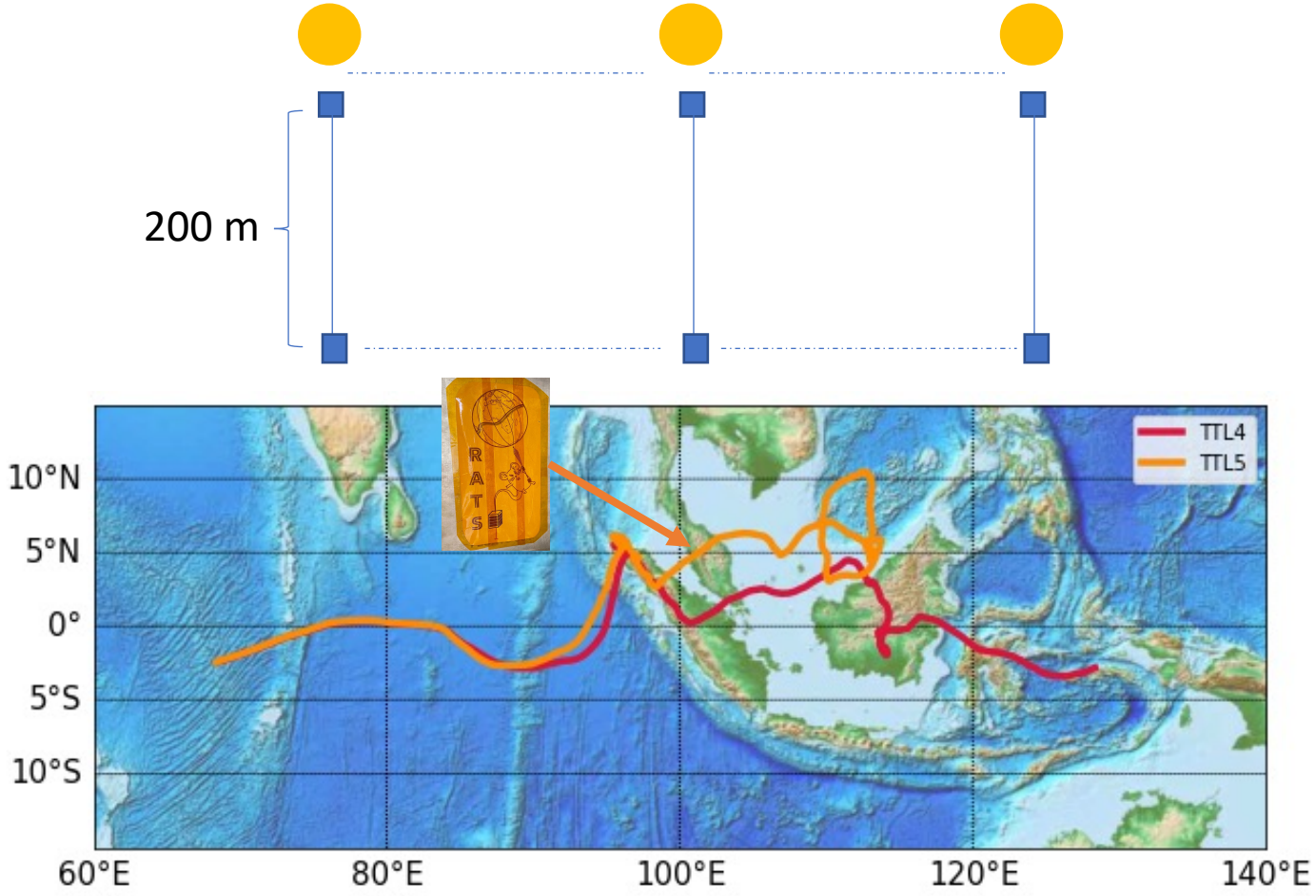
RATS – Reeldown Atmospheric Temperature Sensor





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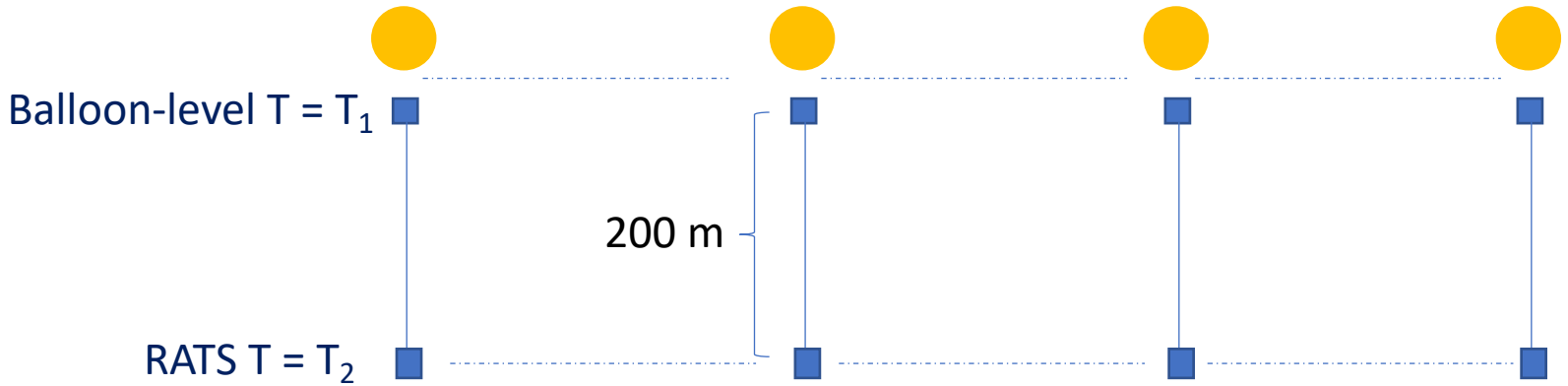

$Co(T'_1 T'_2)$ → $m = \frac{\Delta\phi}{\Delta z}$ → $\lambda = \frac{2\pi}{m}$

- Measurement is sensitive to phase shifts of 0.2 to 1.6 (=pi/2)
- Gives sensitivity of vertical wavelengths between 400m and 6km

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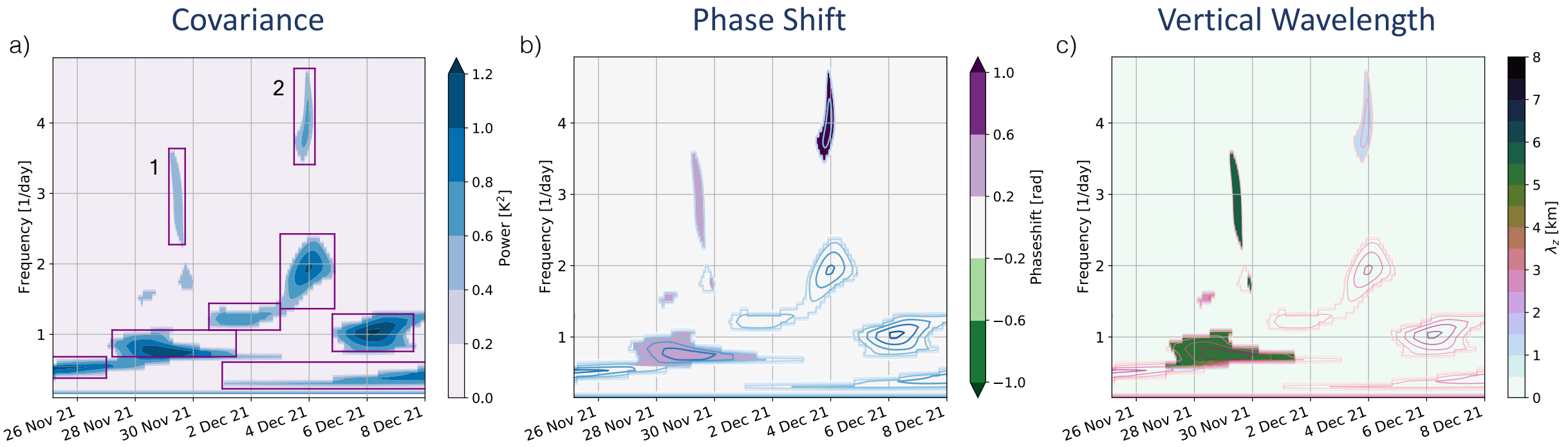

- Wave packets detected at high and low frequencies
- Vertical wavelengths range between 1.5km and 5.5km

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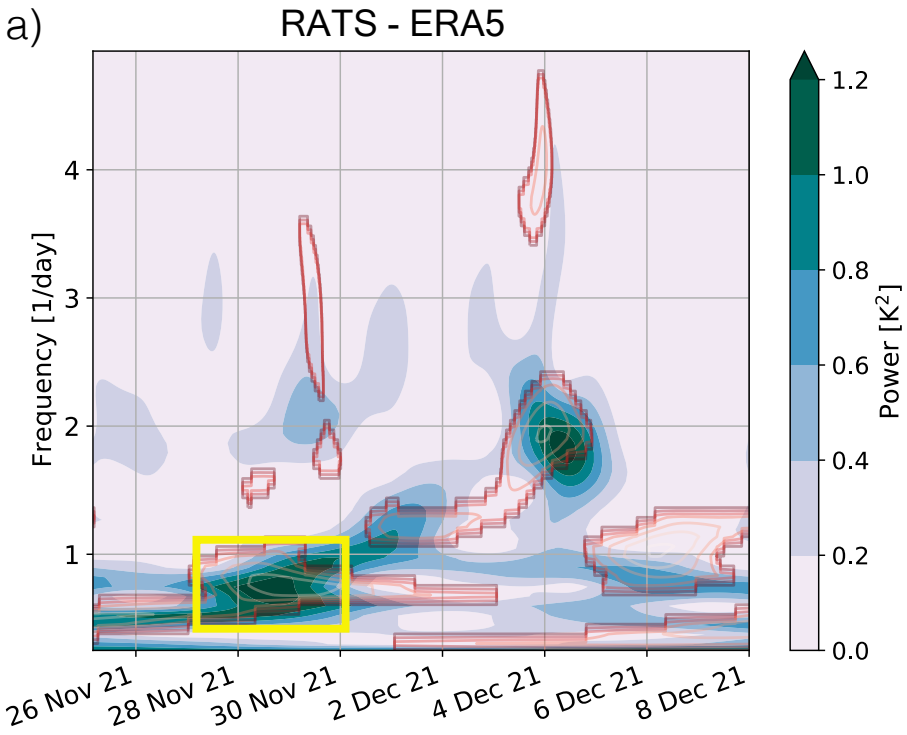
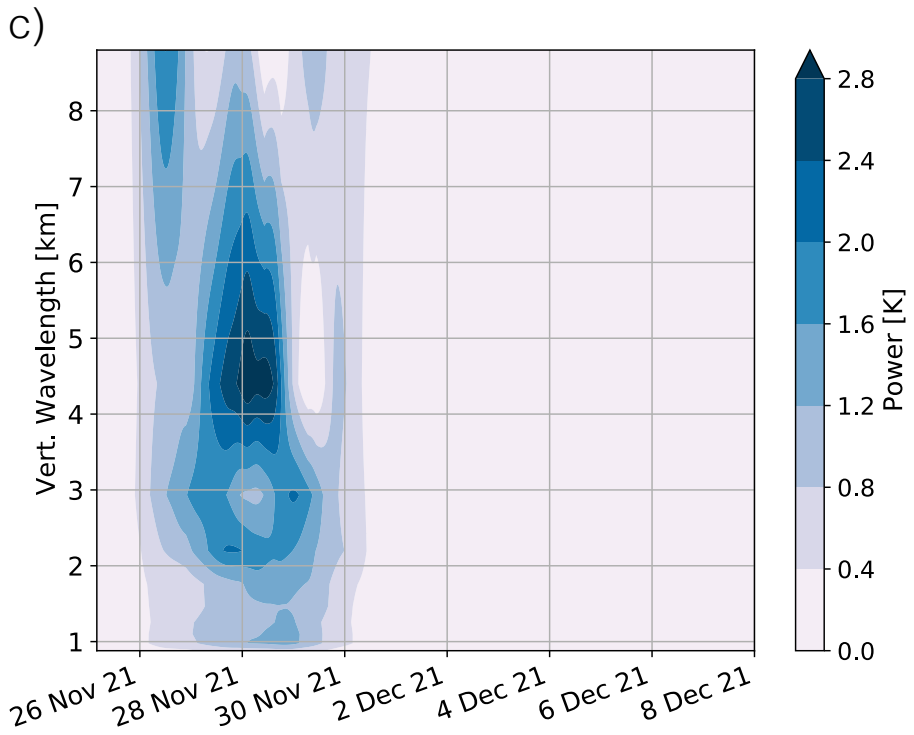
RATS – Reeldown Atmospheric Temperature Sensor





- Low-frequency waves are similar in ERA5, but different temporal evolution
- High-frequency waves are under-represented in ERA5
- Vertical wavelength similar to observation

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Conclusions - RATS

- New instrument to estimate the vertical wavelength along the balloon flight tracks
- Comparison to ERA 5
  - Low-frequency wave packets are similar to observations
  - High-frequency wave packets are missing in ERA 5
  - ERA 5 reproduces the observed vertical wavelength of a low-frequency wave packet
  - Under-representation of wave packets maybe due to representation of convection or vertical resolution
- Planning to distribute this instrument on several balloons on the next Strateole 2 campaign

Bramberger, M., Goetz, D., Alexander, M.J., Kalnajs, L., et al. (2023). Tropical wave observations from the reel-down atmospheric temperature sensor (RATS) in the lowermost stratosphere during Strateole-2. Geophysical Research Letters, 50, e2023GL104711. https://doi.org/10.1029/2023GL104711

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Conclusions - RACHuTS

Cirrus Clouds

- Detection of sub-visible cirrus clouds
- Most of cloud occurrence associated with large-scale waves (EIGW)

Large-scale waves

- EIGWS with short vertical wavelengths not resolved in modern GCMs or re-analyses as e.g. ERA-I, ERA5
- Provide considerable forcing for the QBO in the lowermost stratosphere
- Modulate the life cycle of cirrus clouds in lowermost stratosphere

Bramberger, M., Alexander, M. J., Davis, S., Podglajen, A., Hertzog, A., Kalnajs, L., et al. (2022). First super-pressure balloon-borne fine-vertical-scale profiles in the upper TTL: Impacts of atmospheric waves on cirrus clouds and the QBO. Geophysical Research Letters, 49, e2021GL097596. https://doi.org/10.1029/2021GL097596

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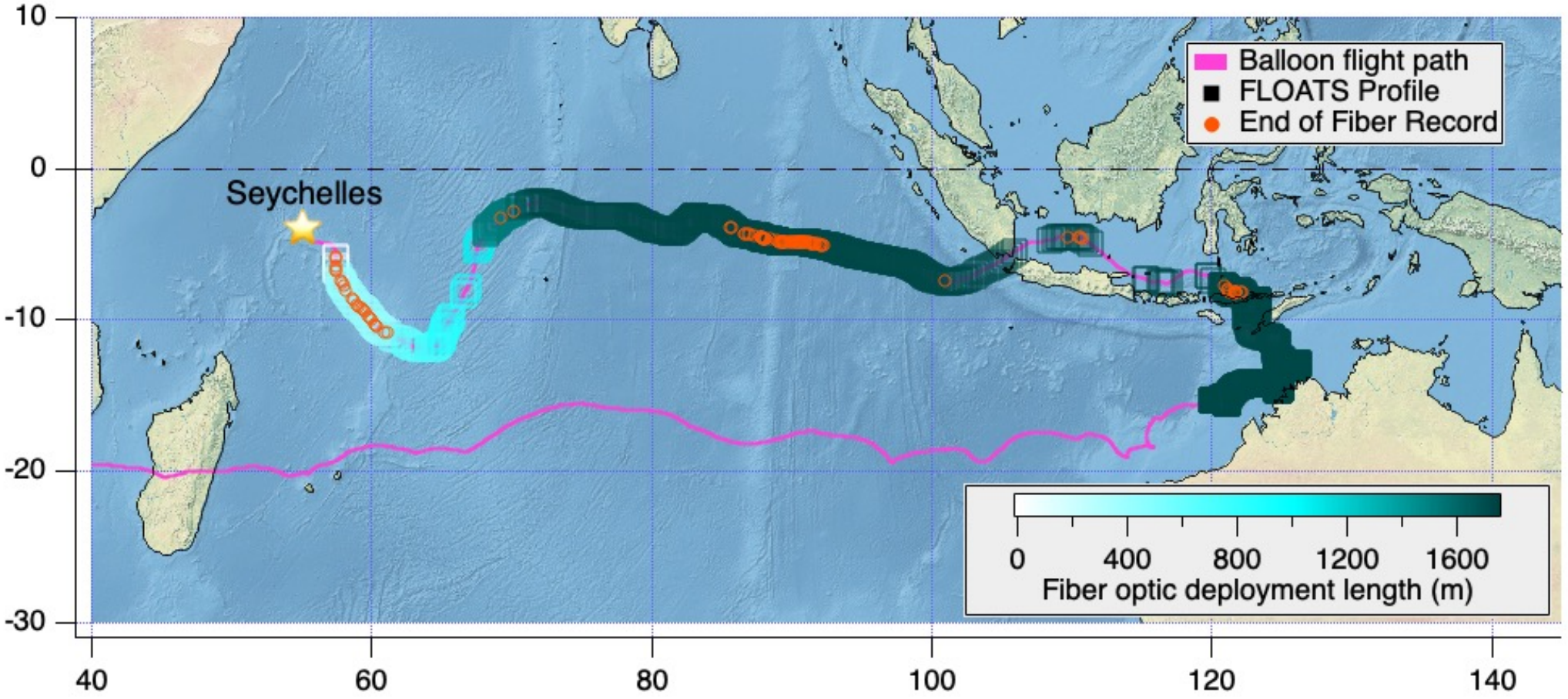
Outlook – FLOATS



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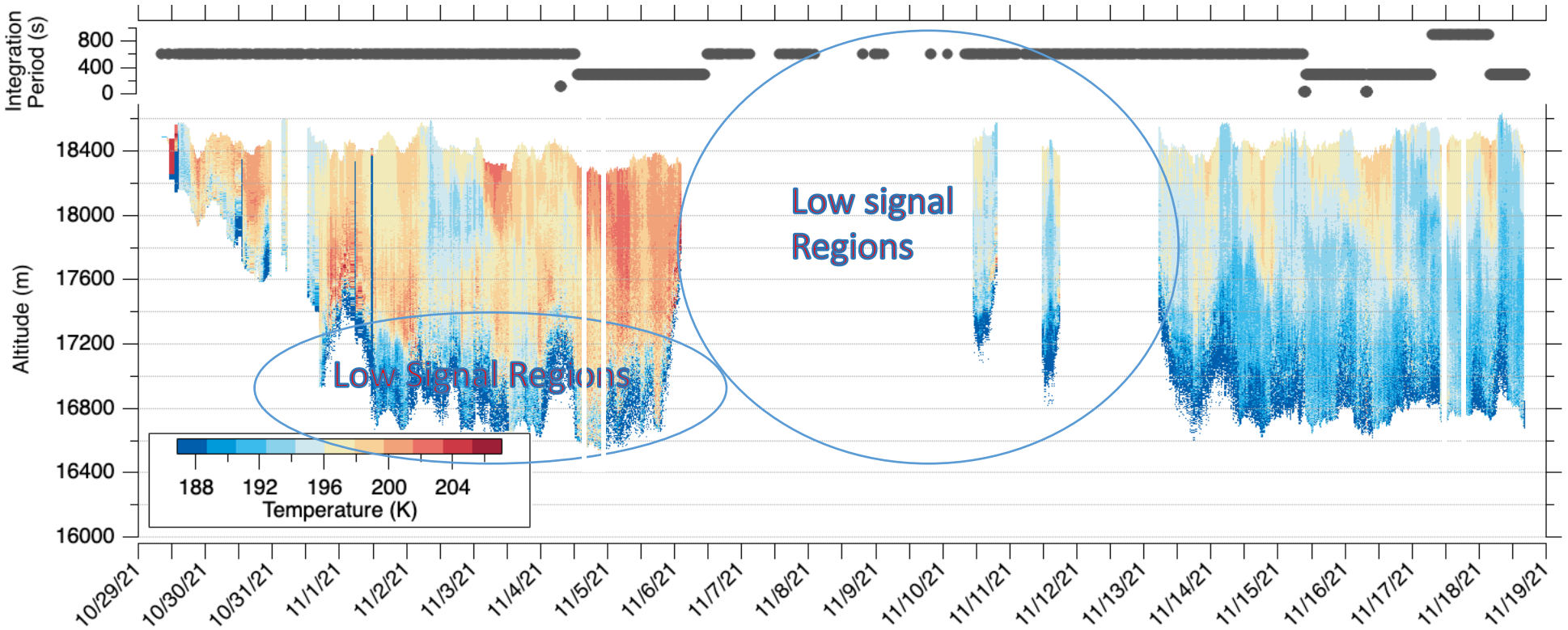
Outlook – FLOATS



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Thank you!
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