# Waves in the Tropical Tropopause Layer

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*Photo by James Guilford*

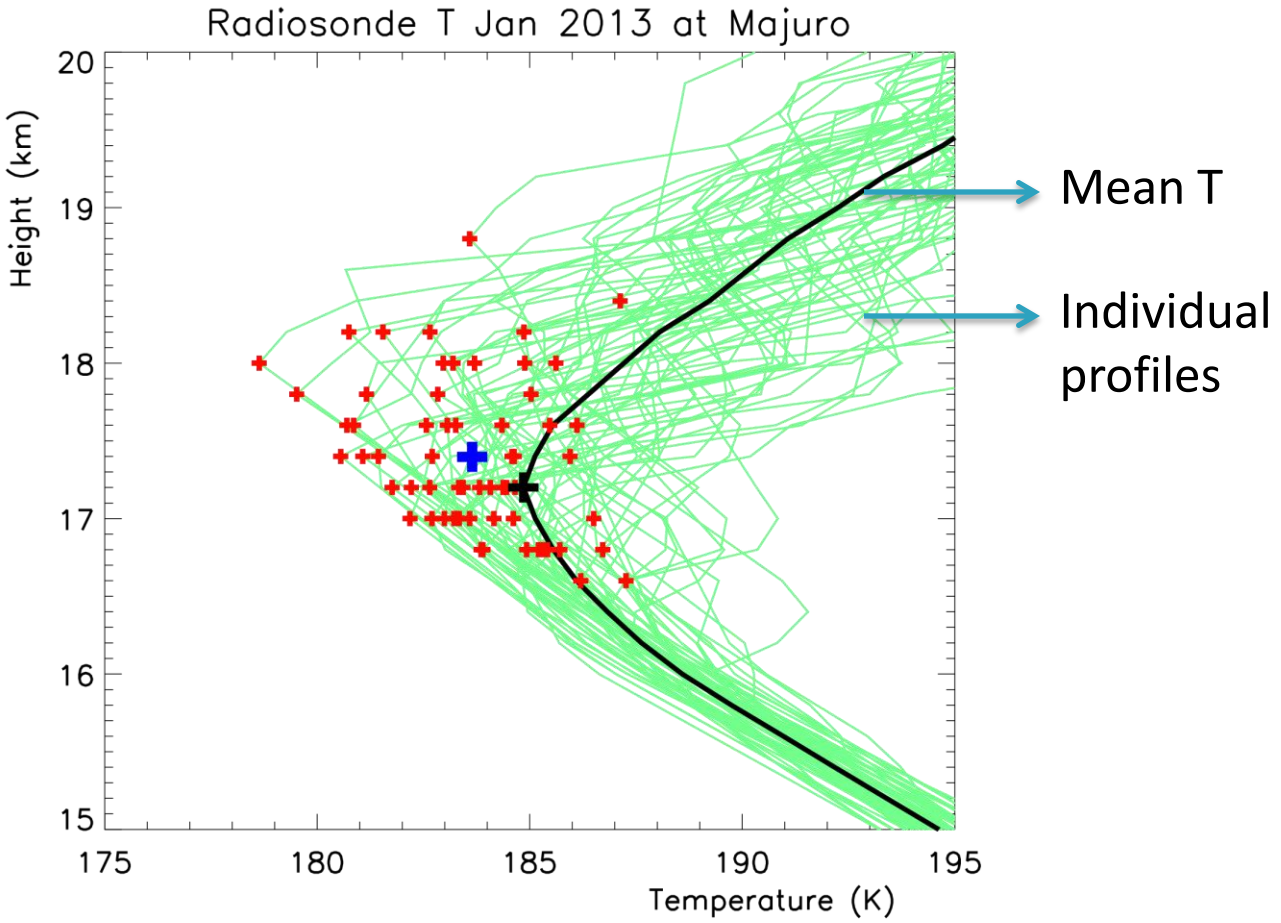
# Why do we care about TTL waves?

- QBO
- TTL upwelling
- Tracer transport/mixing
- Dehydration with cirrus formation
  - Radiation by cirrus
  - Radiation by water vapor

- So, we want to have good representations of waves in models.
- Or, we want to parameterize waves to simulate the TTL processes.

# TTL waves are strong, inducing up to -/+ 6K anomalies

+ : Individual tropopause

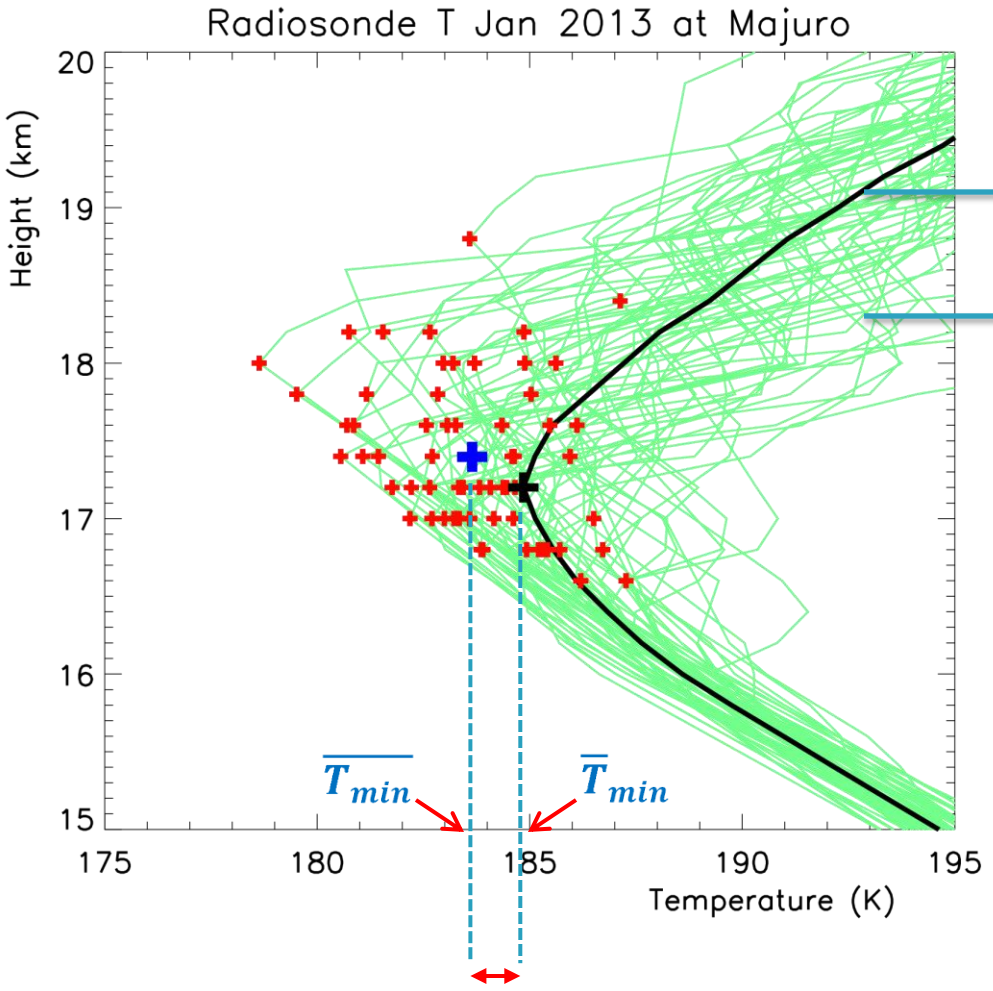



*Kim & Alexander, 2015, GRL*

# Waves lower the mean Cold Point Temperature (CPT)

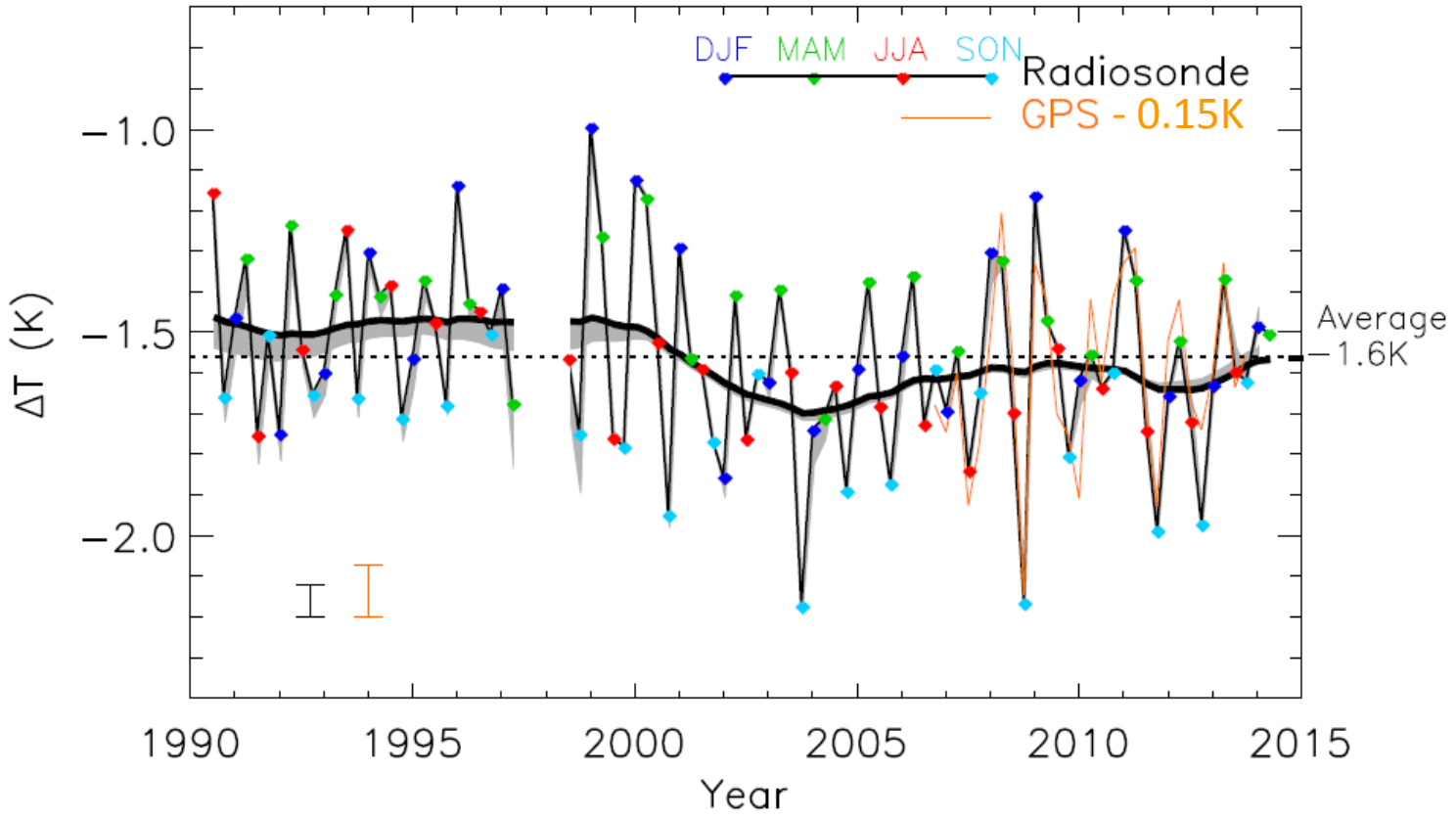
+ : Individual tropopause

+ : Mean of all +



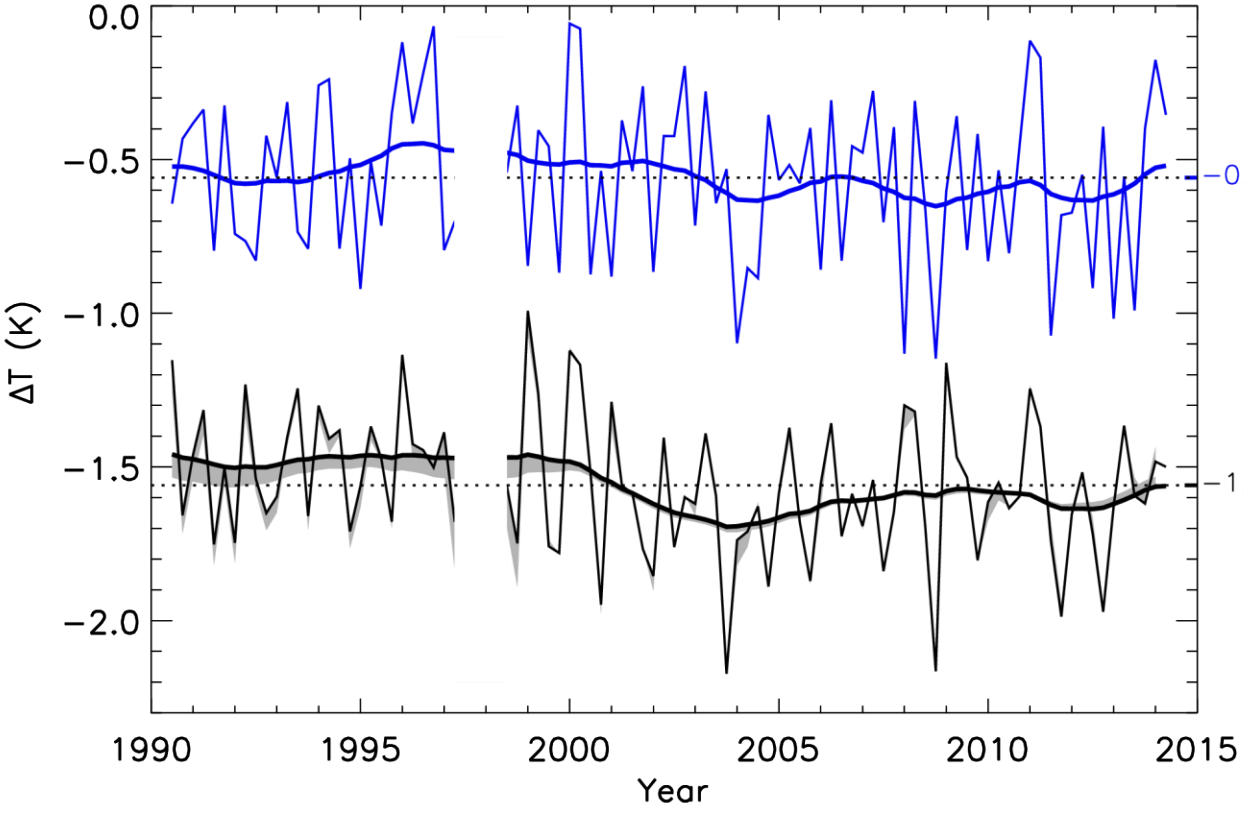

CPT drop by waves (wave impact): $\Delta T = \overline{T_{min}} - \overline{T}_{min}$

# Wave impacts for the last 24 years




- Waves lower CPT by 1.6 K on average (--dash line), corresponding to water vapor of ~1 ppmv ↓ (~25% of total entry).
- The wave impact shows decadal scale changes.

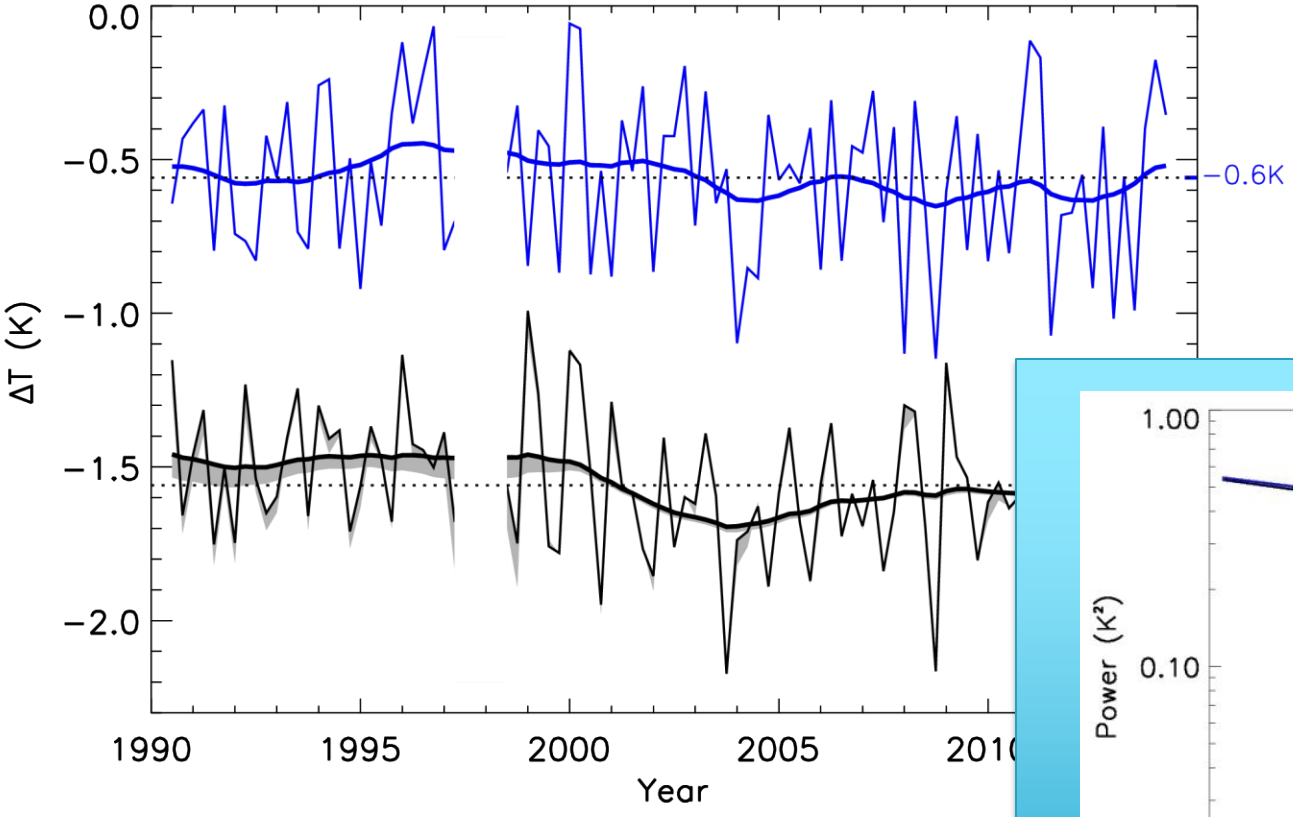
# Wave impacts on CPT in Reanalyses

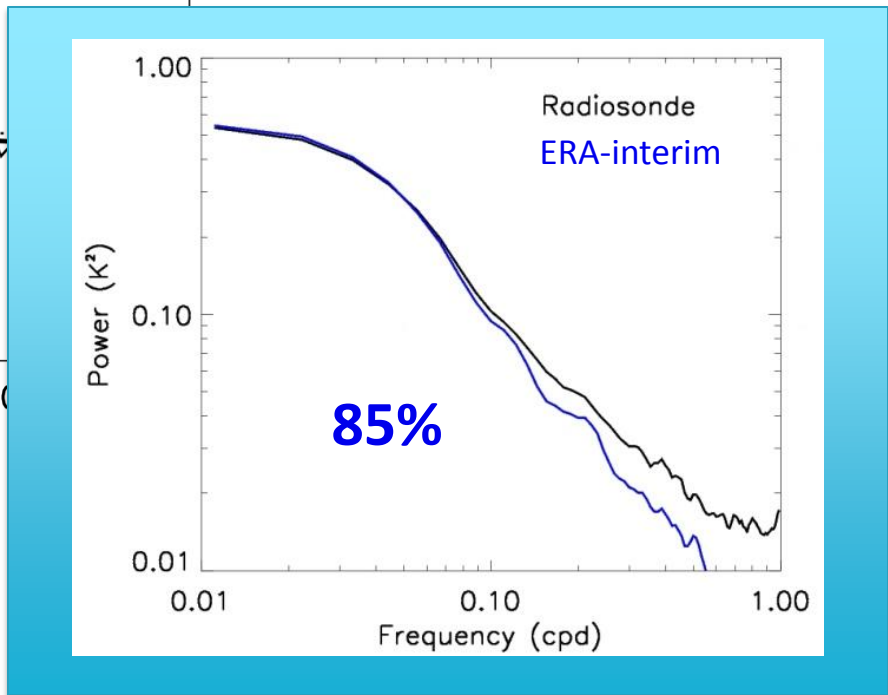



ERA-interim
(similar in MERRA)

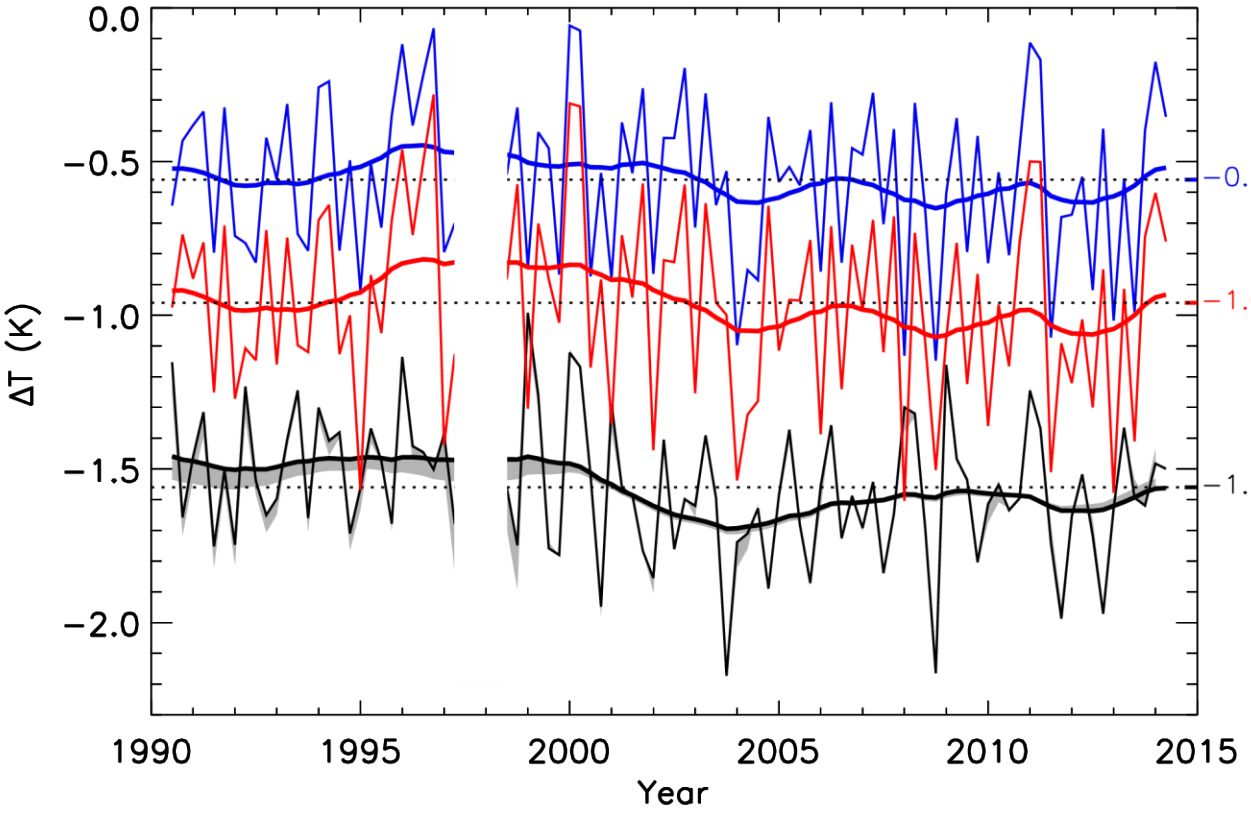
Radiosonde obs

# ~10-20% of TTL frequency spectrum is missing in Reanalyses



# Frequency spectrum enhancement (< 2cpd) improves CPT representation, but still…

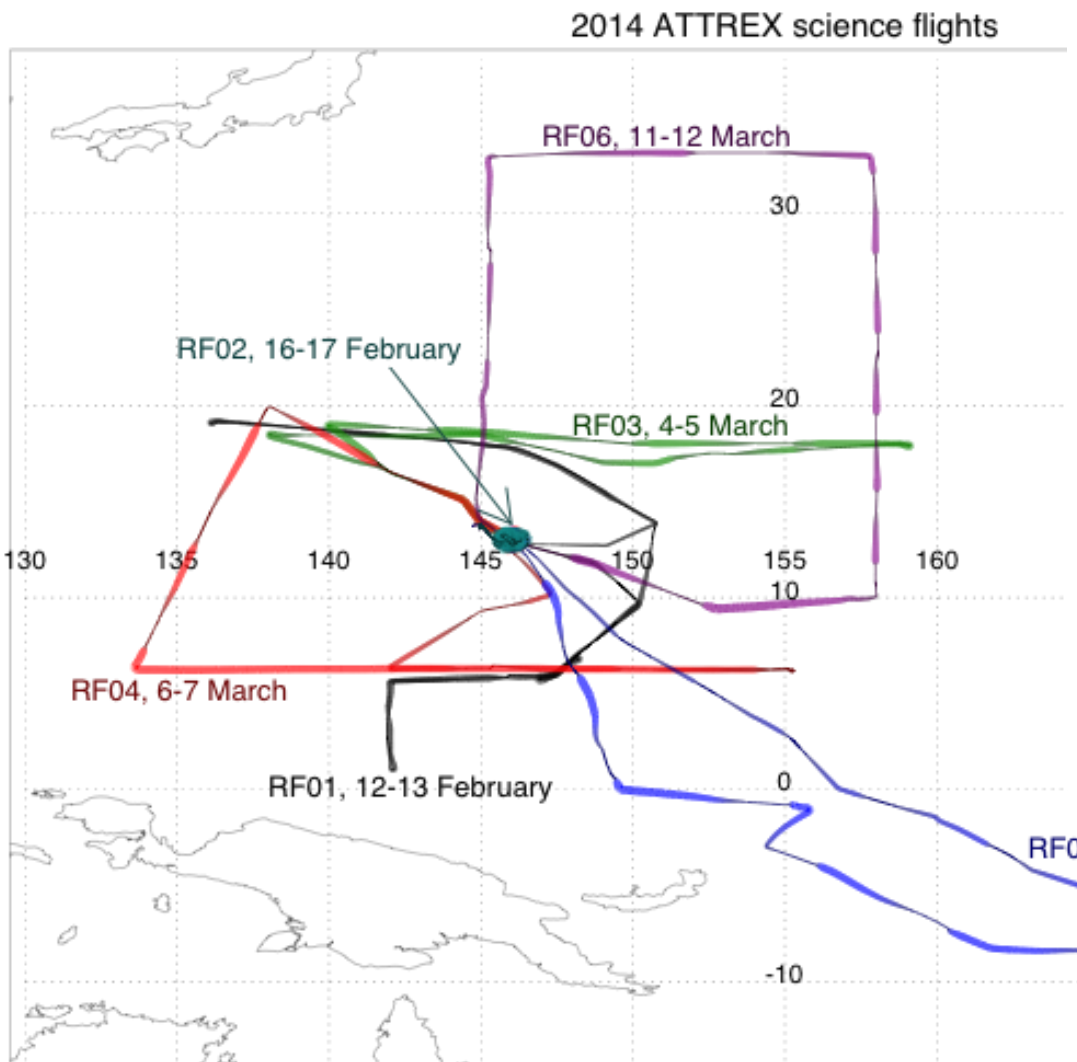


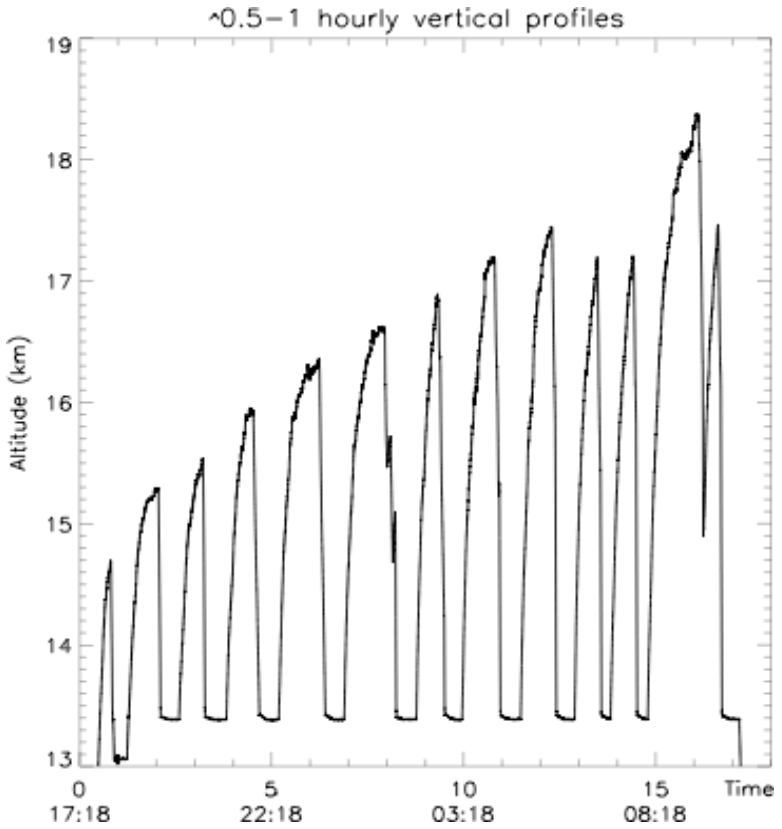

ERA-interim

*Wave parameterization by Kim & Alexander, 2013, GRL ; consistent with Wang et al, 2015, ACD Ueyama et al, 2015, JGR (review)*

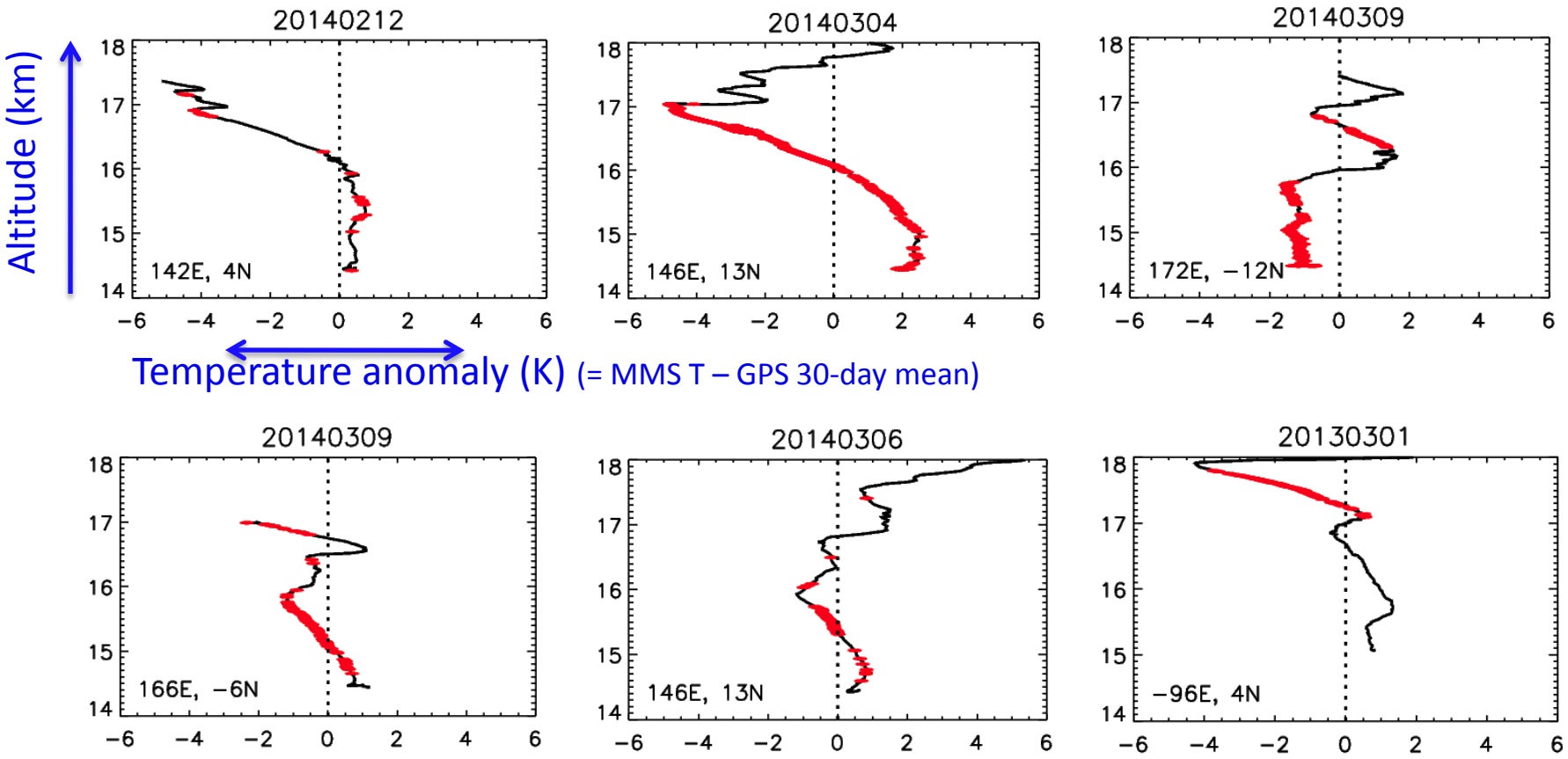
Radiosonde obs

# ATTREX flights include many dive maneuvers(~100), measuring vertical profiles in W-Pacific



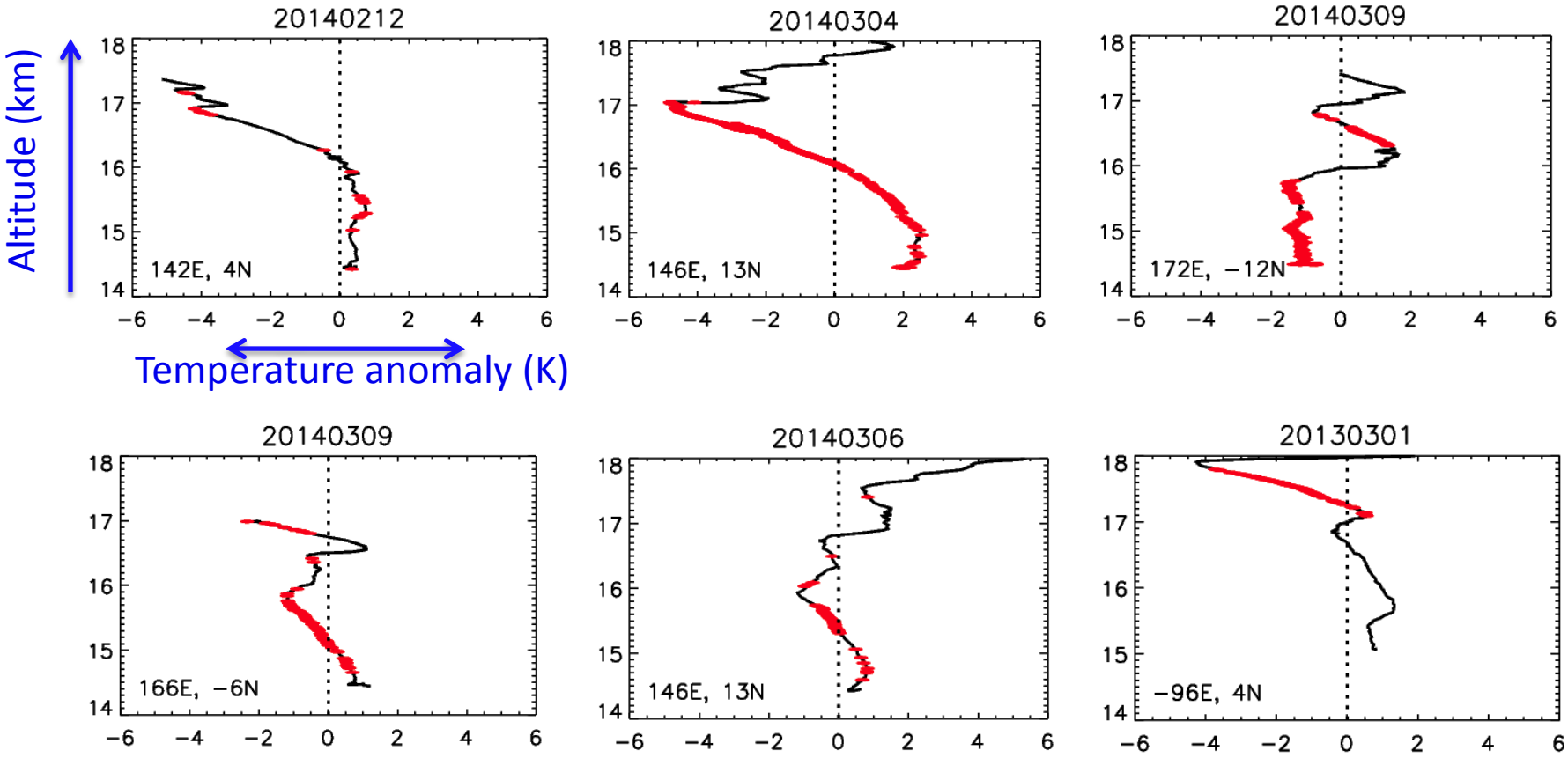



# Examples of ATTREX temperature anomaly profiles:




- Range of vertical scales ( ~ 4 to <1 km) is evident.

# Cloud occurrence is highly related to waves at all vertical scales

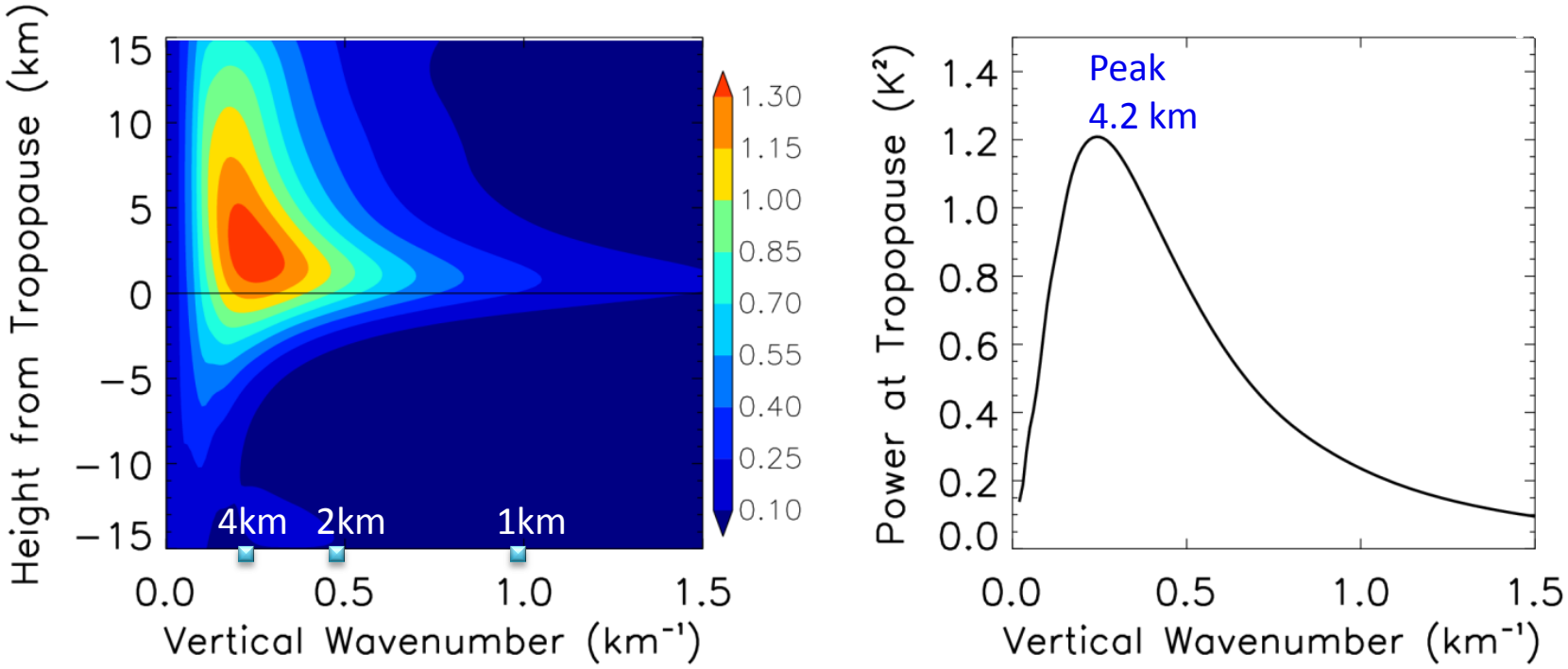



**Red: Cloud Occurrence (measured by FCDP)**

- Clouds are often detected where dT/dz < 0.

# Statistics of vertical wavelet spectrum

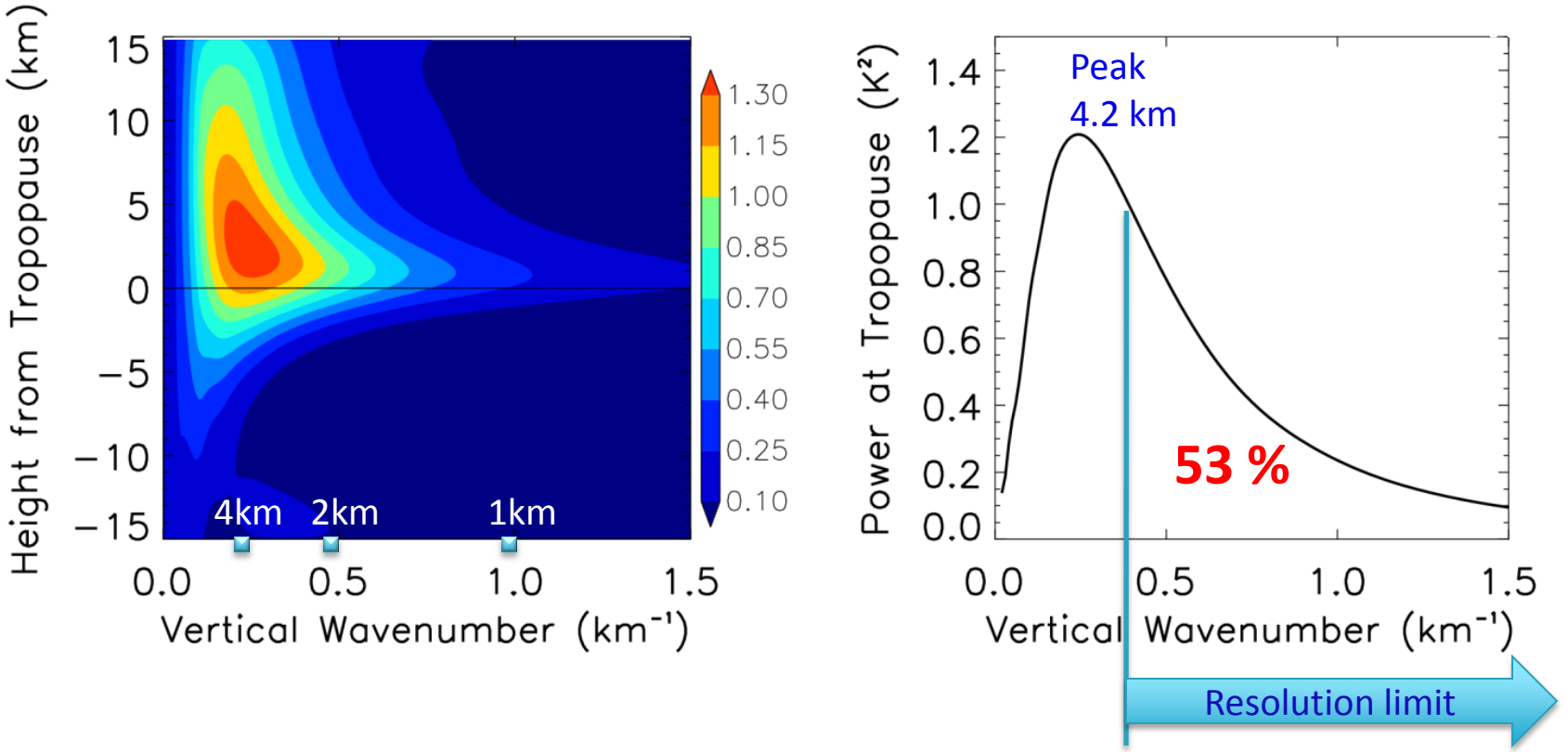
**Temperatures from 5 radiosondes over 24 years**




- Long vertical wavelengths are dominant in the troposphere.
- TTL has enhanced spectrum with shallow scales.

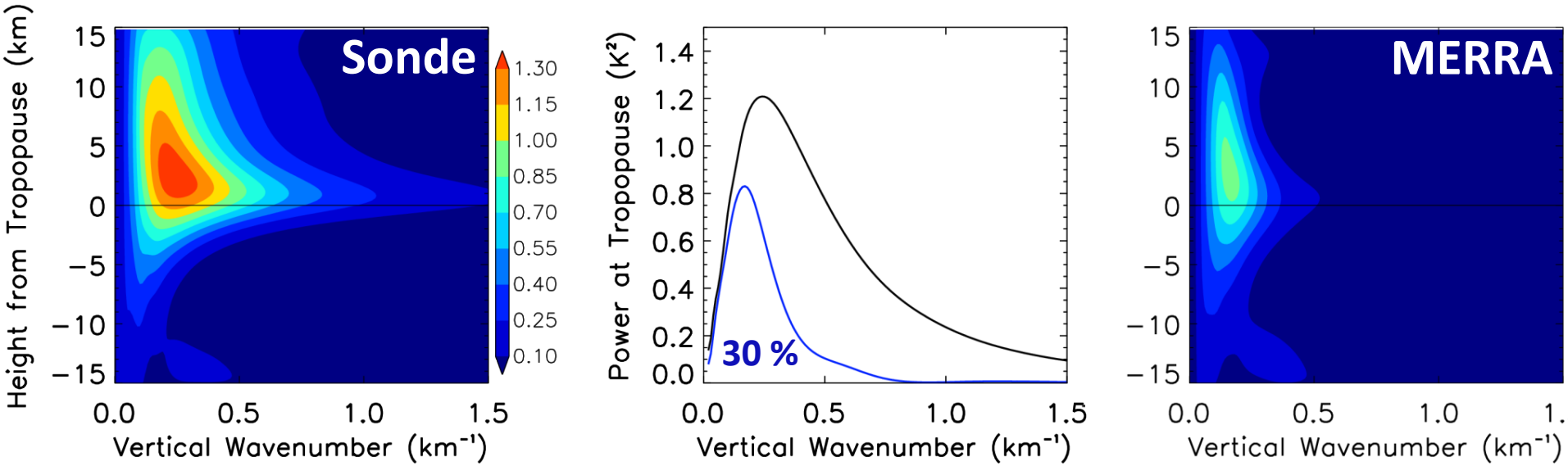
# Half spectrum is at unresolvable scales in current reanalyses!

**Temperatures from 5 radiosondes over 24 years**



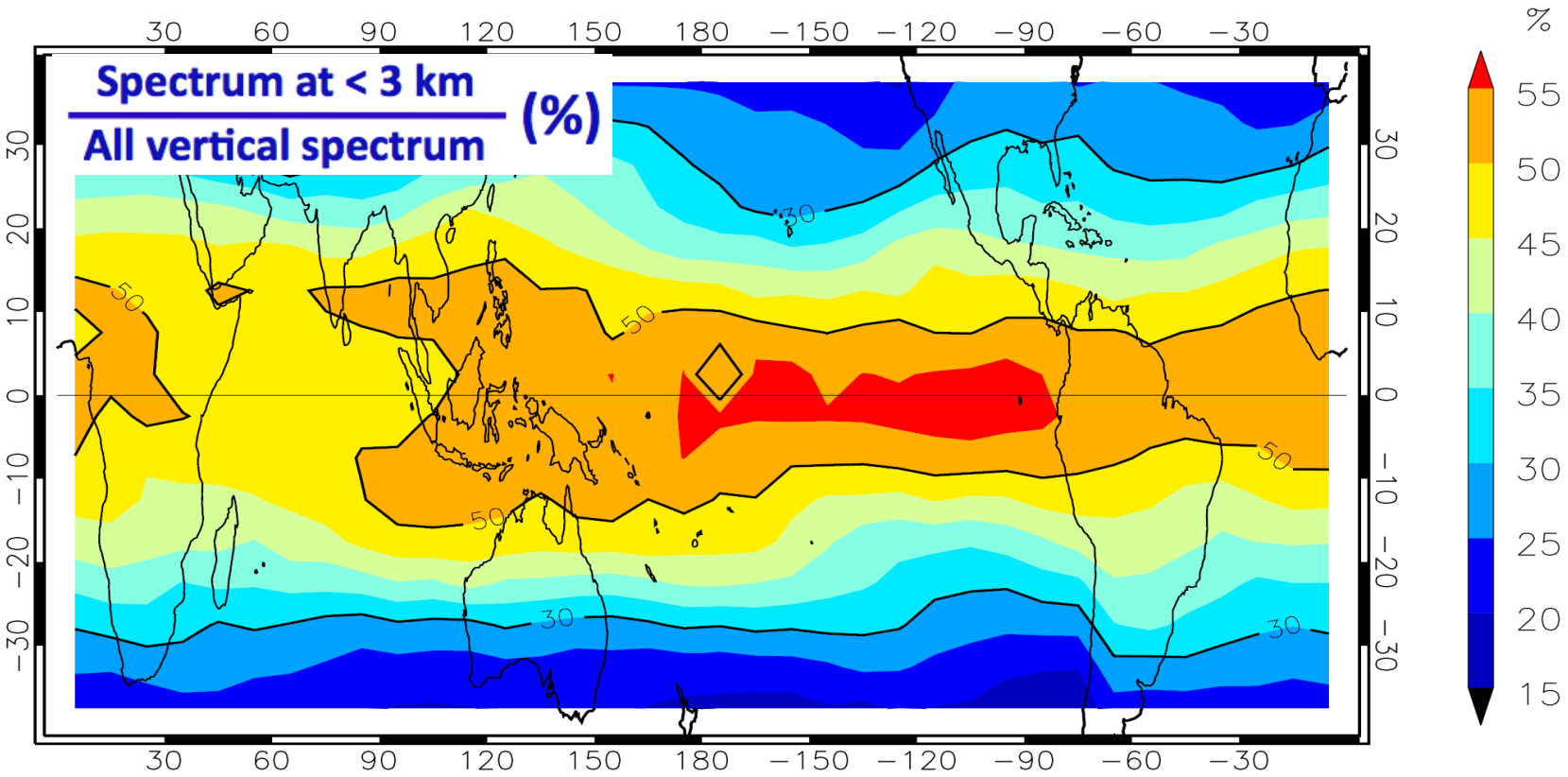

- Long vertical wavelengths are dominant in the troposphere.
- TTL has enhanced spectrum with shallow scales.
- Over half of vertical spectrum comes from $\lambda_z < 2.4$ km (resolution limit).

# Observation vs. MERRA reanalysis



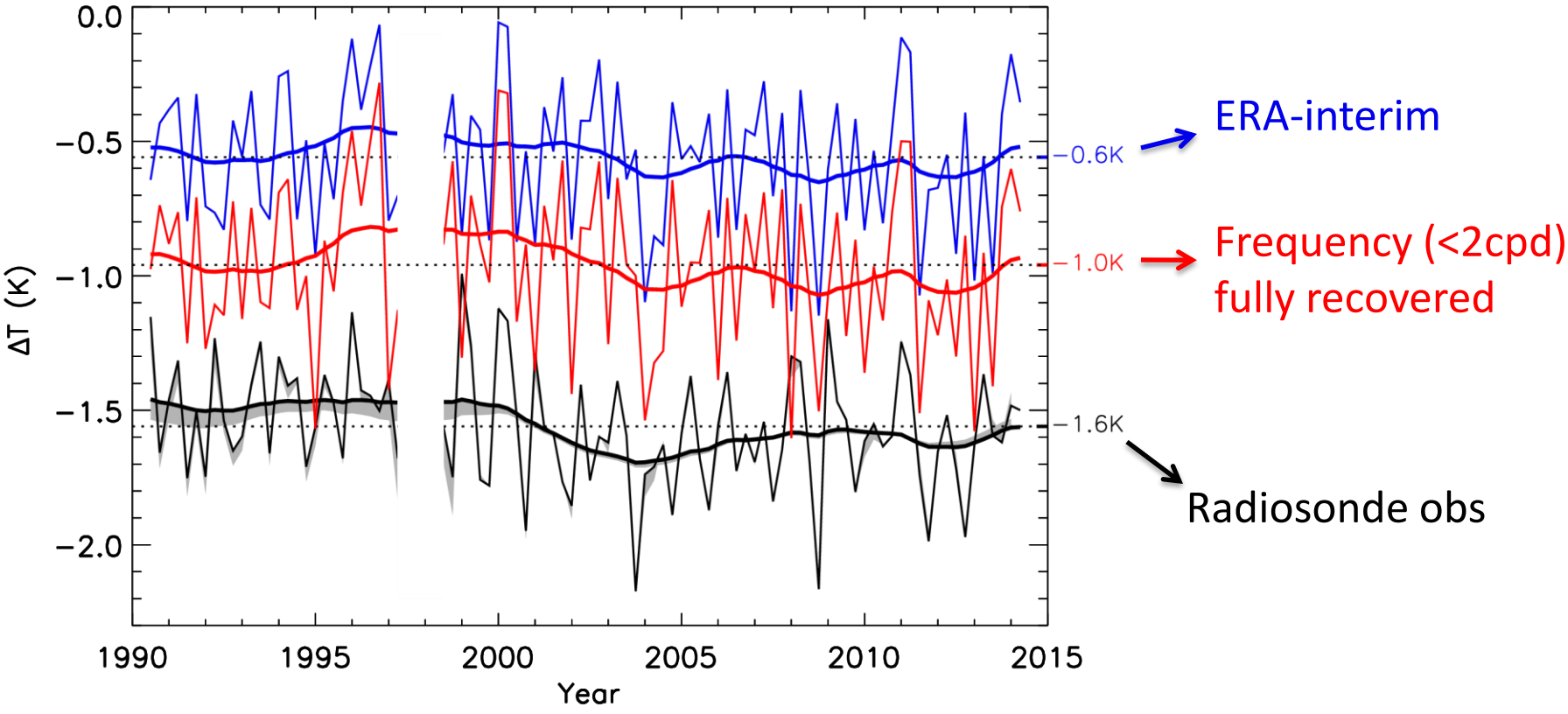

**70% vertical spectrum is missing!**

# Half of GPS vertical spectrum is beyond the z-resolution limit

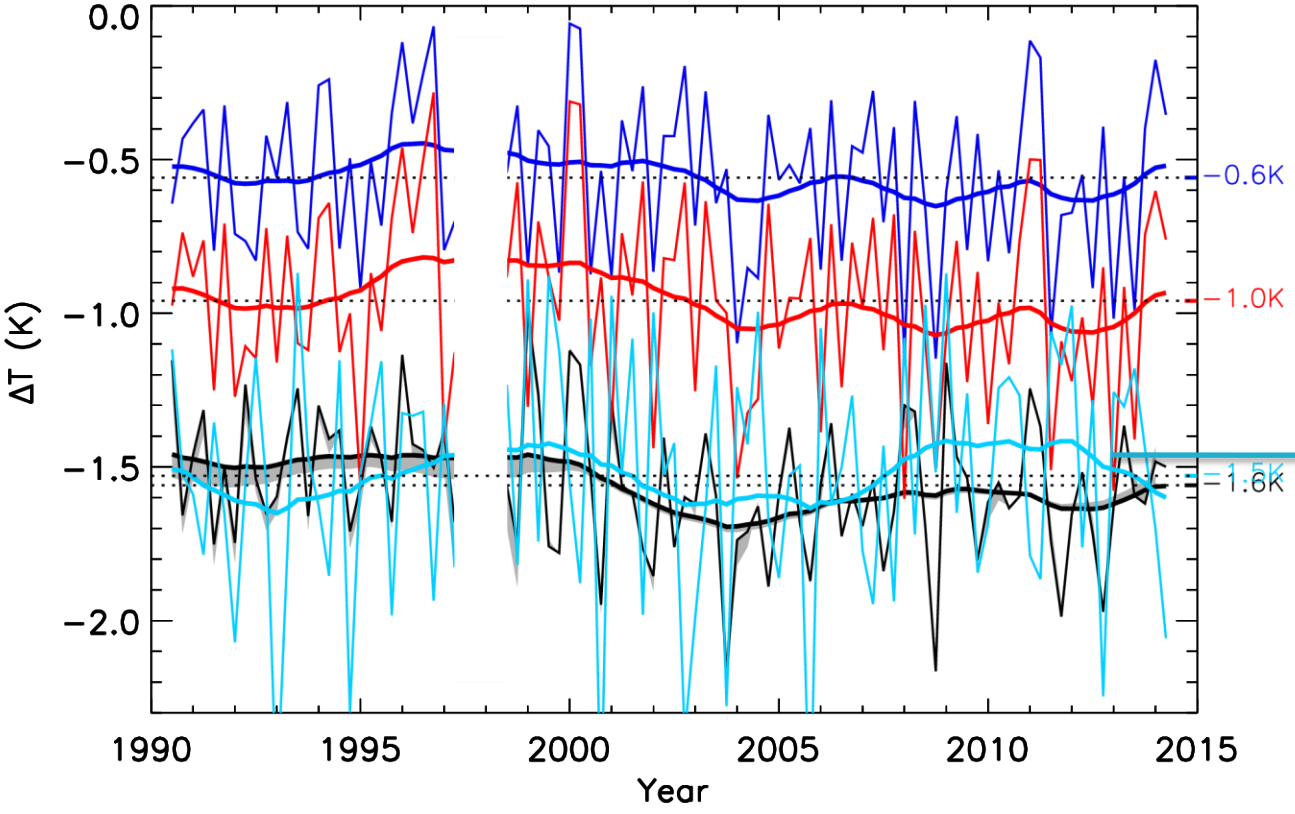



- This portion of vertical spectrum is from unresolvable vertical scales in current analysis & climate models.
- The higher percentage (>50%) in the deep tropics.

# Coming back to delta-T problem..



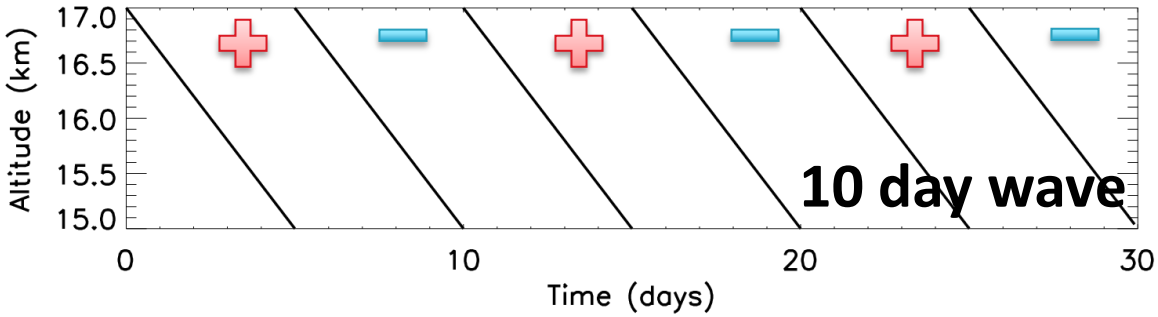
# Adding shallow waves improves the wave impact on CPT



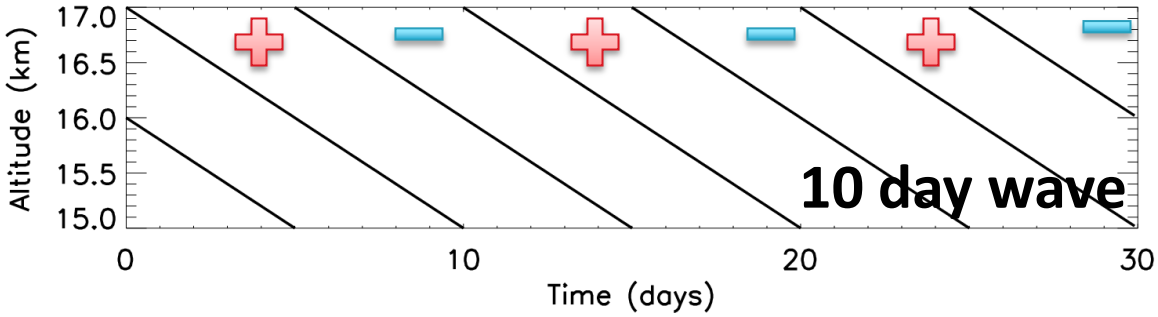

Adding 2km-2K & 1km-2K waves at all altitudes & times

# Schematic of cloud pattern by waves

$\lambda_z$ : 4 km




2 km

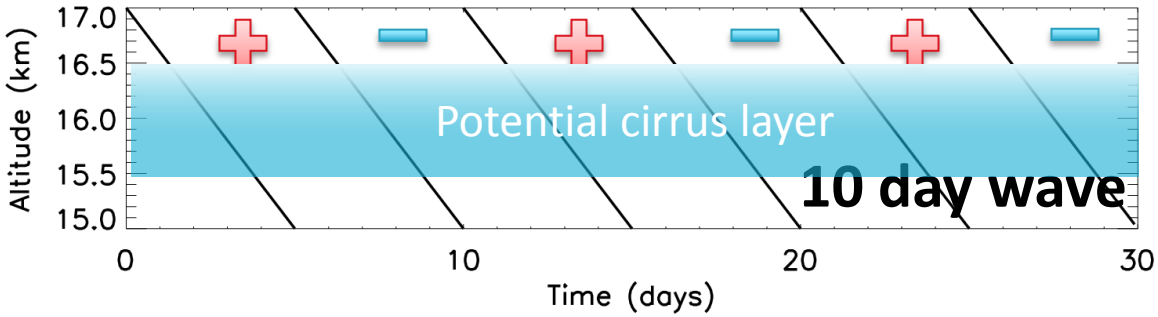


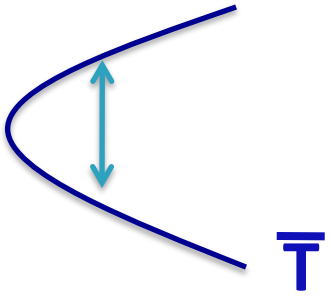

**ASSUMED**

1. Wave phase propagates downward.
2. Background temperature at 15.5-16.5km is cold enough to form cirrus (layer of most clouds in ATTREX W-Pacific flights).
3. Temperature (🡻) & cooling rate (🡹) determine cloud formation.

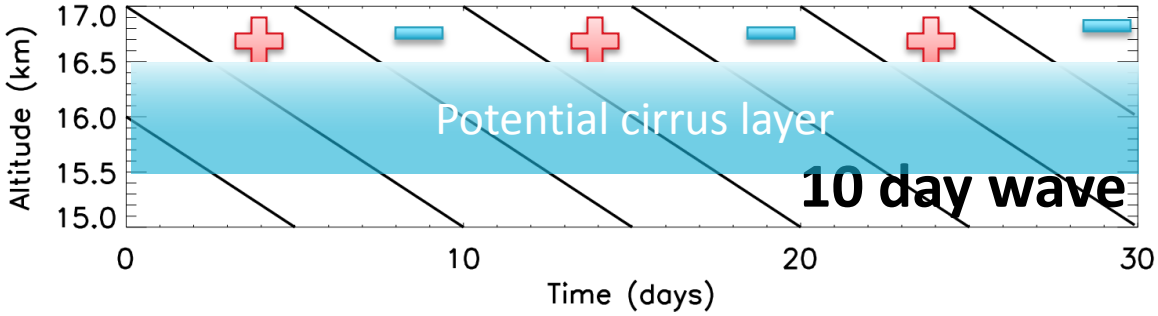
# Schematic of cloud pattern by waves

$\lambda_z$ : 4 km




2 km

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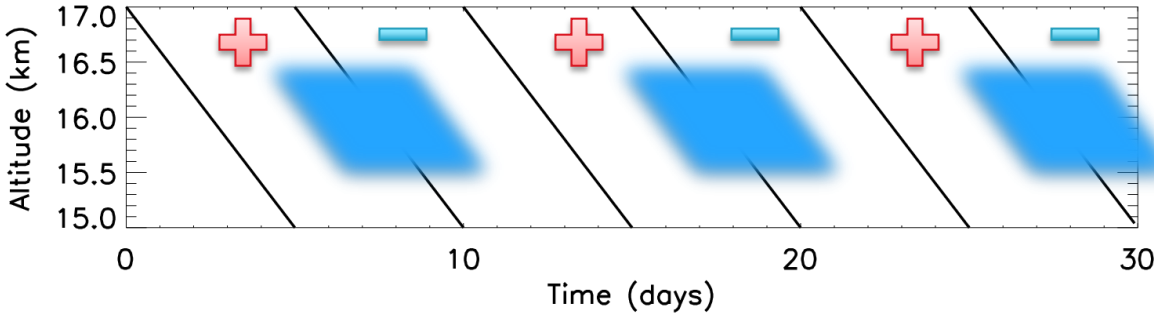
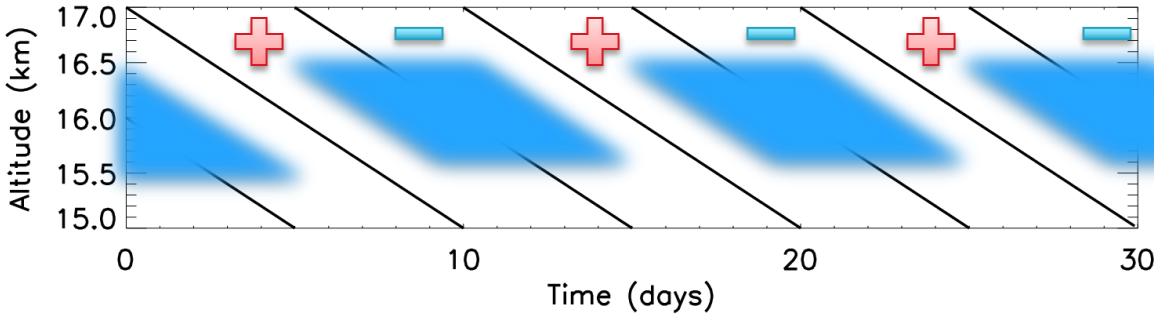
# Shallow waves can make more persistent cirrus

$\lambda_z$ : 4 km




50 % Clouds

2 km

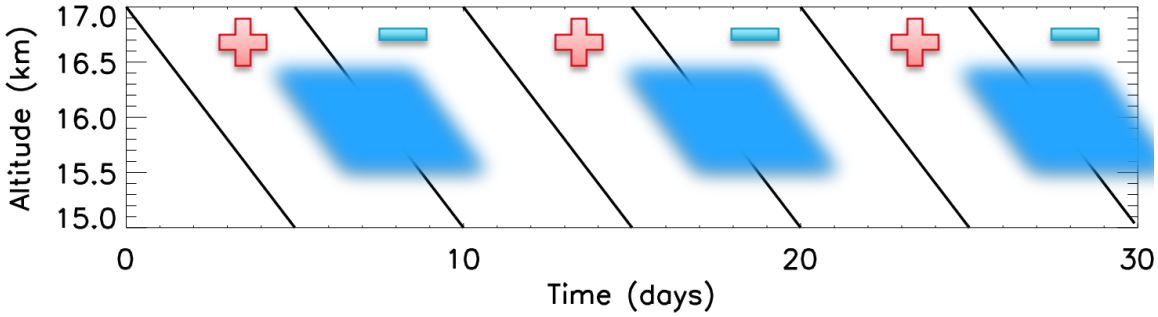



100 % Clouds

- Details of cloud patterns will be determined by other factors: evaporation/sublimation, sedimentation, nearby convection, circulation by radiation, mixing, etc.
- Shallow waves will induce more persistent clouds.
- Different cloud patterns will results in different radiation impacts & water transport.

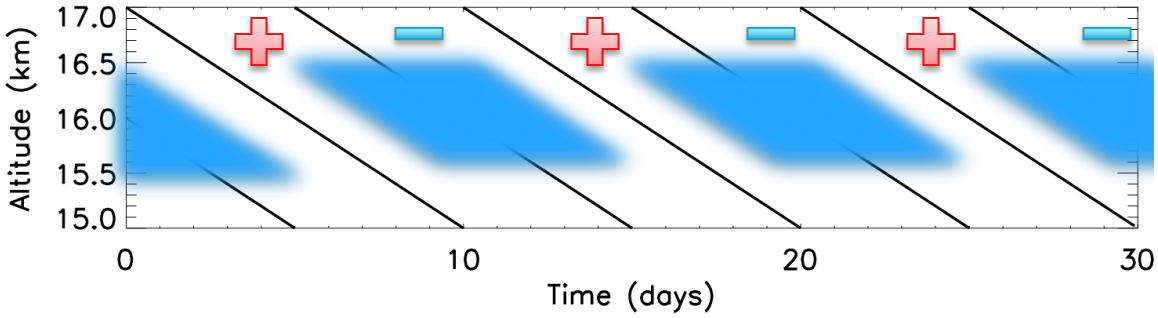
# Shallow waves can induce shallow cloud structures

$\lambda_z$ : 4 km



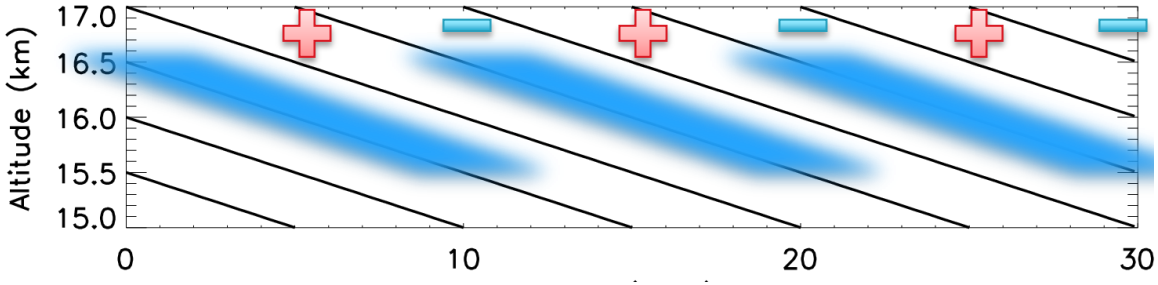

50 % Clouds

2 km




100 % Clouds

1 km



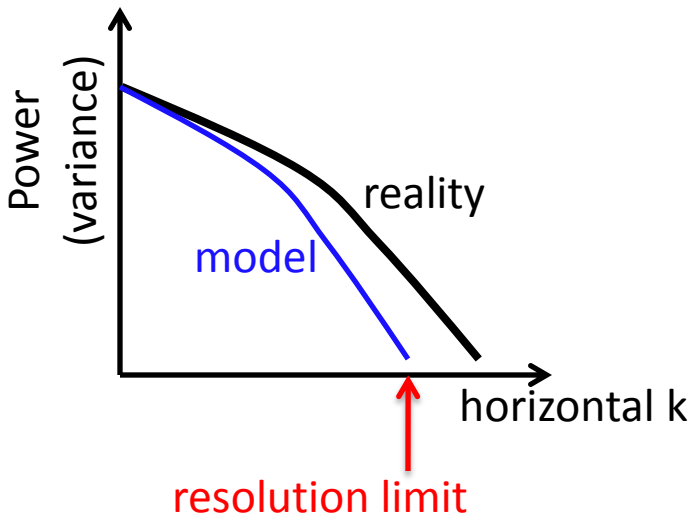

100 % Clouds & Layers

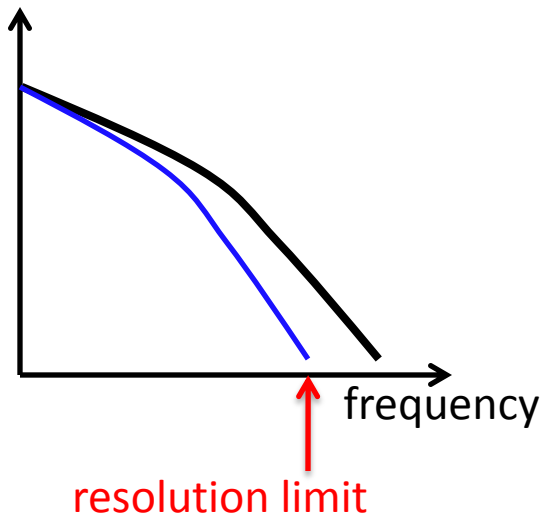
- We have observational evidence from ATTREX! (next talk by Joan Alexander).

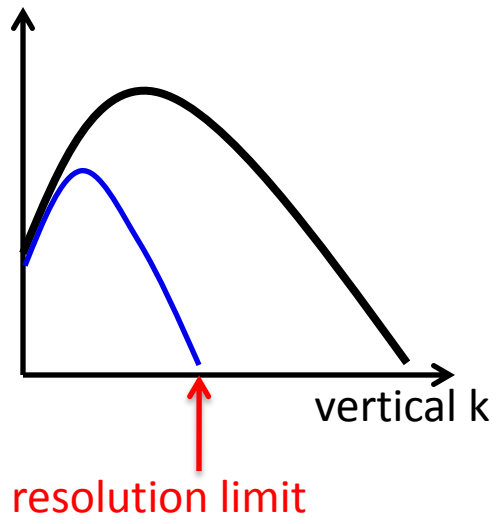
# Conclusion

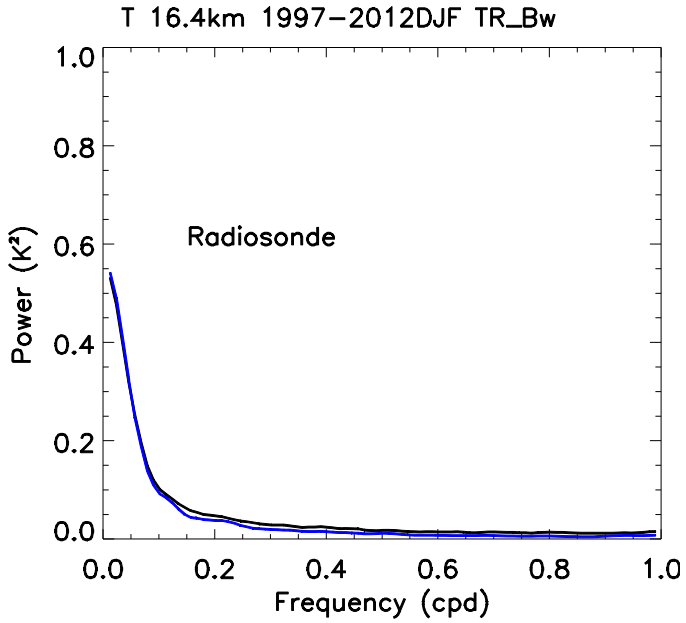
- Waves collectively lower CPT and enhance dehydration.
- Missing waves in reanalyses include both higher frequency and shorter vertical scales.
- Shallow waves will form more persistent cirrus, and even thin multiple layers of clouds.
- 50% of vertical spectrum is at beyond the resolution limit of current reanalysis models; 70% of the vertical spectrum is missing in MERRA.

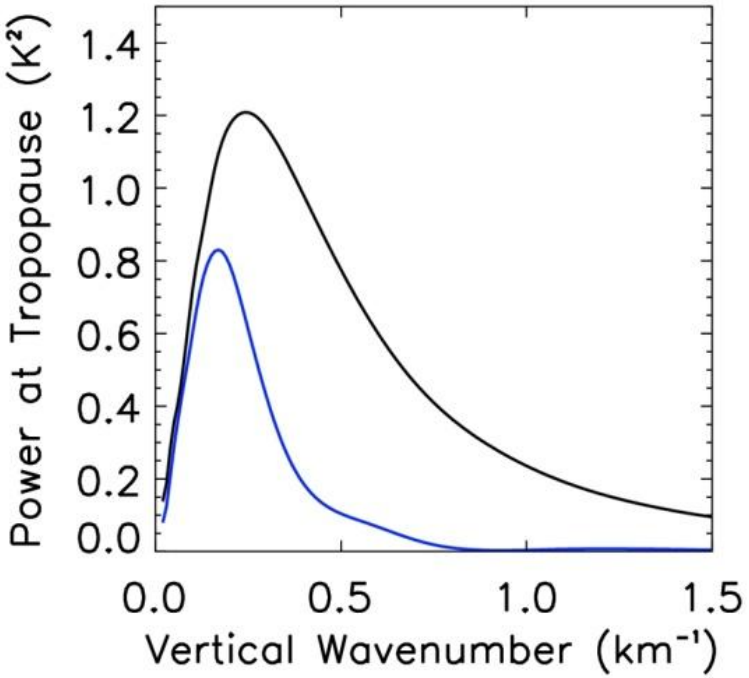
# Can we ignore the missing 70%?

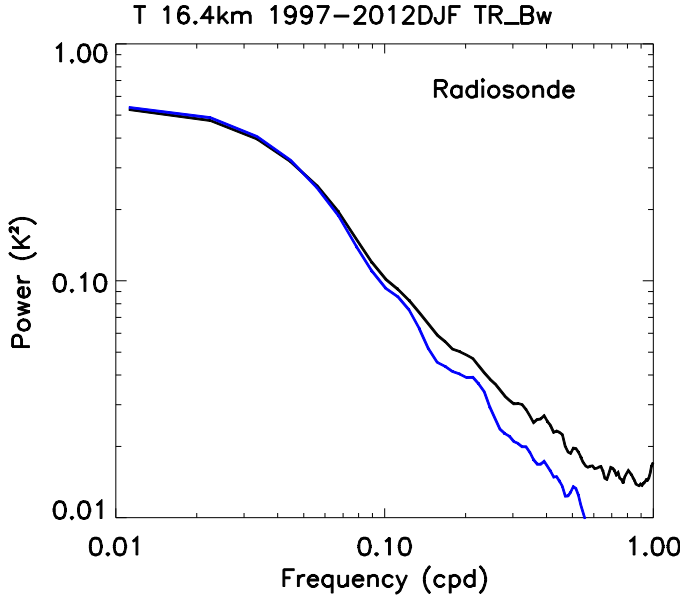


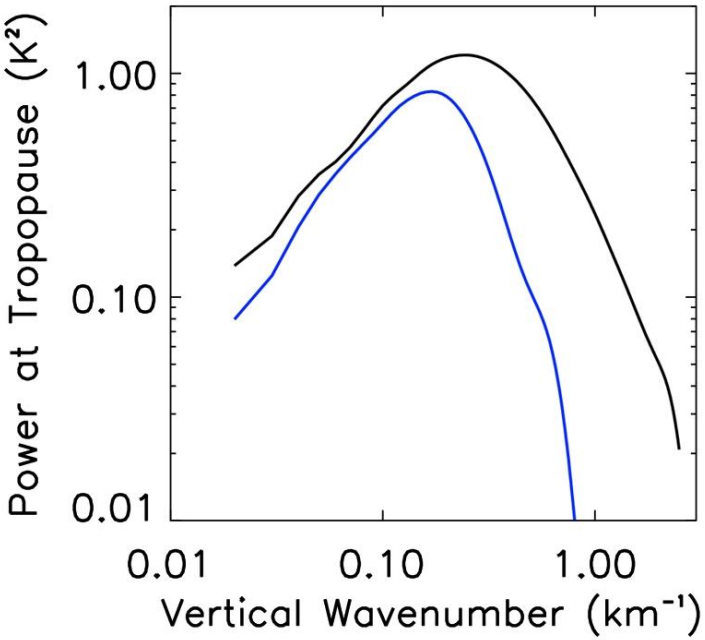




T 16.4km 1997–2012DJF TR_Bw
Radiosonde
Power (K²)
Frequency (cpd)
0.0
0.2
0.4
0.6
0.8
1.0


Power at Tropopause (K²)
Vertical Wavenumber (km⁻¹)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0.5
1.5


T 16.4km 1997–2012DJF TR_Bw
Radiosonde
Power (K²)
Frequency (cpd)
1.00
0.10
0.01


Power at Tropopause (K²)
Vertical Wavenumber (km⁻¹)
1.00
0.10
0.01

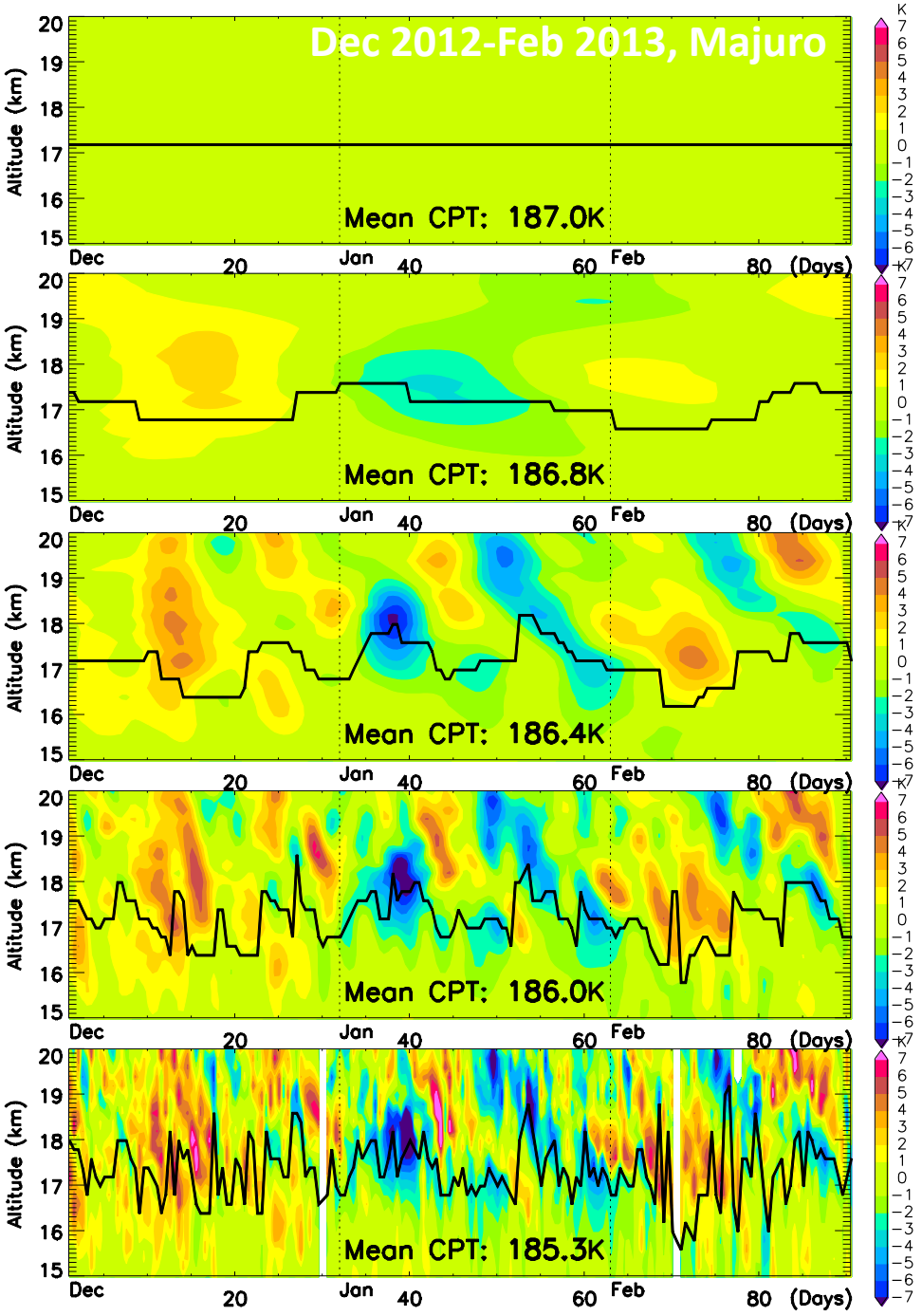
Mean:
**no wave**

Waves
**>30days**

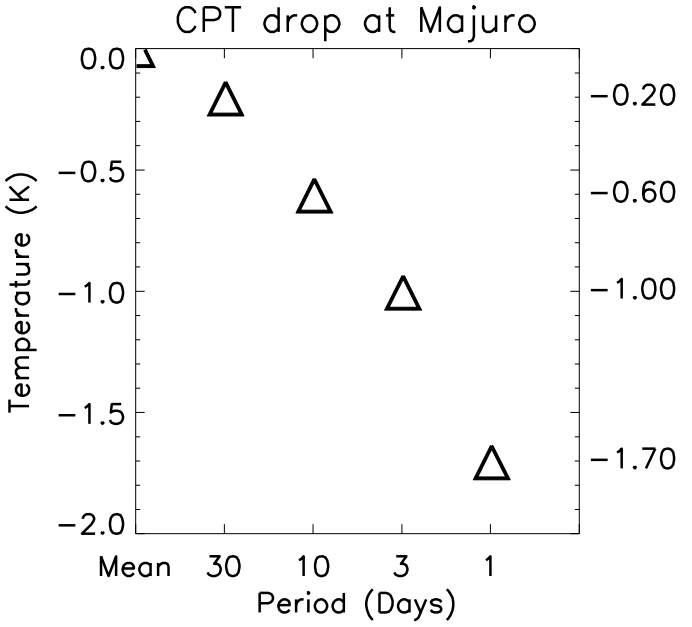
Waves
**>10days**

Waves
**> 3days**

Waves
**> 1days**

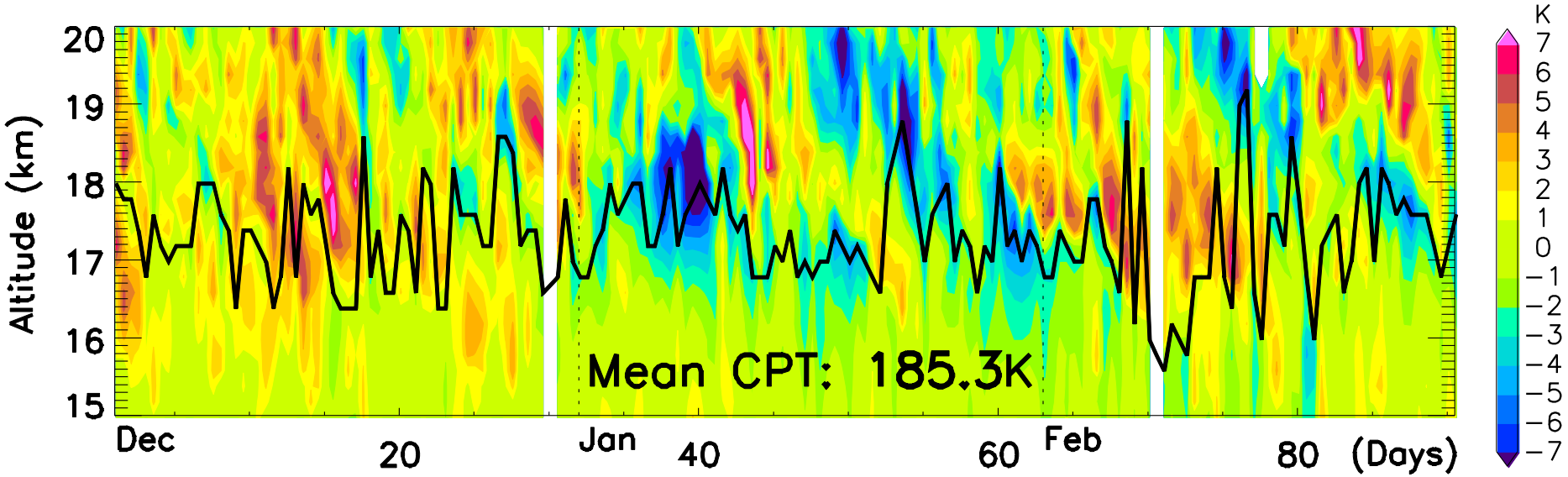



$$\Delta T = \overline{T_{min}} - \overline{T_{min}}$$




**All types (frequencies) of waves contribute to lowering cold point T.**

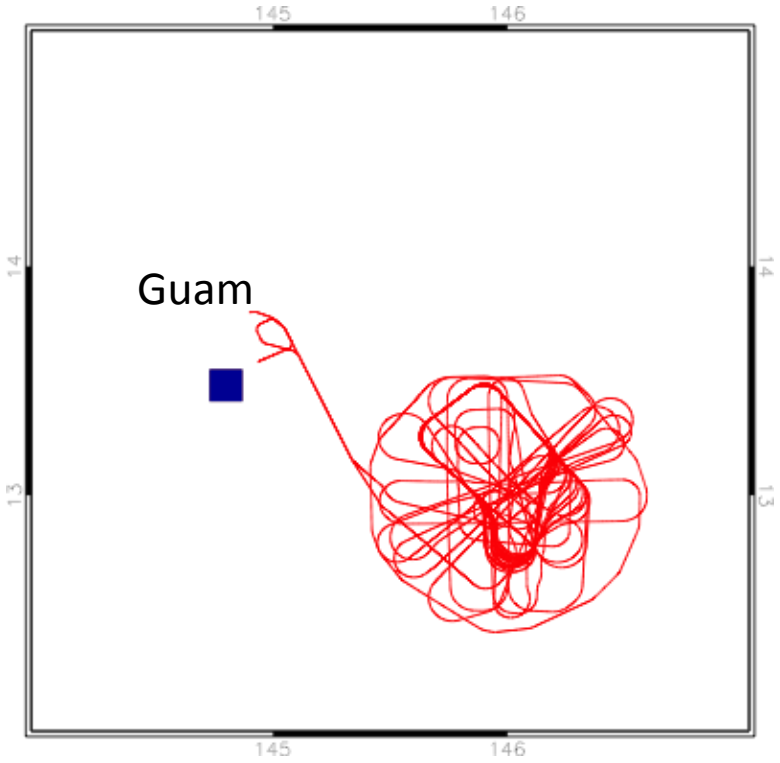
# Ubiquitous Waves in the TTL



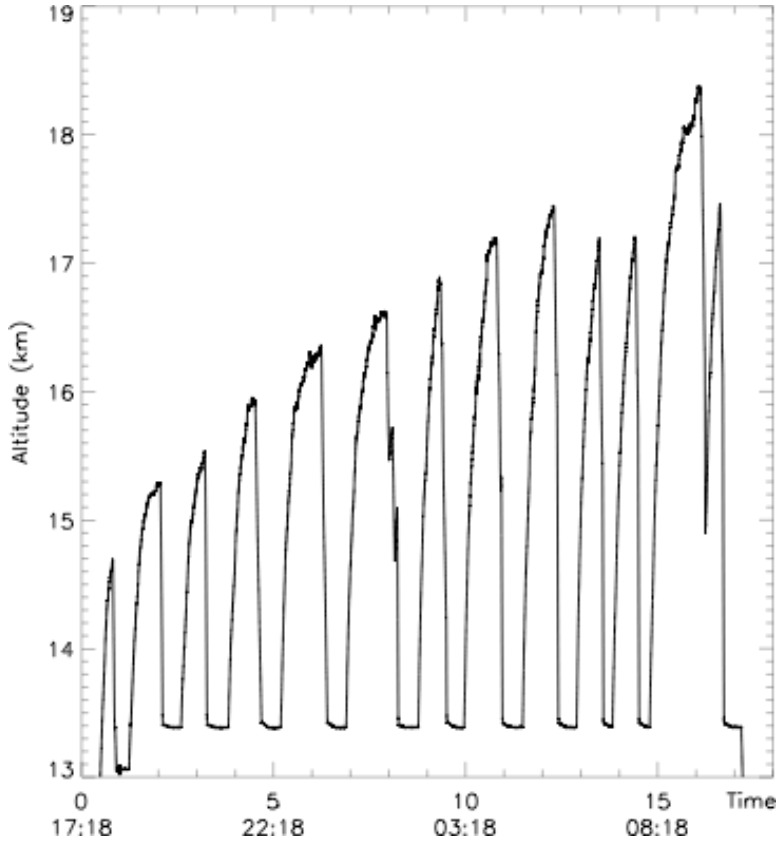

- Waves exist at many scales – horizontal, vertical, and temporal scales.

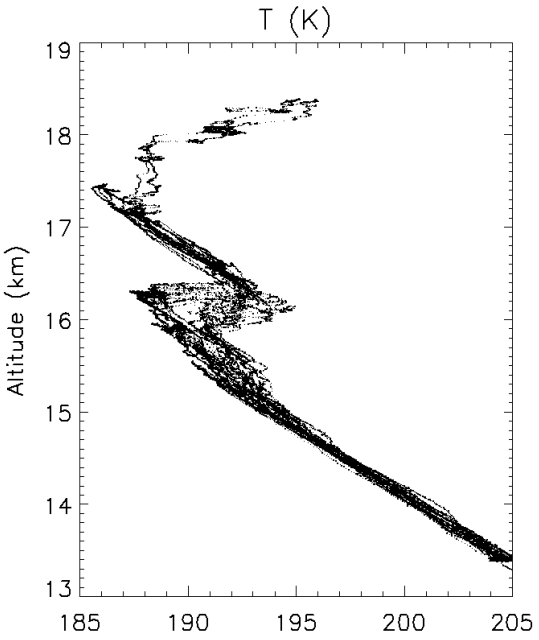
# Nice dives in TTL!

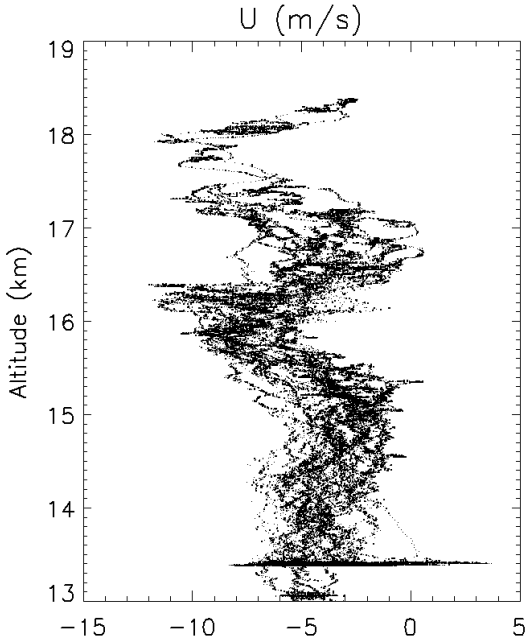
## GH path on Feb 16-17

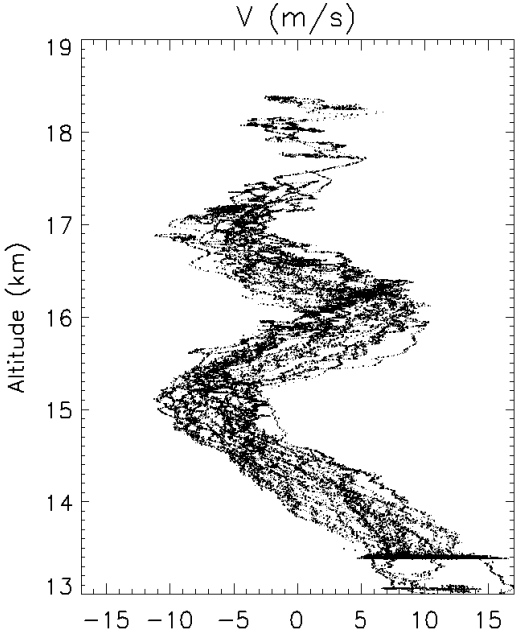


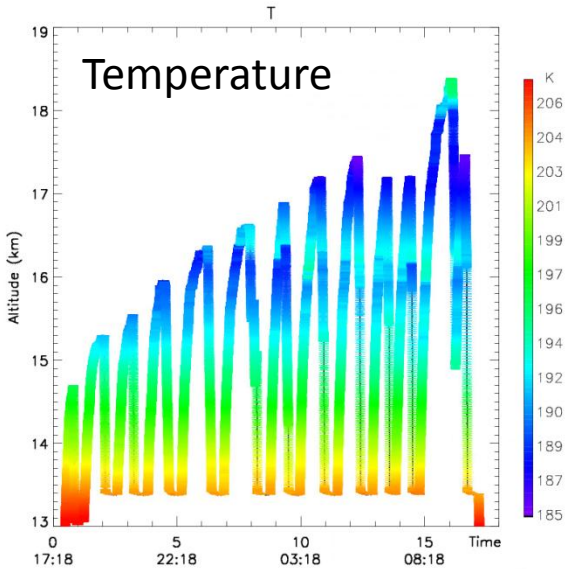

## ~0.5-1 hourly ~24 vertical profiles like continuous radio-/dropsonde

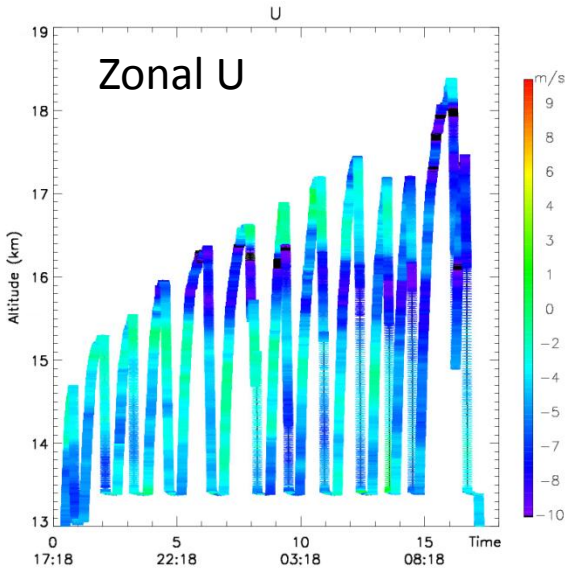


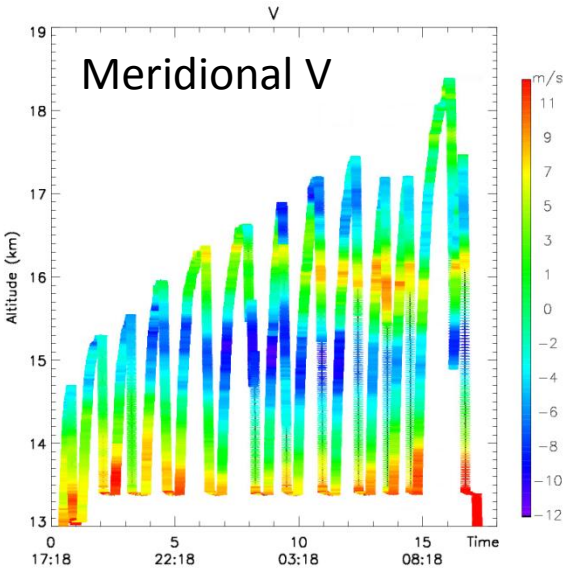

T (K)
Altitude (km)
19
18
17
16
15
14
13
185
190
195
200
205

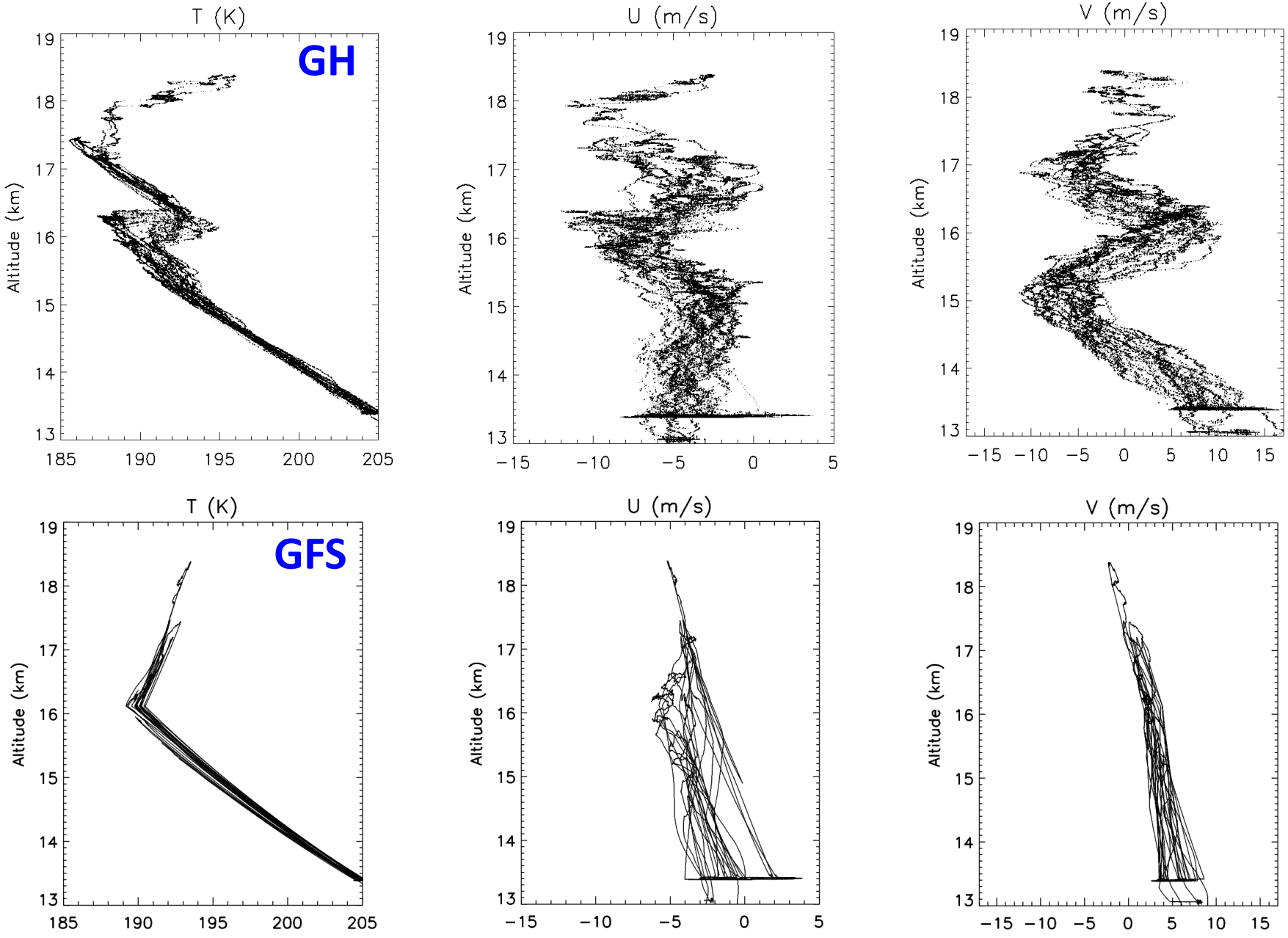

U (m/s)
Altitude (km)
19
18
17
16
15
14
13
−15
−10
−5
0
5


V (m/s)
Altitude (km)
19
18
17
16
15
14
13
−15
−10
−5
0
5
10
15


T
Temperature
Altitude (km)
K
206
204
203
201
199
197
196
194
192
190
189
187
185
0
17:18
5
22:18
10
03:18
15
08:18
Time

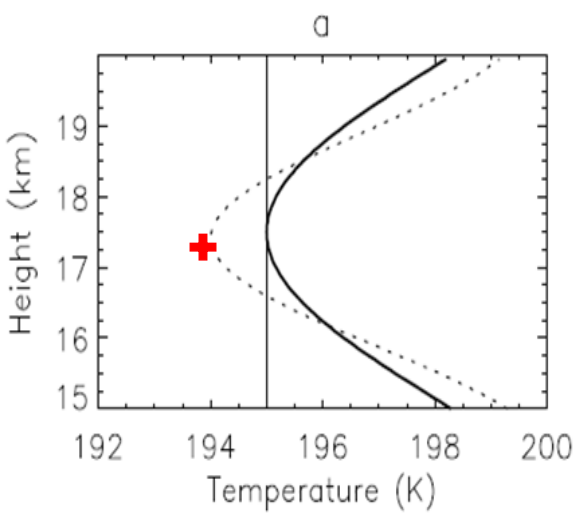

U
Zonal U
Altitude (km)
m/s
9
8
6
4
3
1
0
−2
−4
−5
−7
−8
−10
0
17:18
5
22:18
10
03:18
15
08:18
Time

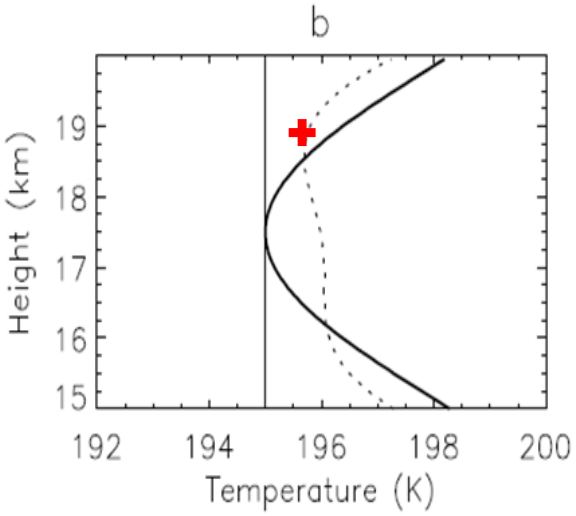

V
Meridional V
Altitude (km)
m/s
11
9
7
5
3
1
0
−2
−4
−6
−8
−10
−12
0
17:18
5
22:18
10
03:18
15
08:18
Time



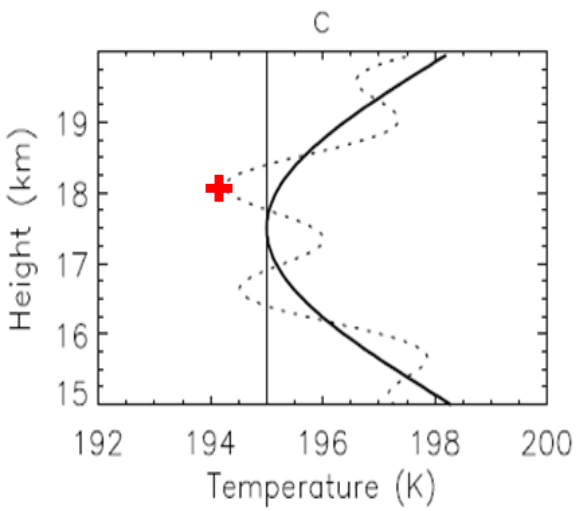

- Current models cannot resolve the scale.

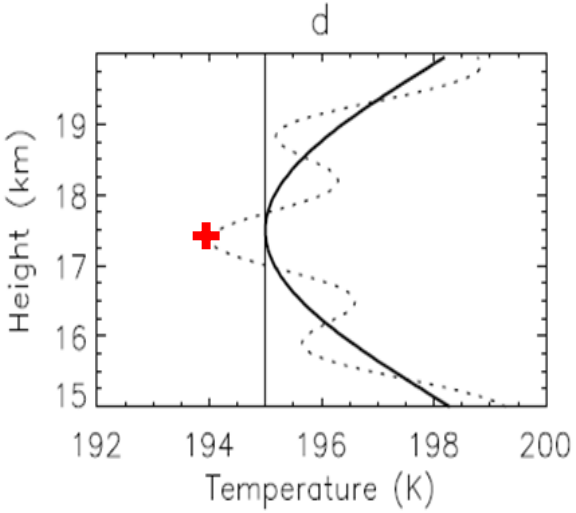
# Why do waves lower CPT?




**Not effective**




**Effectively lower CPT**

Why is this important?

→ Because ascending air will always experience colder T than the mean T; thus, dryer TTL & stratosphere with waves.