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

\[ \text{Individual tropopause} \]

\[ \text{Mean T} \]

\[ \text{Individual profiles} \]

\[ \text{Kim & Alexander, 2015, GRL} \]
Waves lower the mean Cold Point Temperature (CPT)

\[ \Delta T = \overline{T_{min}} - \overline{T_{min}} \]

\( \overline{T_{min}} \): Individual tropopause
\( \overline{T_{min}} \): Mean of all +

Radioonde T Jan 2013 at Majuro

Mean T
Individual profiles

CPT drop by waves (wave impact):
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

![Graph showing temperature changes over years with ERA-interim (similar in MERRA) and Radiosonde observations.]

\[\Delta T \text{ (K)}\]

Year:
- 1990
- 1995
- 2000
- 2005
- 2010
- 2015

Value:
- 0.6 K
- 1.6 K

- 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...

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

ERA-interim

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.

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

Red: Cloud Occurrence (measured by FCDP)
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!

- 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..

Frequency (<2cpd) fully recovered

ERA-interim

Radiosonde obs
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

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

\[ \lambda_z : 4 \text{ km} \]

Potential cirrus layer

\[ 2 \text{ km} \]

Potential cirrus layer

10 day wave

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 (\(\downarrow\)) & cooling rate (\(\uparrow\)) determine cloud formation.
Shallow waves can make more persistent cirrus

\[ \lambda_z : \begin{align*} 
 4 \text{ km} & : 50 \% \text{ Clouds} \\
 2 \text{ km} & : 100 \% \text{ Clouds} 
\end{align*} \]

- 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 result in different radiation impacts & water transport.
Shallow waves can induce shallow cloud structures

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

- $\lambda_z$: 4 km (50% Clouds)
- 2 km (100% Clouds)
- 1 km (100% Clouds & Layers)
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%?
All types (frequencies) of waves contribute to lowering cold point T.

\[
\Delta T = \overline{T_{min}} - \overline{T_{min}}
\]

CPT drop at Majuro
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
- Current models cannot resolve the scale.
Why do waves lower CPT?

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