Gravity Wave and Kelvin Wave Activity in the Tropical Lower Stratosphere

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Multiscale Dynamics in the TTL

- Planetary-scale circulations (e.g. adiabatic cooling by Brewer-Dobson upwelling)
- Convectively coupled equatorial waves (broad spectrum, incl. Kelvin waves)
- Convection (incl. large-scale indirect temperature response)
- Horizontal mixing (due to Rossby wave breaking) with extratropical lowermost stratosphere
- Vertical mixing, e.g. due to overshooting convection, breaking gravity waves
Upper Troposphere / Lower Stratosphere

Gettelman et al. exUTLS review paper, 2011
Vertical Transport just above the Tropical Tropopause: Residual Circulation Upwelling vs. (vertical) Mixing

In other words, air is “marked,” on emergence above the highest cloud tops, like a signal recorded on an upward moving magnetic tape.

Tape Recorder

Signal in $\text{H}_2\text{O}$
Mote et al., 1996:

An atmospheric tape recorder: The imprint of tropical tropopause temperatures on stratospheric water vapor

In other words, air is “marked,” on emergence above the highest cloud tops, like a signal recorded on an upward moving magnetic tape.

Tape Recorder Signal in $\text{H}_2\text{O}$

Is the tape recorder signal caused by vertical advection within the stratospheric residual circulation?
Synthetic tape recorder by solving simple 1-d transport Eq., similar to Mote et al. (1998), but with seasonally varying transport coefficients

\[ \partial_t \chi = -\bar{\omega}^* \partial_p \chi + \partial_p (K_p \partial_p \chi) - \alpha_p (\chi - \chi_{ML}) + S \]

vertical advection   vertical mixing/diffusion   horizontal mixing/dilution
Modeled vs. Observed Tape Recorder Signal

Modeling MLS H₂O

80 hPa H₂O

Mote et al. (1998)
Synthetic
MLS

ppmv

Months

J  F  M  A  M  J  J  A  S  O  N  D
Vertical mixing as important as vertical advection!

quadrupled(!) vertical mixing compared to Mote et al. (but same vertical advection & horizontal mixing)

(for ERAi, optimal solution requires 10 times vertical mixing and 5 times horizontal mixing)
Synthetic tape recorder from 1-d transport model in \textit{isentropic coordinates} → \textit{vertical mixing mostly negligible} (but horizontal mixing important during boreal spring / summer)

→ \textit{vertical mixing contribution in p-coordinates largely due to adiabatic processes} (e.g. gravity wave breaking)
Effective vertical transport velocity for tracer in p-coordinates:

\[ \partial_t \overline{\chi} + \omega_{\text{eff}} \partial_p \overline{\chi} = 0 \quad \text{with} \quad \omega_{\text{eff}} \approx \overline{\omega}^* + \partial_p \overline{\omega'} \overline{\chi'} \left( \partial_p \overline{\chi} \right)^{-1} \]
Effective vertical transport velocity for tracer in $p$-coordinates:

$$\partial_t \bar{\chi} + \omega_{\text{eff}} \partial_p \bar{\chi} = 0$$

with

$$\omega_{\text{eff}} \approx \bar{\omega}^* + \partial_p \bar{\omega'} \bar{\chi'} \left(\partial_p \bar{\chi}\right)^{-1}$$

Effective transport velocity for tracer in isentropic coordinates:

$$\partial_t \bar{\chi}^* + Q_{\text{eff}} \partial_\theta \bar{\chi}^* = 0$$
Effective vertical transport velocity for tracer in p-coordinates:

\[ \frac{\partial}{\partial t} \overline{\chi} + \omega_{\text{eff}} \frac{\partial}{\partial p} \overline{\chi} = 0 \]

with

\[ \omega_{\text{eff}} \approx \overline{\omega}^* + \frac{\partial p \omega' \chi' (\partial_p \chi)^{-1}}{} \]

Effective transport velocity for tracer in isentropic coordinates:

\[ \frac{\partial}{\partial t} \overline{\chi}^* + Q_{\text{eff}} \frac{\partial}{\partial \theta} \overline{\chi}^* = 0 \]

Quasi-adiabatic vertical mixing (e.g. due to gravity wave breaking):

\[ \overline{\omega' \theta'} \approx \overline{\omega' \chi'} \frac{\partial p \theta}{\partial_p \chi} \]
Effective vertical transport velocity for tracer in p-coordinates:

$$\partial_t \bar{\chi} + \omega_{\text{eff}} \partial_p \bar{\chi} = 0$$

with

$$\omega_{\text{eff}} \approx \bar{\omega}^* + \partial_p \bar{\omega}' \bar{\chi}' \left( \partial_p \bar{\chi} \right)^{-1}$$

Effective transport velocity for tracer in isentropic coordinates:

$$\partial_t \bar{\chi}^* + Q_{\text{eff}} \partial_\theta \bar{\chi}^* = 0$$

Quasi-adiabatic vertical mixing (e.g. due to gravity wave breaking):

$$\bar{\omega}' \bar{\theta}' \approx \bar{\omega}' \bar{\chi}' \frac{\partial_p \bar{\theta}}{\partial_p \bar{\chi}}$$

Diabatic heating in steady state:

$$\bar{Q} \approx \bar{\omega}^* \partial_p \bar{\theta} + \partial_p \bar{\omega}' \bar{\theta}'$$
Effective vertical transport velocity for tracer in p-coordinates:

\[ \partial_t \bar{\chi} + \omega_{\text{eff}} \partial_p \bar{\chi} = 0 \]

with \( \omega_{\text{eff}} \approx \bar{\omega}^* + \partial_p \bar{\omega}' \bar{\chi}' (\partial_p \bar{\chi})^{-1} \)

Effective transport velocity for tracer in isentropic coordinates:

\[ \partial_t \bar{\chi}^* + Q_{\text{eff}} \partial_\theta \bar{\chi}^* = 0 \]

Quasi-adiabatic vertical mixing (e.g. due to gravity wave breaking):

\[ \bar{\omega}' \bar{\theta}' \approx \bar{\omega}' \bar{\chi}' \frac{\partial \bar{\theta}}{\partial \bar{\chi}} \]

Diabatic heating in steady state:

\[ \bar{Q} \approx \bar{\omega}^* \partial_p \bar{\theta} + \partial_p \bar{\omega}' \bar{\theta}' \]

\[ \bar{Q} \approx Q_{\text{eff}} \]

\[ \bar{\omega}' \bar{\chi}' \approx \left[ \omega_{\text{eff}} - Q_{\text{eff}} (\partial_p \bar{\theta})^{-1} \right] \frac{(\partial_\theta \bar{\chi})^2}{\partial_{\theta\theta} \bar{\chi}} \]
\[
\omega' \chi' \approx \left( \omega_{\text{eff}} - Q_{\text{eff}} \left( \partial_p \bar{\theta} \right)^{-1} \right) \left( \frac{\partial \bar{\chi}}{\partial \bar{\theta} \bar{\chi}} \right)^2
\]
Conclusions Part I

• Vertical mixing near tropical tropopause has been pointed at (e.g. Flannaghan & Fueglistaler, 2014), but is often neglected

• We find important contribution by quasi-adiabatic vertical mixing (due to gravity wave breaking?) to transport just above the tropical tropopause

• Insights into vertical mixing by comparing effective vertical transport in pressure vs. isentropic coordinates

• Implications for cloud formation & dehydration (e.g. in trajectory simulations as in Jensen & Pfister, 2004+)
Tropical Lower Stratospheric Kelvin Wave Momentum Flux from Radiosoundings

Sjoberg, Birner, Johnson, in preparation
Thomson (Kelvin) Waves:

Monday, 17th March 1879.

Professor KELLAND, President, in the Chair.

The following Communications were read:—

   By Sir William Thomson.
Kim & Son (2012): Kelvin wave composite from GPS data:
MJO modulation of TTL dynamics (results from DYNAMO): Gan Island

Madden & Julian (1972)

Erin Dagg (MS thesis)
MJO modulation of TTL dynamics (results from DYNAMO): Manus Island

MJO filter
(a) 20-80 day, Manus Island

Kelvin wave filter
(b) 7-20 day, Manus Island

Erin Dagg (MS thesis)
Following Holton et al. 2001 (idea from Kousky & Wallace 1971 and Sato & Dunkerton 1997):

$$u' w' = -\frac{R \omega_d}{H N^2} Q_{uT}$$

Vertical momentum flux

Intrinsic frequency

u'-T' Quadrature spectrum

Kelvin/gravity wave dispersion relation:

$$\omega_d = \omega - k \bar{u} = -\frac{kN}{m}$$

Wallace & Kousky (1968)
Example:

Gan Island (0.7°S, 73.2°E)
DYNAMO, January 2012

High-vertical resolution radiosoundings!
Climatology (2003–2013) for Manus ARM sounding site (2.0°S, 147.4°E)

**Total momentum flux [mPa]**

**Vertical wavelength**

**Quadrature spectrum [K m s$^{-1}$]**

**Horizontal wavelength** (x 1000 km)
QBO composite (2003–2013) for Manus ARM sounding site (2.0°S, 147.4°E)

→ Kelvin wave momentum flux drives E'y→W'y transition (as expected) and is suppressed in westerly QBO phase
MJO modulation of lower stratospheric Kelvin wave activity?

→ inconclusive (difference not statistically significant)

Manus ARM sounding site (2.0°S, 147.4°E)
Conclusions – Part II

- Quadrature $u'$-$T'$ spectrum applied to radiosoundings → Kelvin wave momentum flux

- Strongest lower stratospheric wave activity during boreal winter/spring (inferred using Manus site in west pacific)

- Possibly modulation by MJO, but inconclusive

- Kelvin wave driving of QBO easterly→westerly transition confirmed (cf. many previous studies – e.g. Sato & Dunkerton, 1997; Ern & Preusse, 2009)