Gravity Wave and Kelvin Wave Activity in the Tropical Lower Stratosphere

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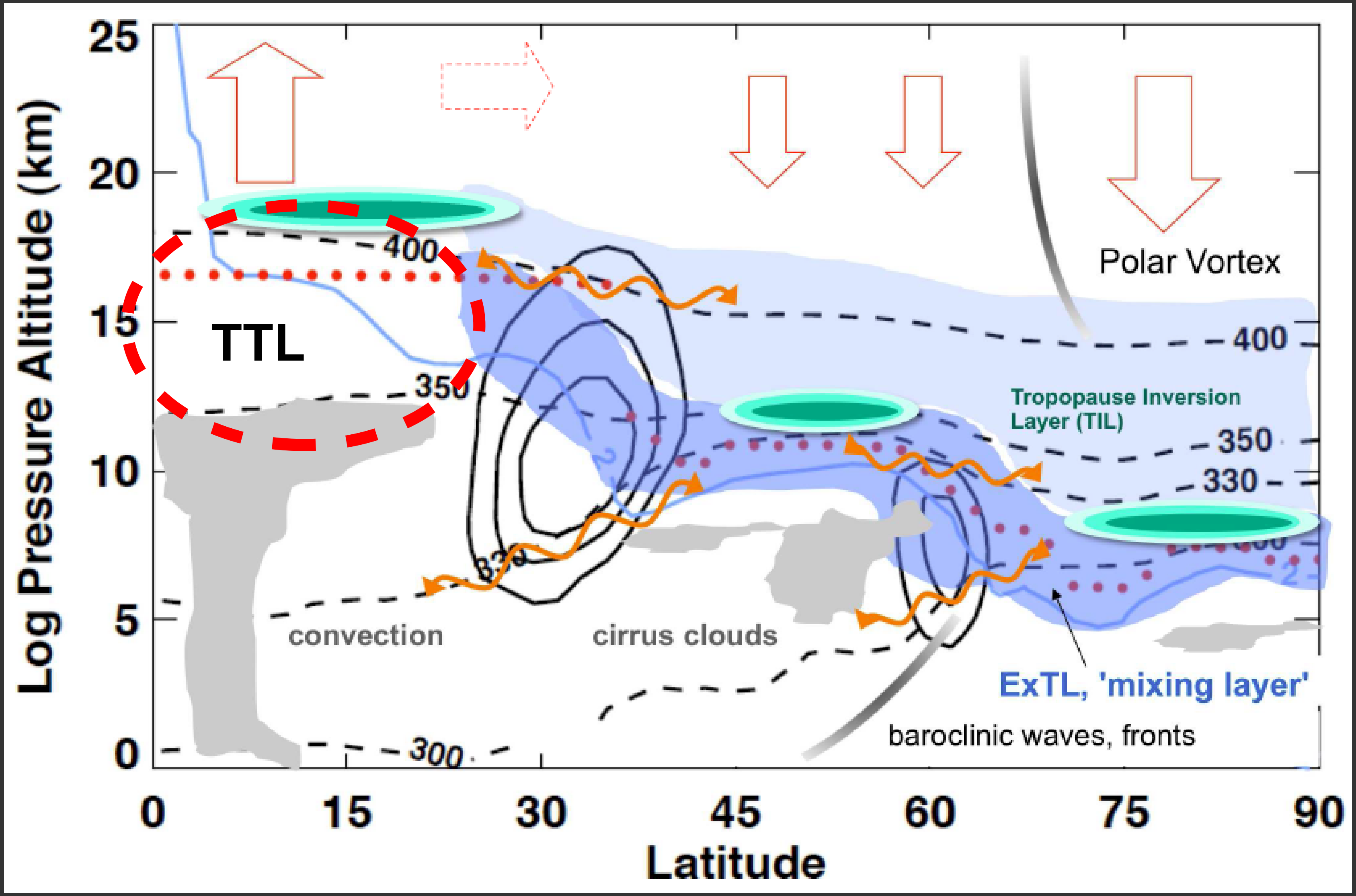
Multiscale Dynamics in the TTL

- 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

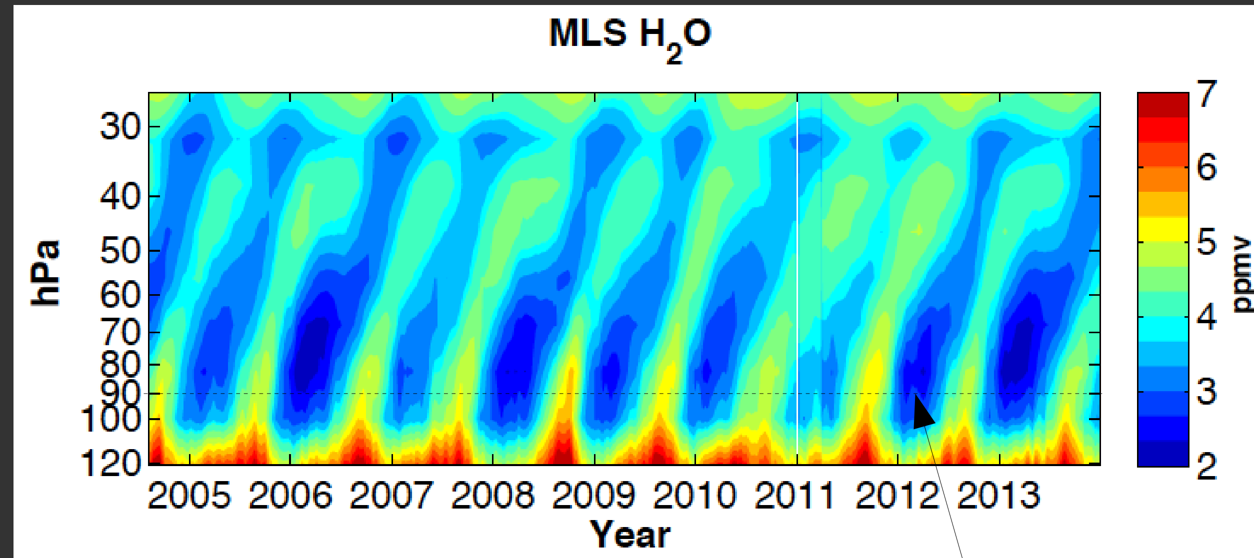
Glanville & Birner 2016, Atmos. Chem. Phys. Discuss.

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 H_2O



cold point tropopause

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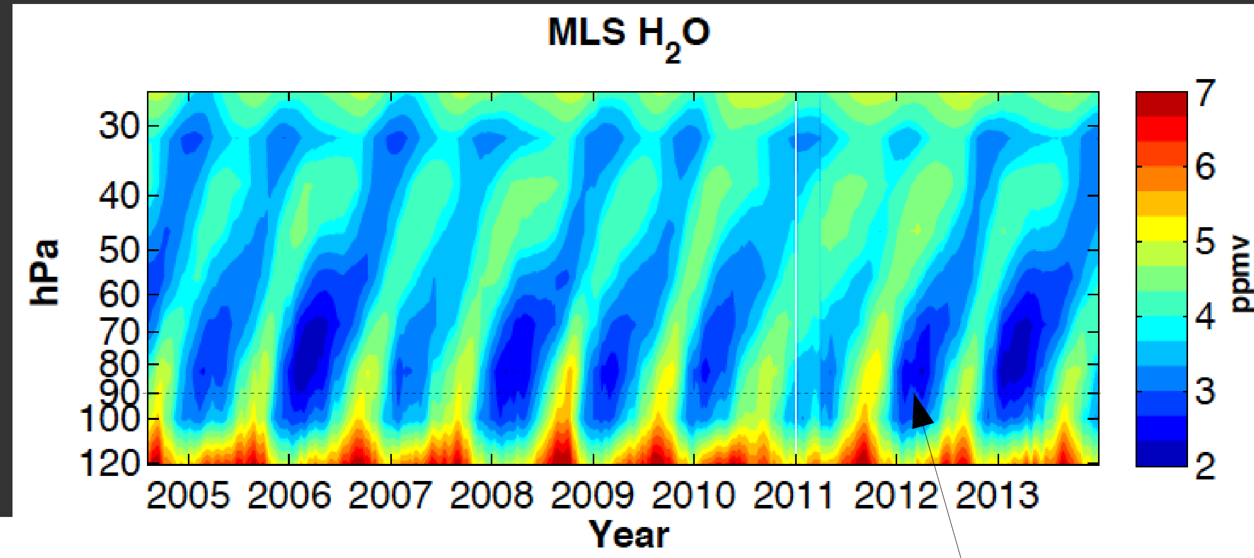

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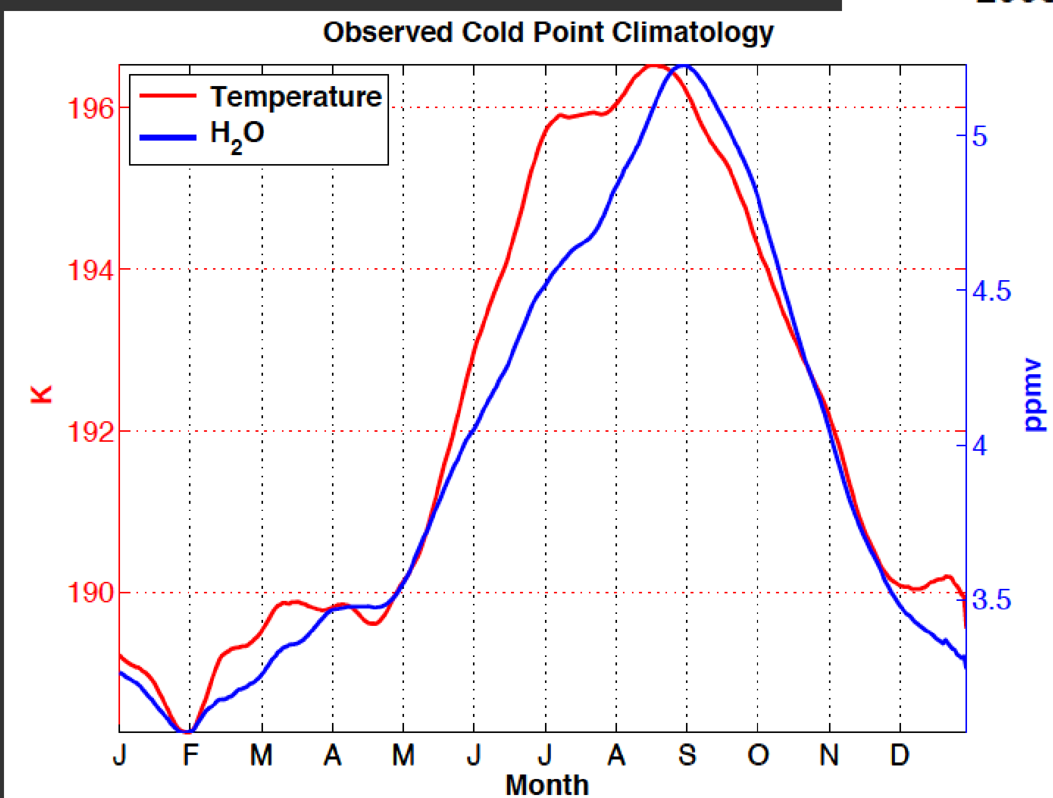


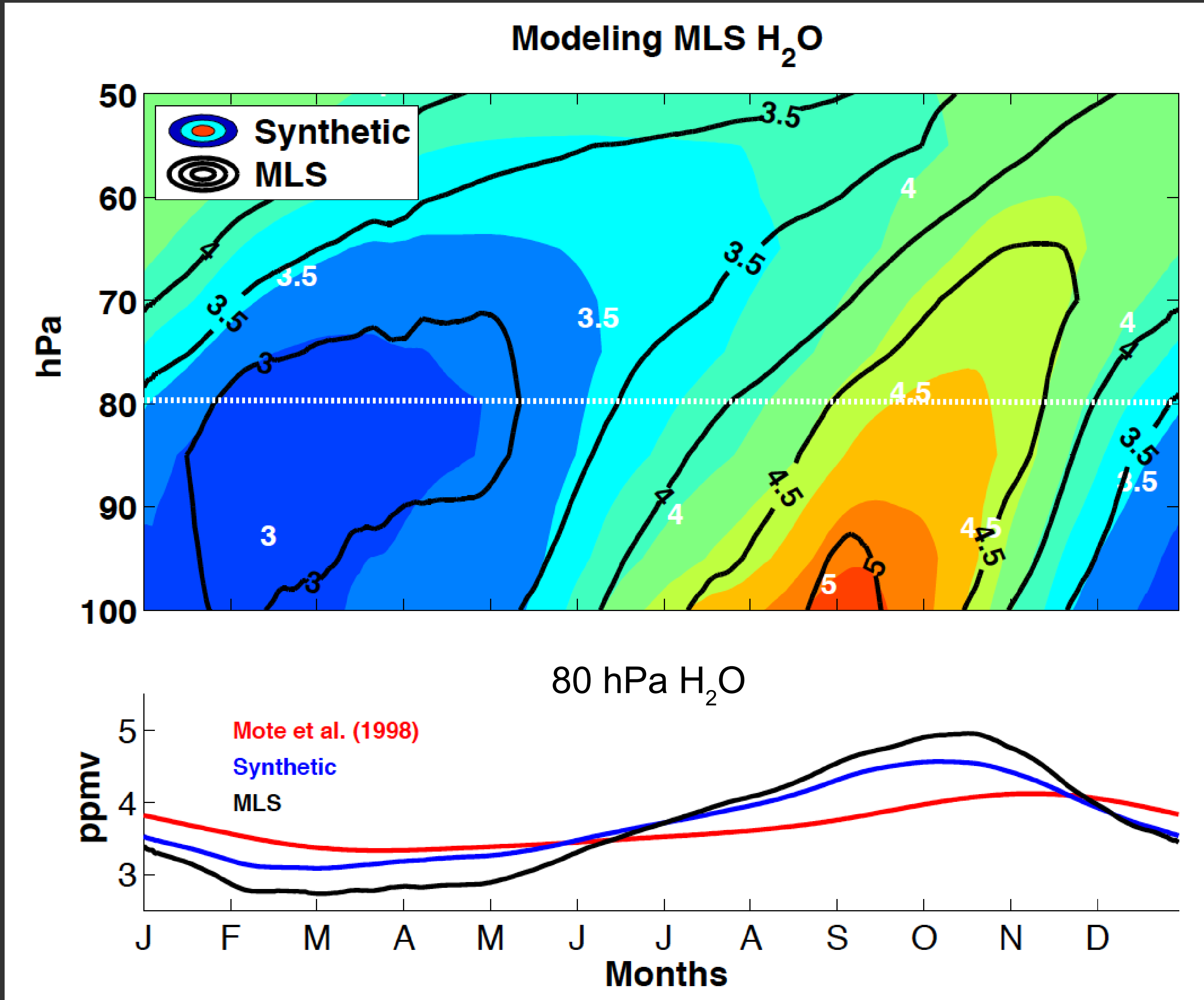
Is the tape recorder signal caused by vertical advection within the stratospheric residual circulation?

Synthetic tape recorder by solving simple 1-d transport Eq., similar to Mote et al. (1998), but with **seasonally varying transport coefficients**

$$\partial_t \overline{\chi} = -\overline{\omega}^* \partial_p \overline{\chi} + \partial_p (K_p \partial_p \overline{\chi}) - \alpha_p (\overline{\chi} - \overline{\chi}_{ML}) + S$$

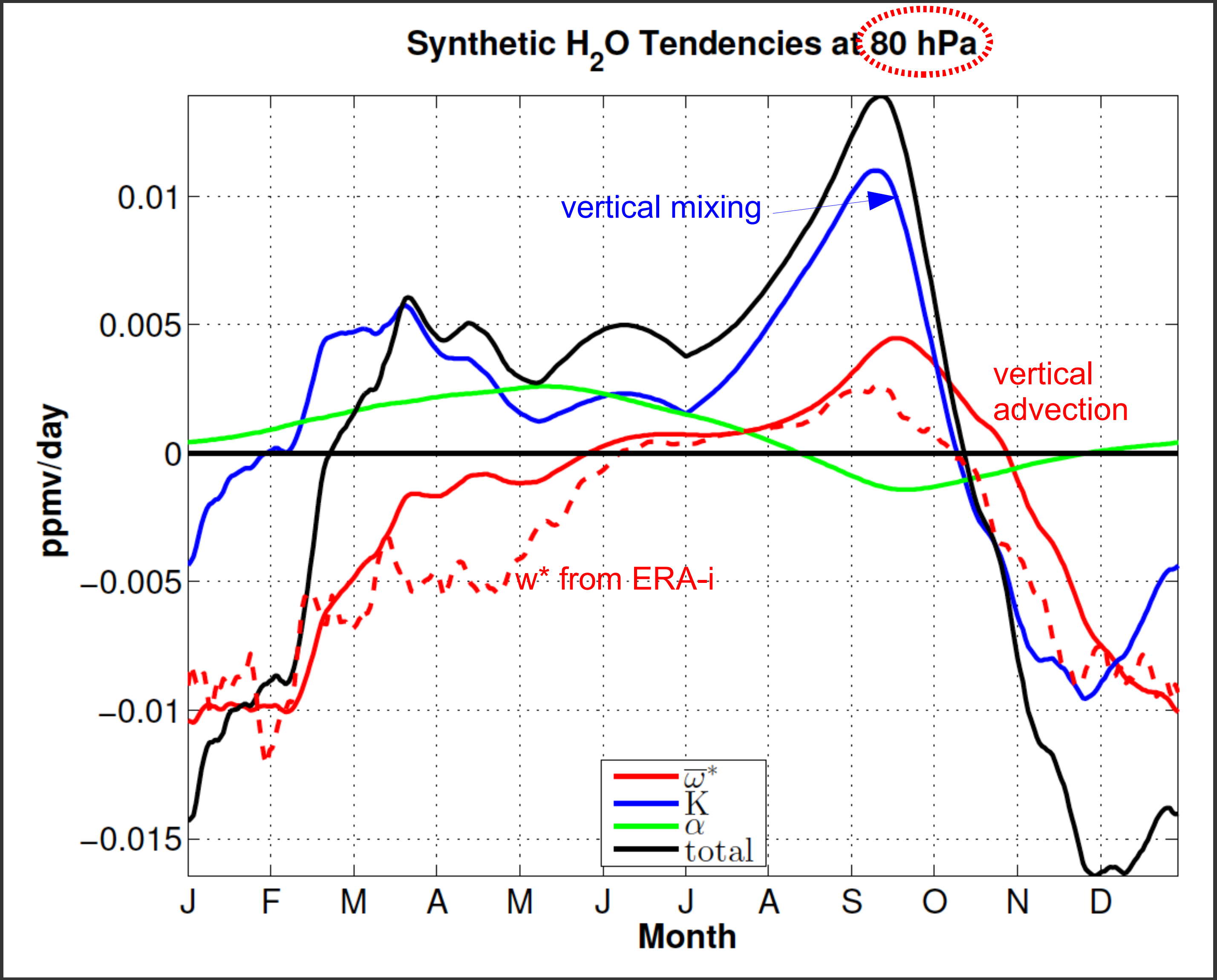
vertical advection | vertical mixing/diffusion | horizontal mixing/dilution

Modeled vs. Observed Tape Recorder Signal



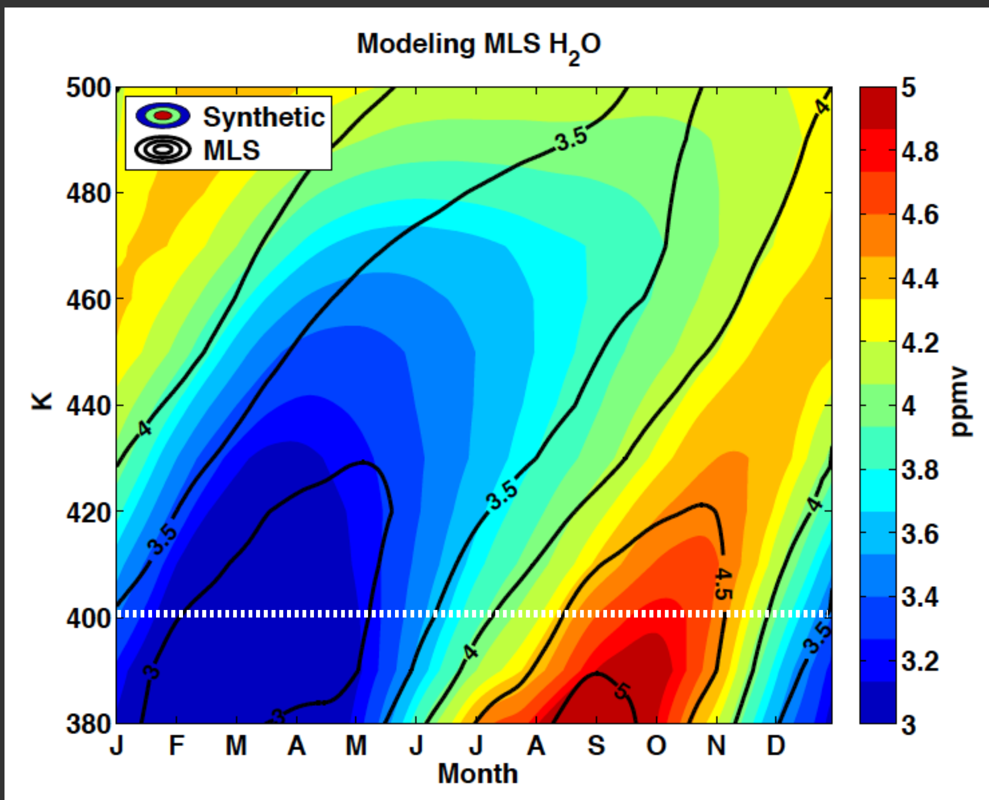
Vertical mixing as important as vertical advection!

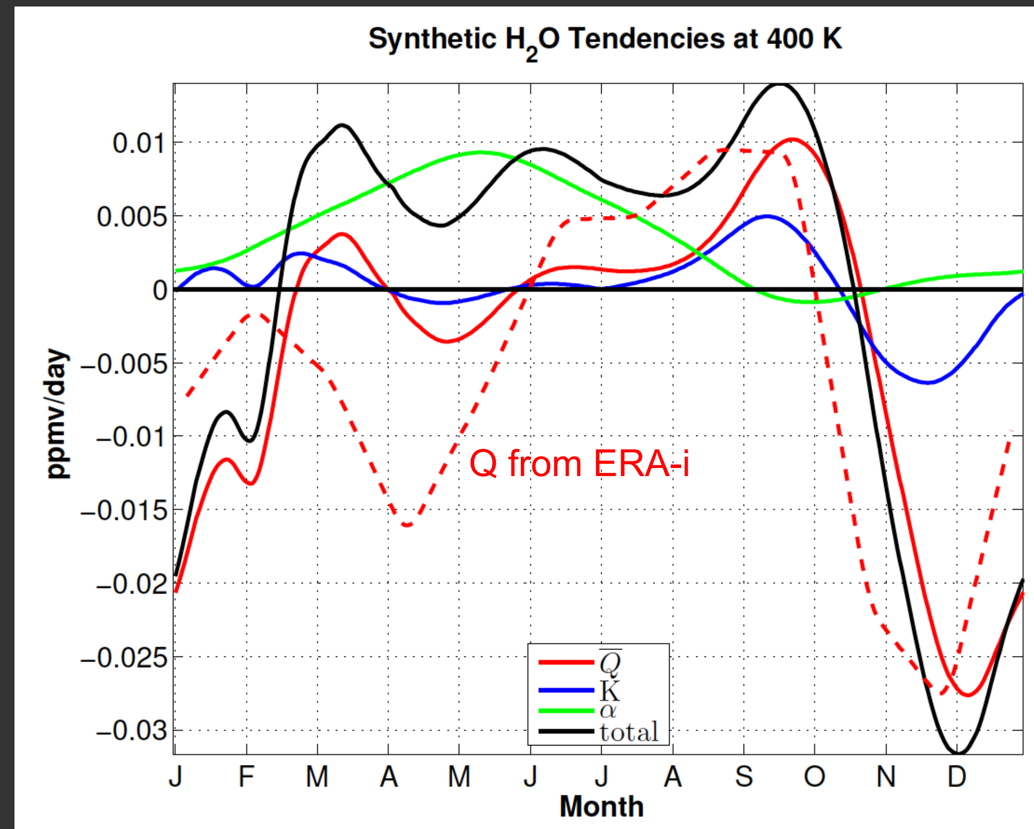
quadrupled(!) vertical mixing compared to Mote et al (but same vertical advection & horizontal mixing)



(for ERAi, optimal solution requires 10 times vertical mixing and 5 times horizontal mixing)

Synthetic tape recorder from 1-d transport model in isentropic coordinates → vertical mixing mostly negligible (but horizontal mixing important during boreal spring / summer)





→ 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:

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

with

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

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Effective transport velocity for tracer in isentropic coordinates:

$$\partial_t \overline{\chi}^* + Q_{\mathrm{eff}} \partial_\theta \overline{\chi}^* = 0$$

Effective vertical transport velocity for tracer in p-coordinates:

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Effective transport velocity for tracer in isentropic coordinates:

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

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

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

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Diabatic heating in steady state:

$$\overline{Q} \approx \overline{\omega}^* \partial_p \overline{\theta} + \partial_p \overline{\omega' \theta'}$$

Effective vertical transport velocity for tracer in p-coordinates:

$$\partial_t \overline{\chi} + \omega_{\text{eff}} \partial_p \overline{\chi} = 0$$ with $$\omega_{\text{eff}} \approx \overline{\varpi}^* + \partial_p \overline{\omega' \chi'} (\partial_p \overline{\chi})^{-1}$$

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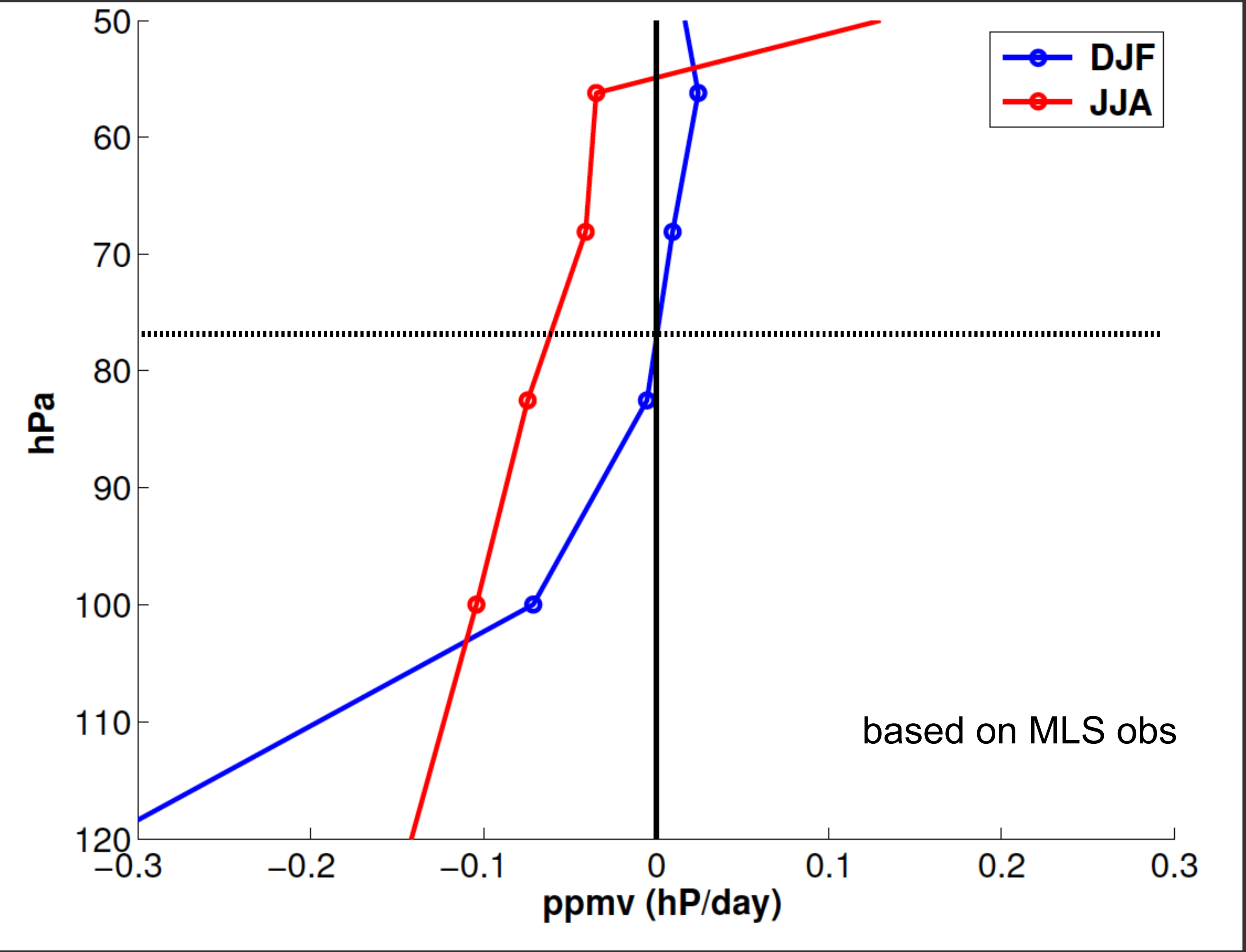
$$\overline{Q} \approx Q_{\text{eff}} \longrightarrow \overline{\omega' \chi'} \approx \left[\omega_{\text{eff}} - Q_{\text{eff}} \left(\partial_p \overline{\theta} \right)^{-1} \right] \frac{\left(\partial_{\bar{\theta}} \overline{\chi} \right)^2}{\partial_{\bar{\theta}\bar{\theta}} \overline{\chi}}$$

$$\overline{\omega'\chi'} \approx \left[\omega_{\mathrm{eff}} - Q_{\mathrm{eff}}\left(\partial_p\overline{\theta}\right)^{-1}\right] \frac{\left(\partial_{\bar{\theta}}\overline{\chi}\right)^2}{\partial_{\bar{\theta}\bar{\theta}}\overline{\chi}}$$

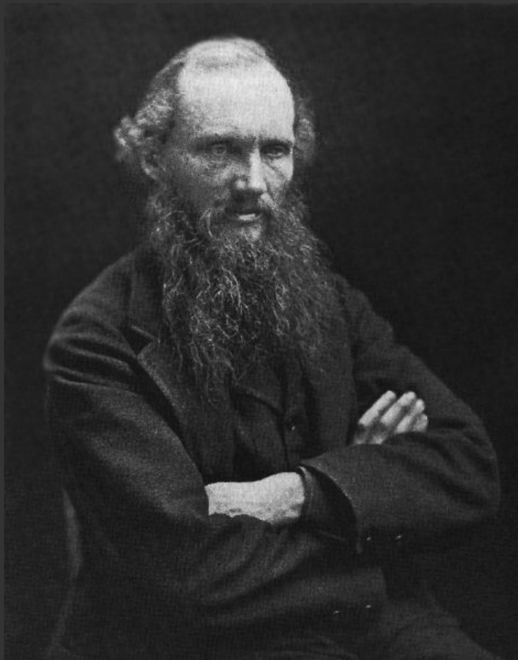


Conclusions Part I

- 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:

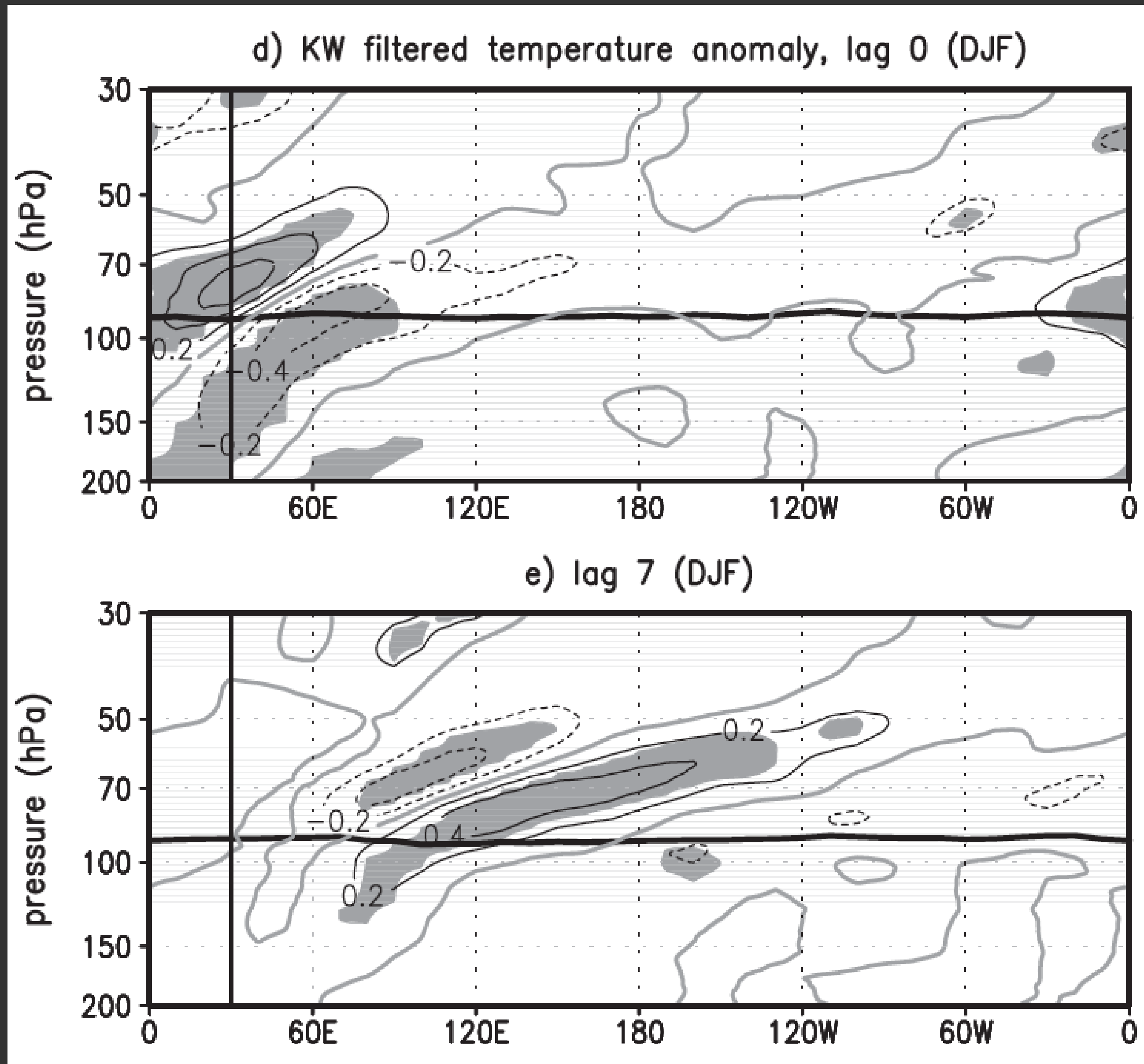
Monday, 17*th March* 1879.

Professor KELLAND, President, in the Chair.

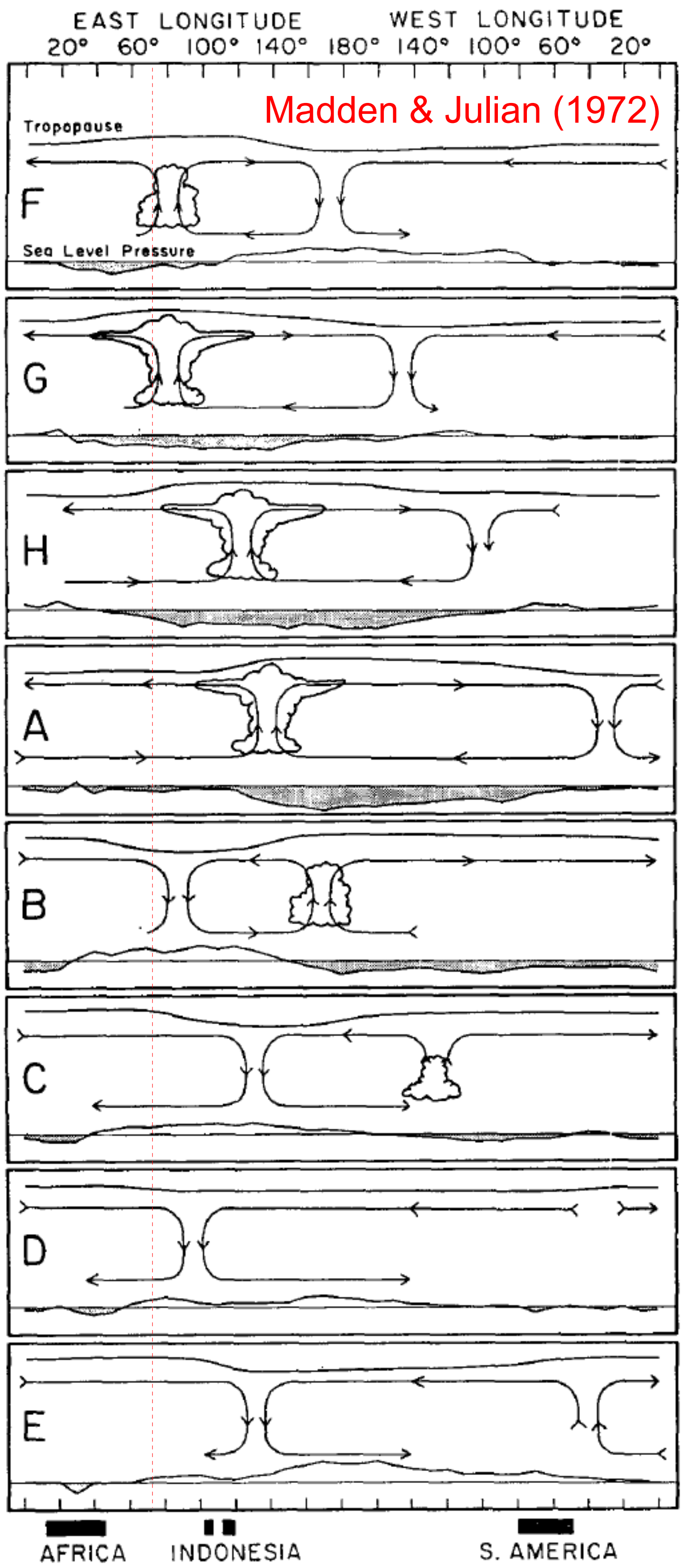
The following Communications were read :—

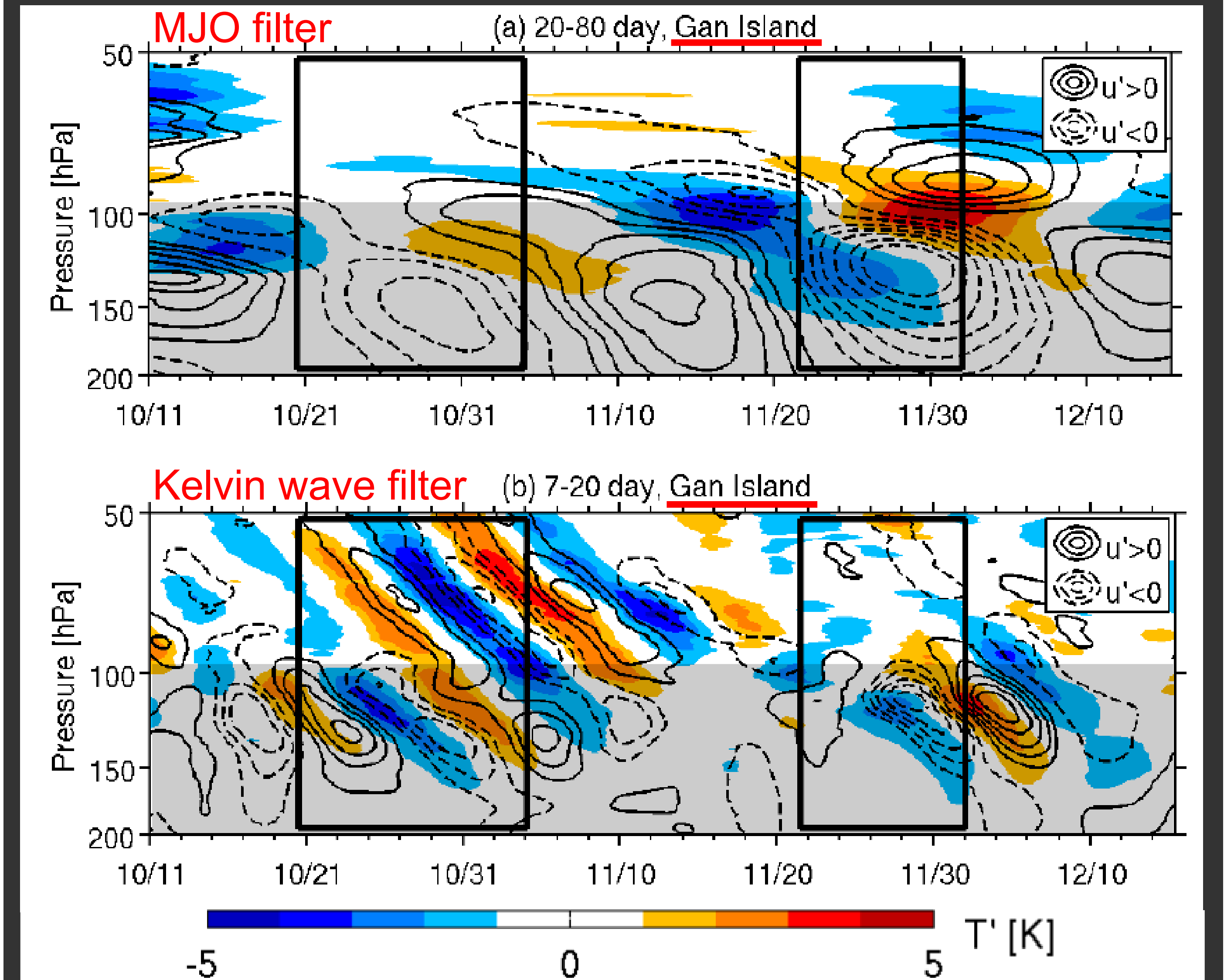
1. On Gravitational Oscillations of Rotating Water. By Sir William Thomson.

Kim & Son (2012): Kelvin wave composite from GPS data:



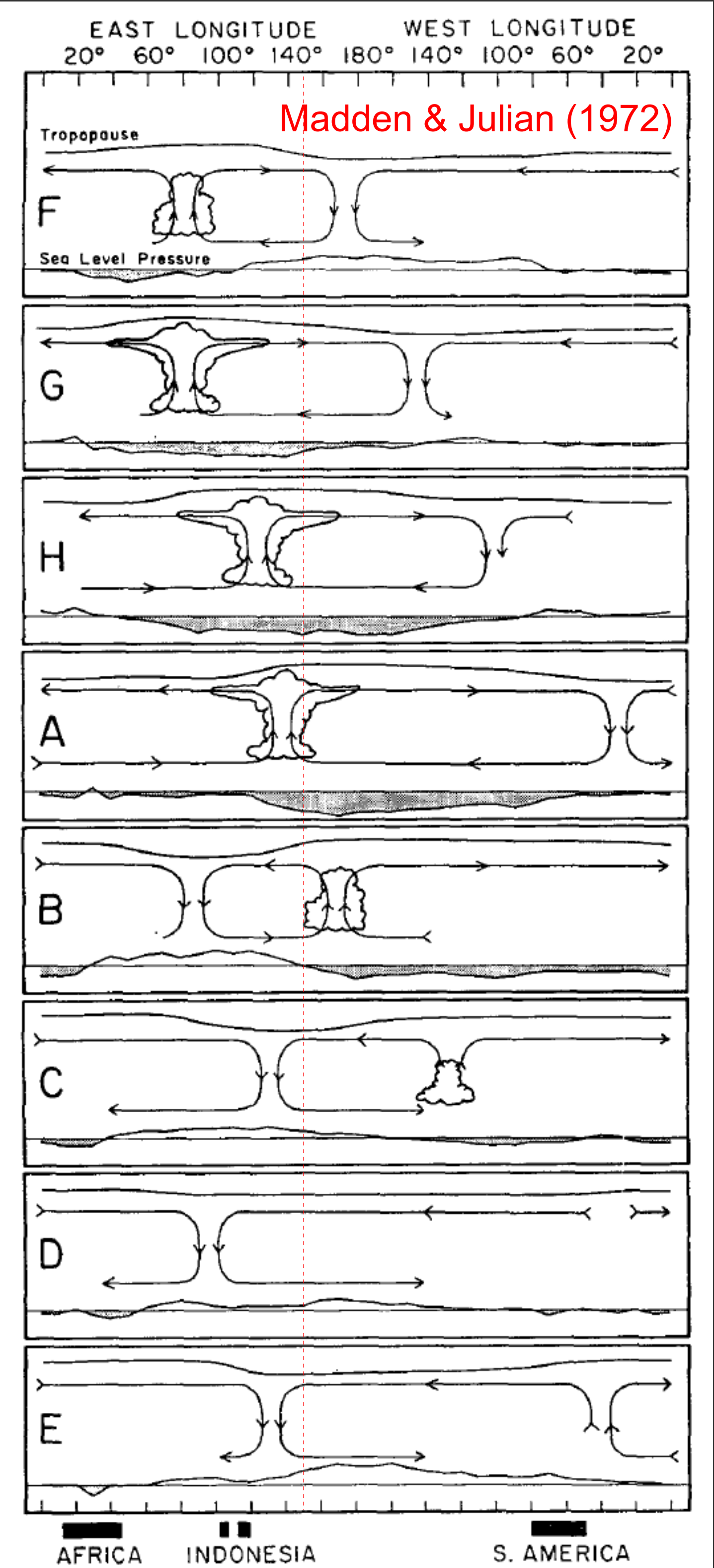
MJO modulation of TTL dynamics (results from DYNAMO): Gan Island

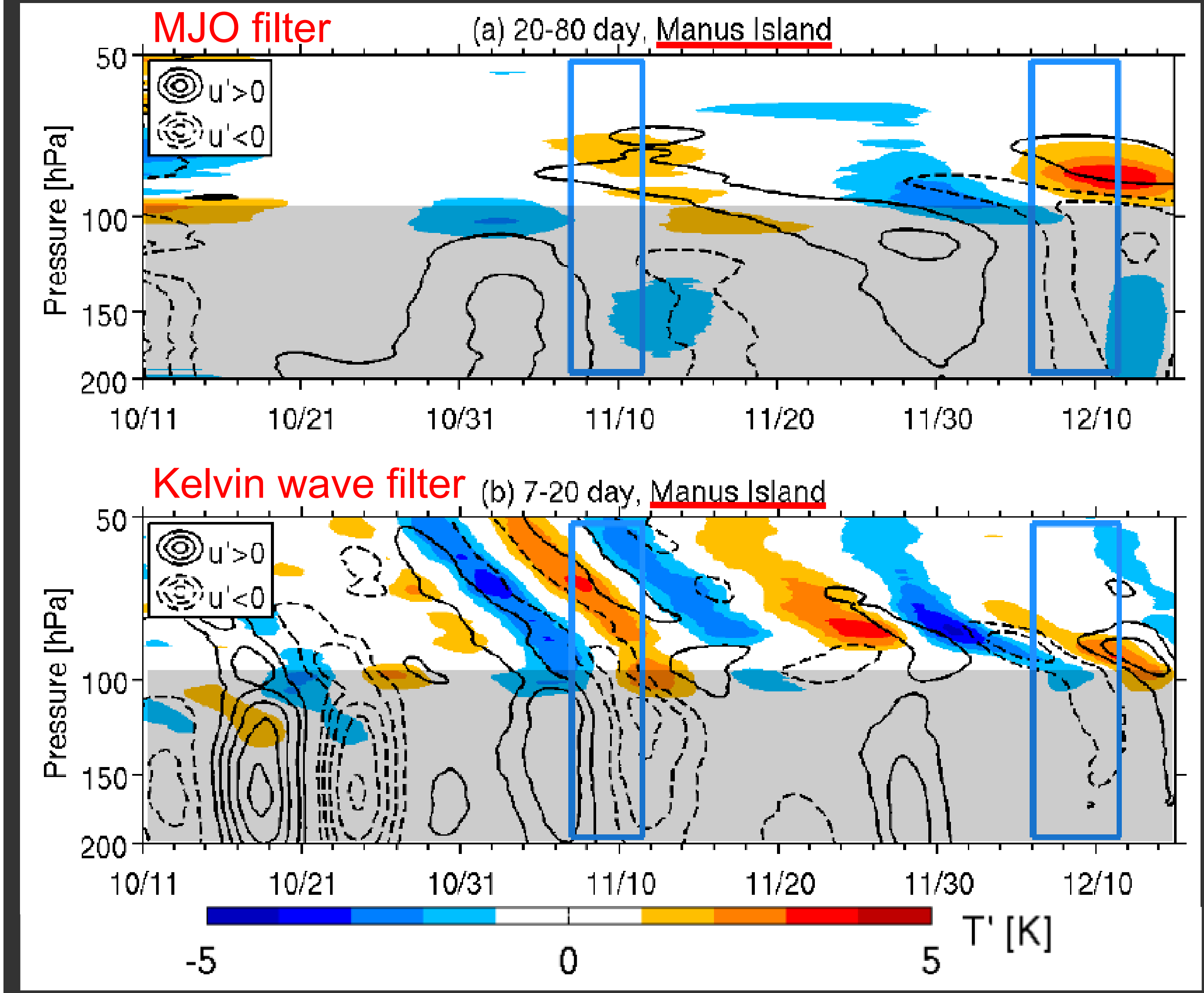




Erin Dagg (MS thesis)

MJO modulation of TTL dynamics (results from DYNAMO): Manus Island





Erin Dagg (MS thesis)

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

Intrinsic frequency

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

Vertical momentum flux

u'-T' Quadrature spectrum

Kelvin/gravity wave dispersion relation:

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

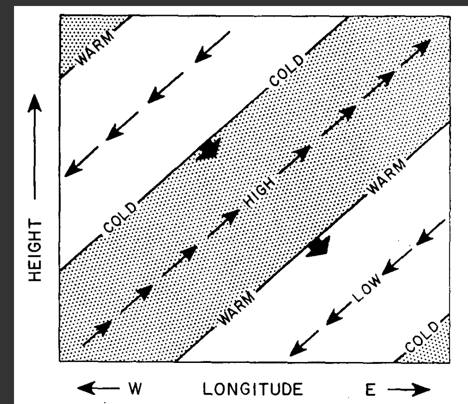


FIG. 7. Idealized cross section along a latitude circle showing phases of the zonal wind, temperature, pressure, and vertical motion oscillations associated with Kelvin waves, as deduced from theoretical considerations.

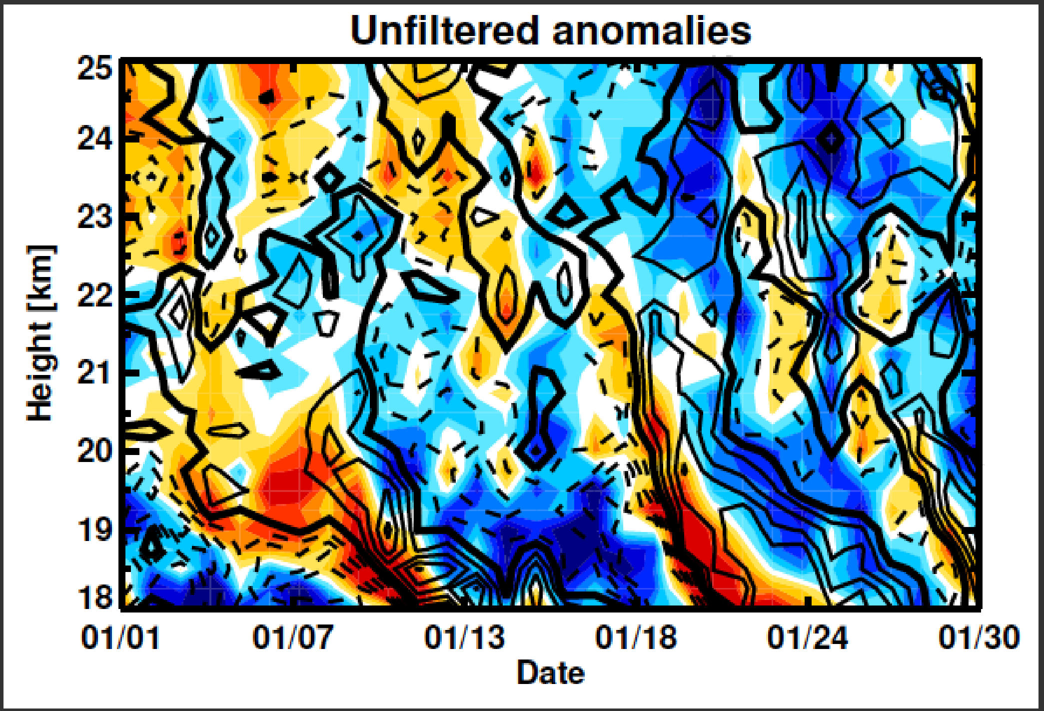
Wallace & Kousky (1968)

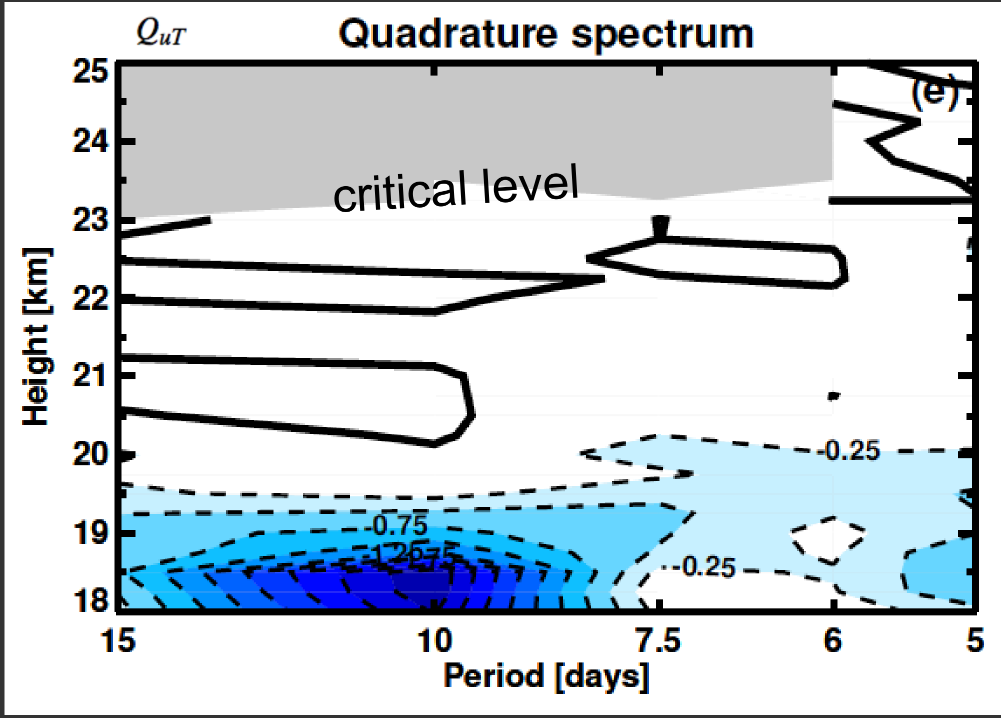
Example:

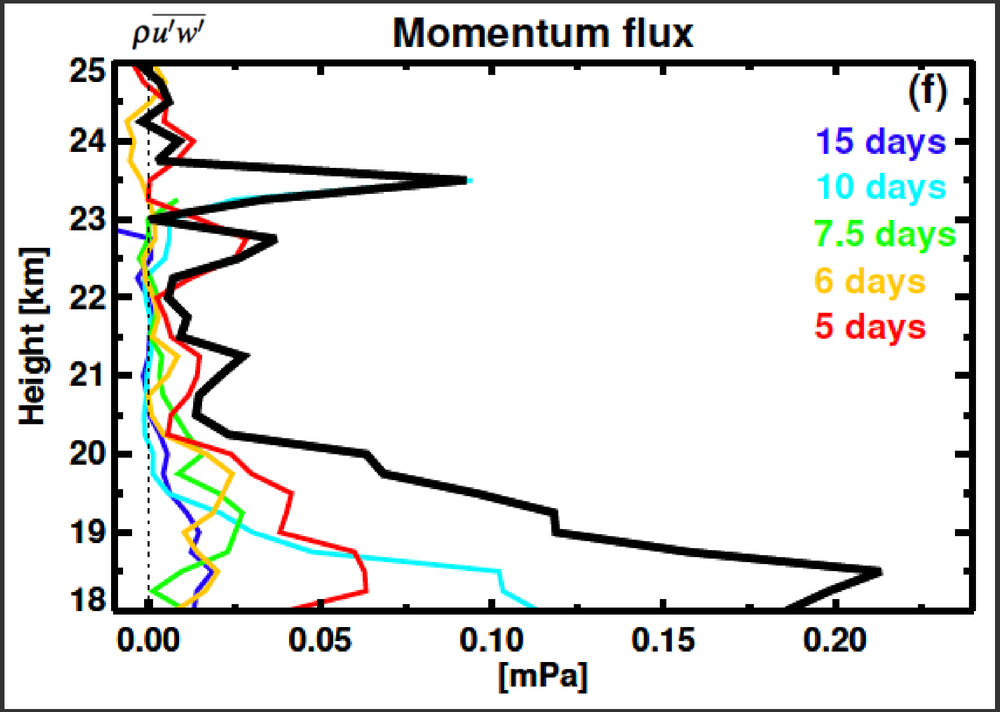
Gan Island (0.7°S, 73.2°E)
DYNAMO, January 2012

High-vertical resolution radiosoundings!

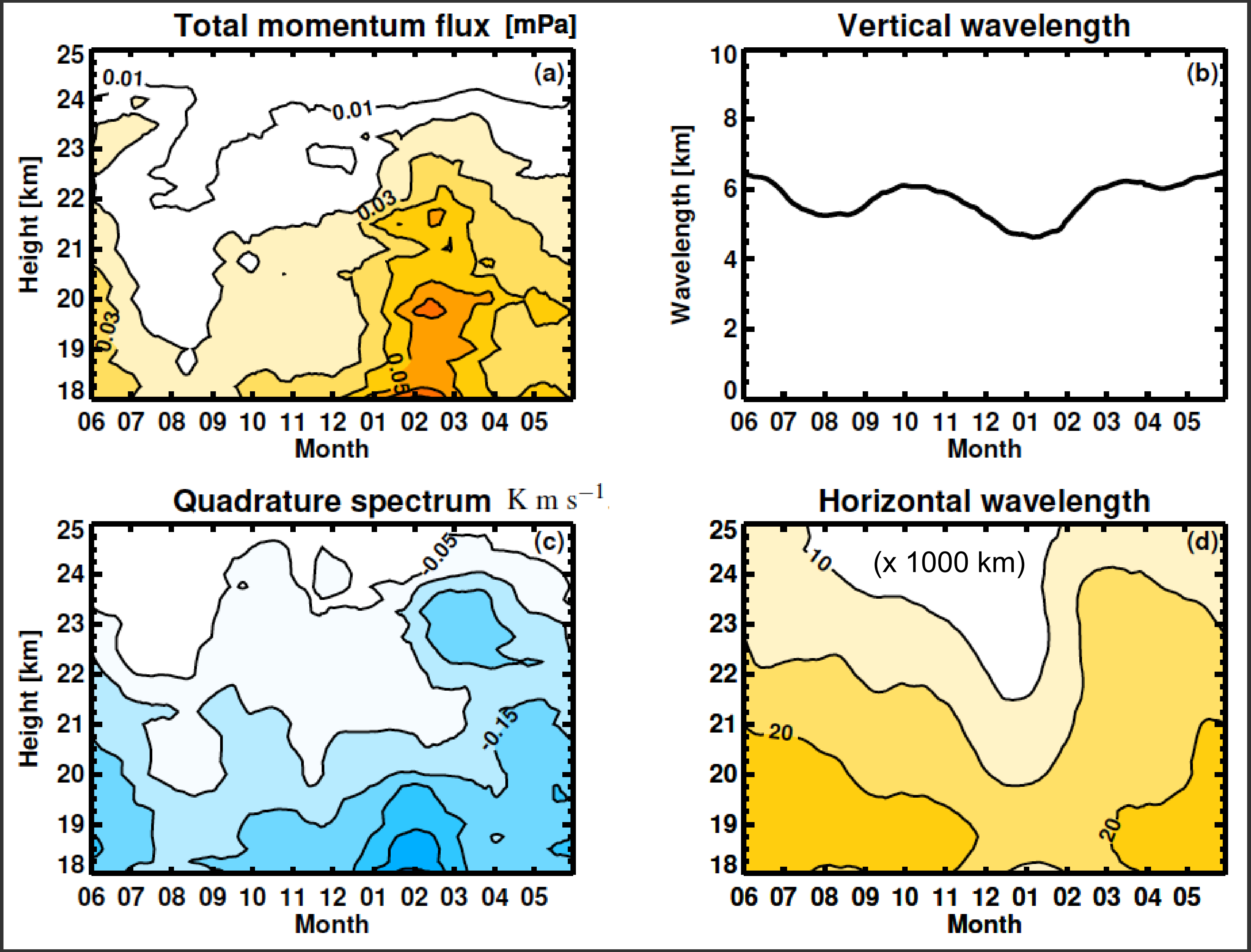
T' (shading, 1 K) & u' (contours, 3 m/s)



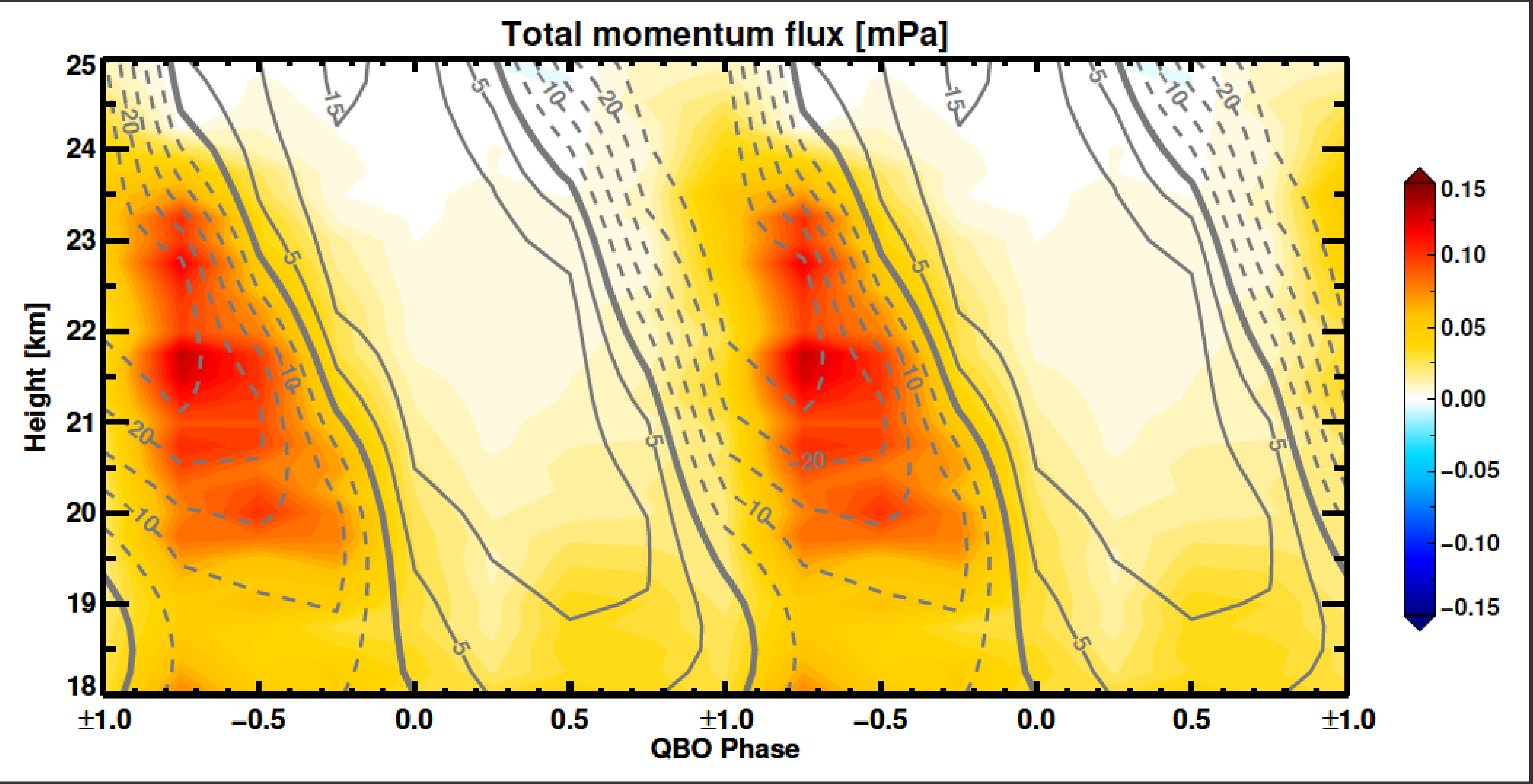




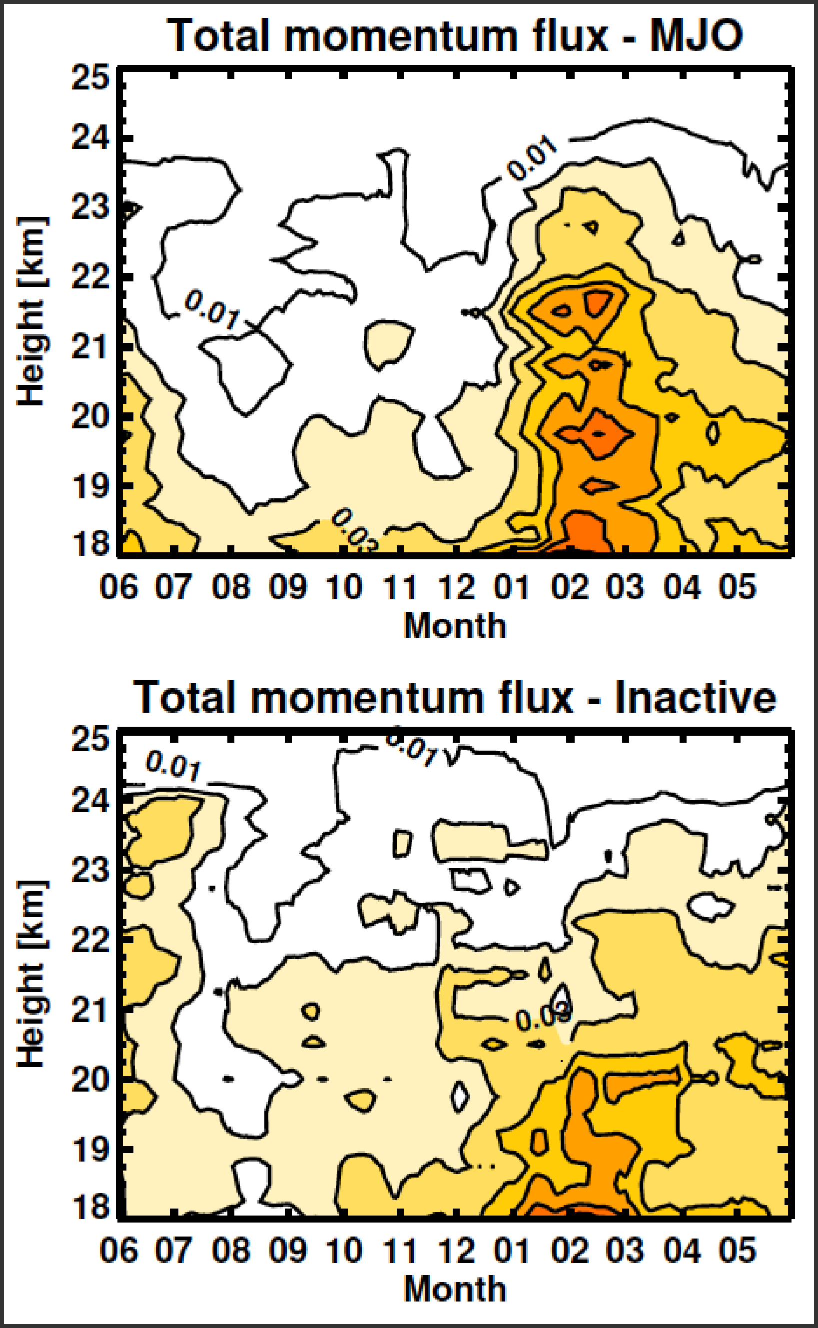
Climatology (2003–2013) for Manus ARM sounding site (2.0°S, 147.4°E)



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)