What drives the annual cycle in tropical tropopause temperatures?

Peter Haynes

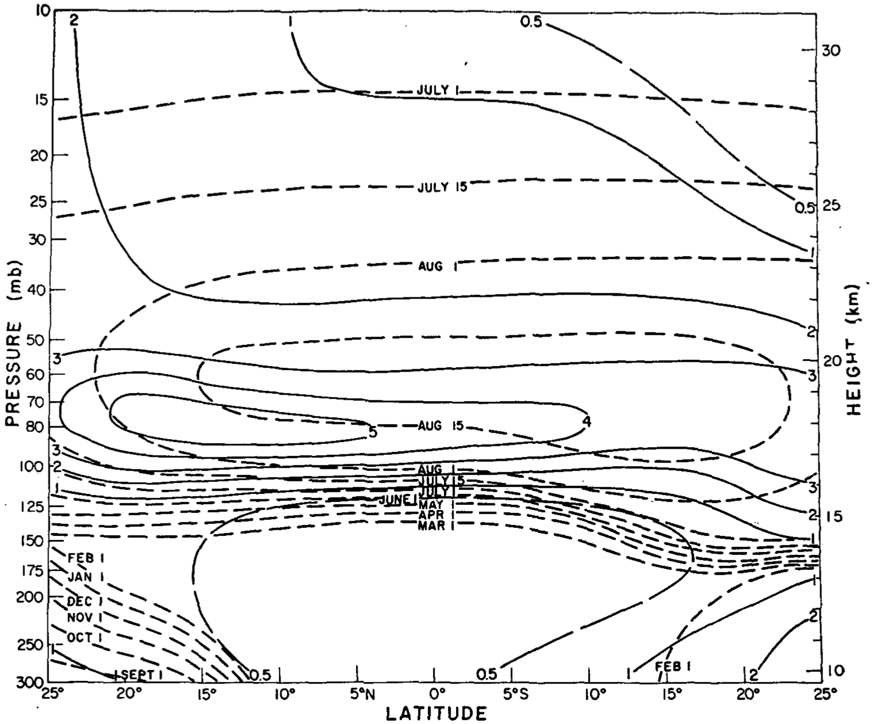
University of Cambridge
Department of Applied Mathematics and Theoretical Physics (DAMTP)

Cambridge Centre for Climate Science (CC*f*CS)

Université Fédérale Toulouse Midi-Pyrénées

(PHH acknowleges collaborations with Stephan Fueglistaler, Alison Ming, Peter Hitchcock, Amanda Maycock and others)

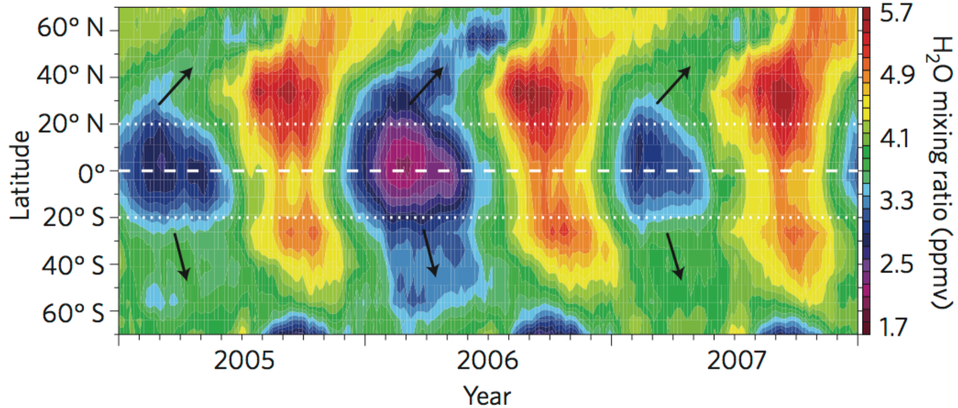
DAMTP **CC*f*CS**



Reed and Vlcek (1969)

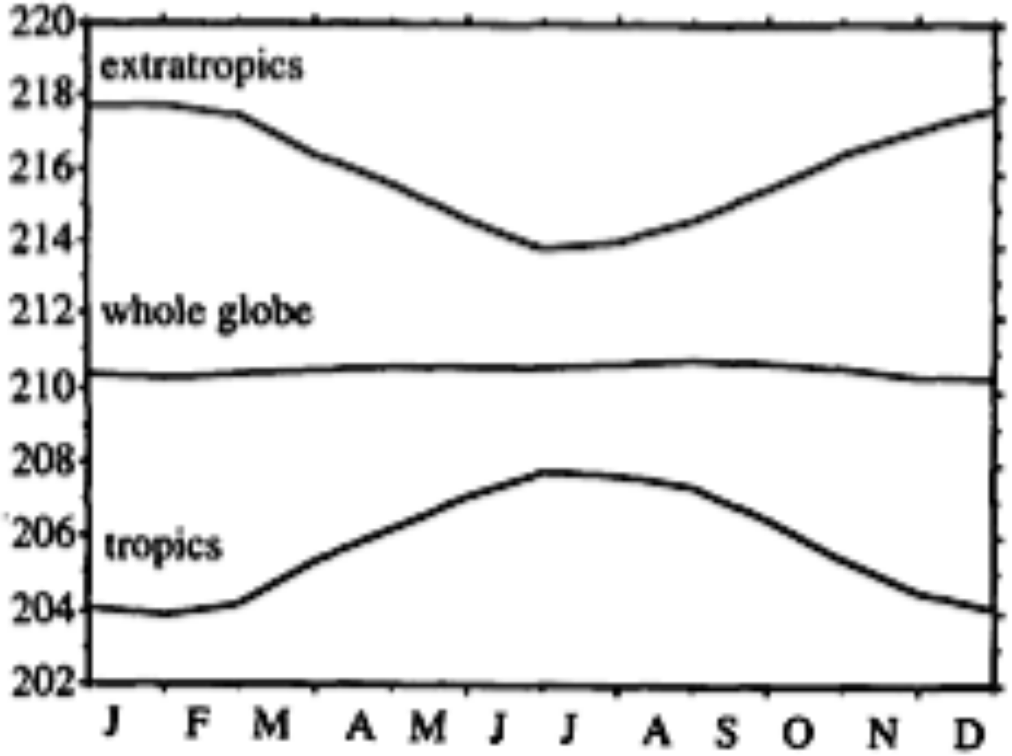
MLS annual cycle in water vapour

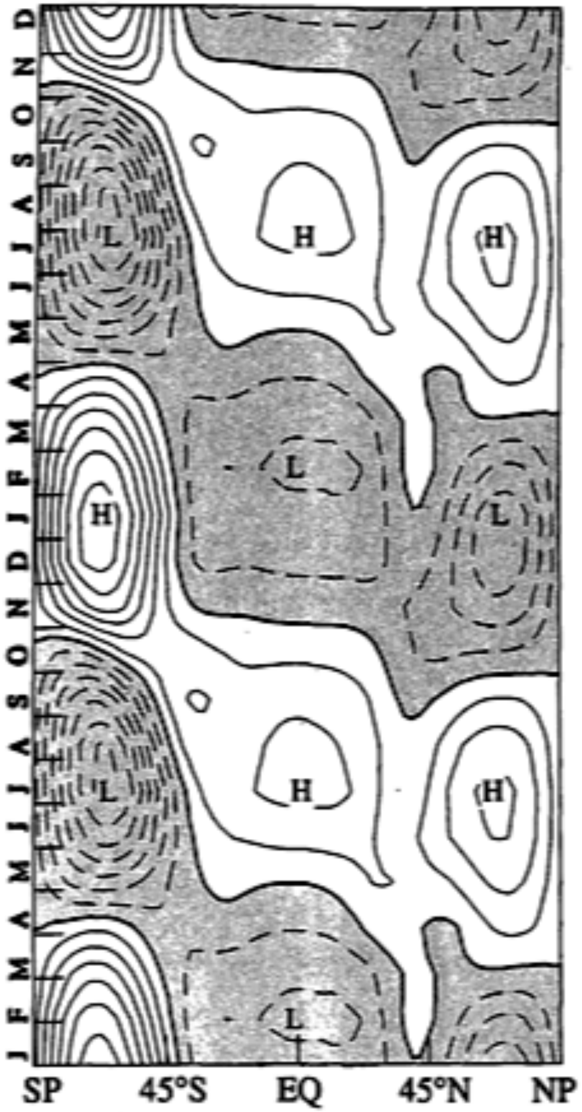
Randel and Jensen (2013)



Yulaeva et al (1994)

Annual cycle in 100mb temperatures
(MSU channel 4)





Transformed Eulerian-mean equations

(Eliassen-Palm flux divergence appears as complete eddy forcing of mean flow)

$$\overline{u}_t + \cancel{\frac{1}{a\,\cos\,\phi}\,\overline{v}^*\,\partial_\phi\,(\overline{u}\,\cos\,\phi)} + \cancel{\overline{w}^*\,\partial_z\overline{u}} - f\,\overline{v}^* = \frac{1}{\rho_0\,a\,\cos\,\phi}\nabla\cdot\vec{F}, \tag{1}$$

$$f\,\partial_z\overline{u} + \frac{R}{H}\,\frac{1}{a}\,\partial_\phi\overline{T} = 0, \tag{2}$$

$$\frac{1}{a\,\cos\,\phi}\,\partial_\phi\,(\overline{v}^*\,\cos\,\phi) + \frac{1}{\rho_0}\,\partial_z\,(\rho_0\overline{w}^*) = 0, \tag{3}$$

$$\overline{T}_t + \cancel{\frac{1}{a}\,\overline{v}^*\,\partial_\phi\overline{T}} + \overline{S}\,\overline{w}^* = \overline{Q} - \alpha\,\overline{T}. \tag{4}$$

simple representation of radiative transfer

Forcing gives rise to response in both velocity and meridional circulation – proportion of each depends on shape of forcing distribution and on timescale (relative to radiative timescale)

STRATOSPHERE (internal variability, sensitivity to external forcing)

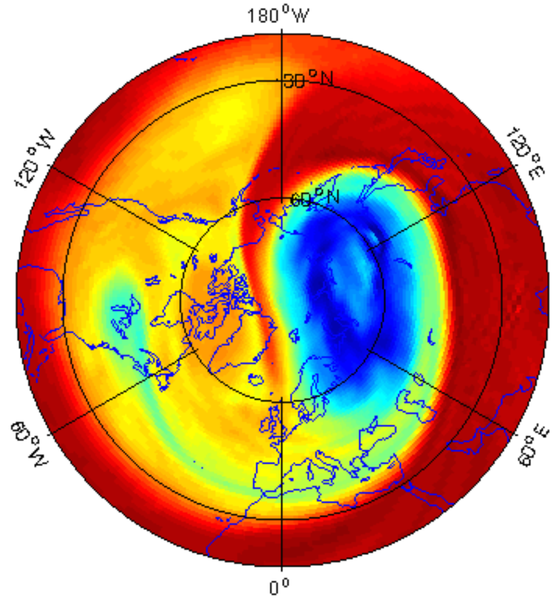
MEAN FLOW ⟵ *TWO–WAY INTERACTION BETWEEN WAVES/EDDIES AND MEAN FLOW* ⟶ LARGE–SCALE ROSSBY WAVES

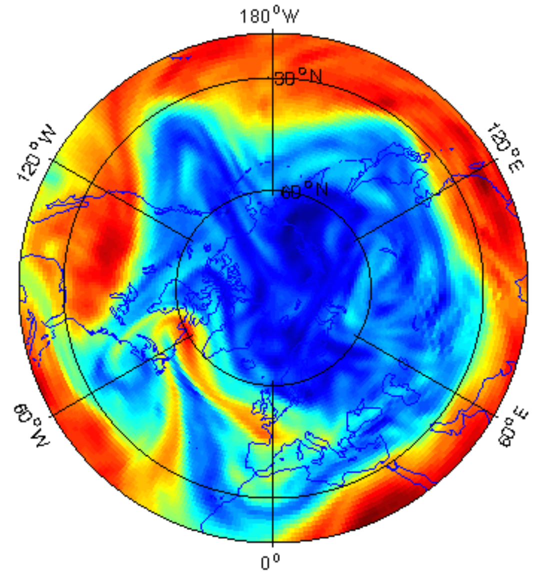
↕ *DYNAMICS OF MEAN CIRCULATION*

↕ *UPWARD AND DOWNWARD WAVE PROPAGATION*

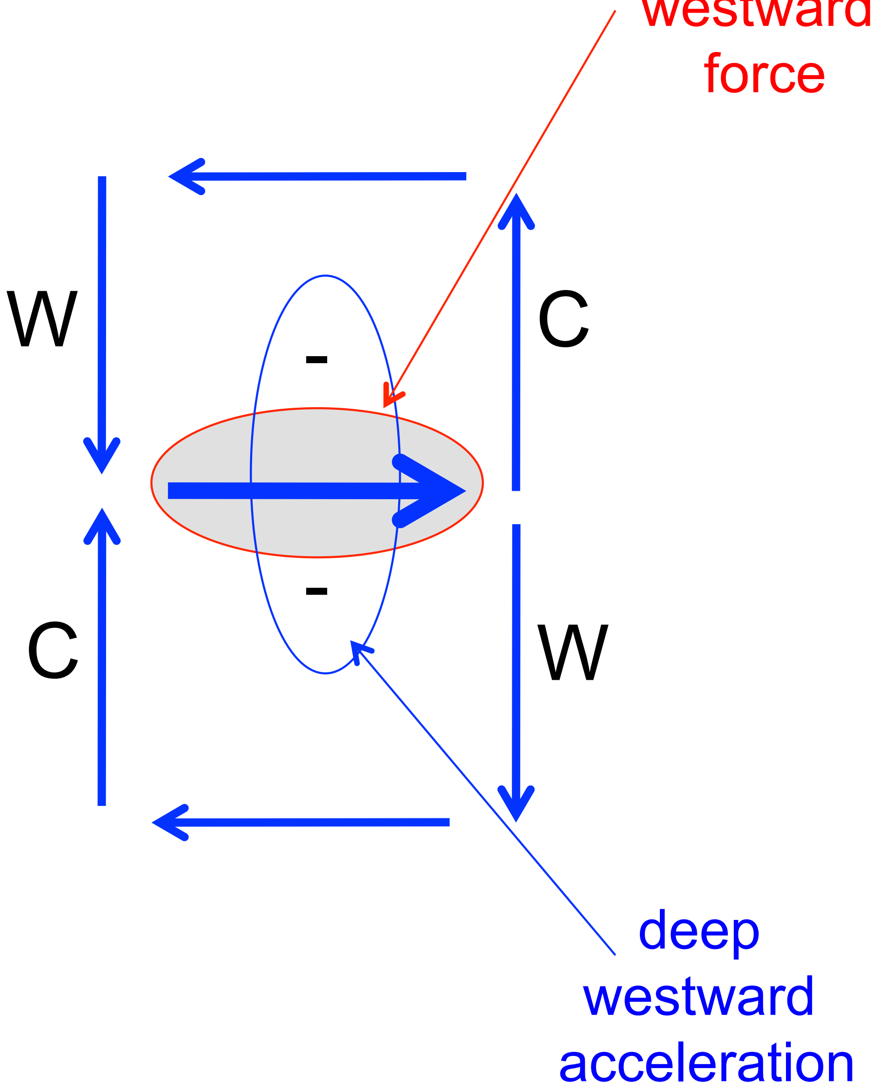
MEAN FLOW ⟵ *TWO–WAY INTERACTION BETWEEN WAVES/EDDIES AND MEAN FLOW* ⟶ SYNOPTIC–SCALE EDDIES

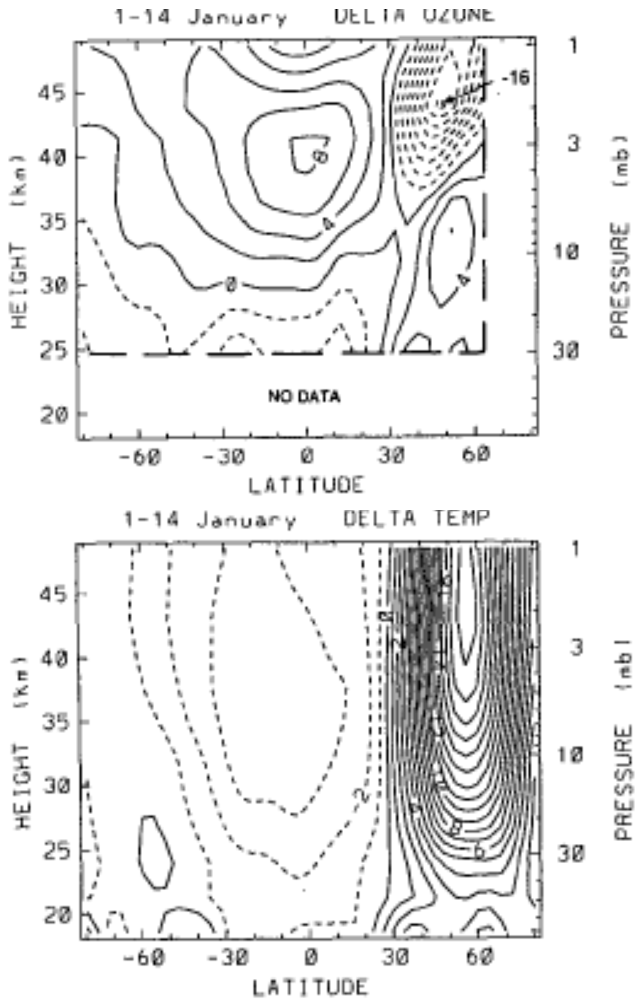
TROPOSPHERE (low–frequency annular variability)





Schematic response to localised force





Stratospheric wave event (Randel 1993)

Effect of radiative damping

Holton et al (1995)

Response to localised forcing with frequency ω

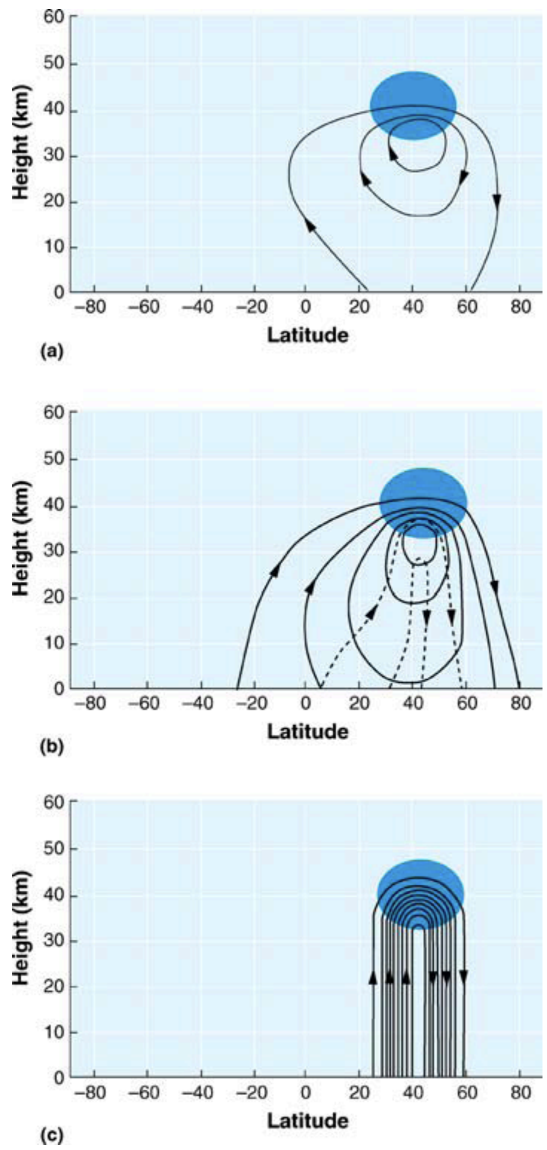
$\omega \gg \alpha$

short time scales

$\omega \sim \alpha$

$\omega \ll \alpha$

long time scales



Steady state limit

$$\boxed{\overline{w}^*(\phi, z) = \frac{1}{a\rho_0(z)\cos\phi}\frac{\partial}{\partial\phi}\left[\int_z^\infty \frac{\nabla.\mathbf{F}}{2\Omega a \sin\phi}|_{\phi=\mathrm{const.}}\, dz'\right]}$$

(Haynes et al, 1991)

Steady upwelling at any location (ϕ , z) is determined by wave force above that location – 'downward control principle'. Steady circulation *requires* wave force.

"Low latitude singularity".

Does it make any sense to consider $\nabla.\mathbf{F}$ as specified?

Time averaged BDC is controlled by time average wave force.

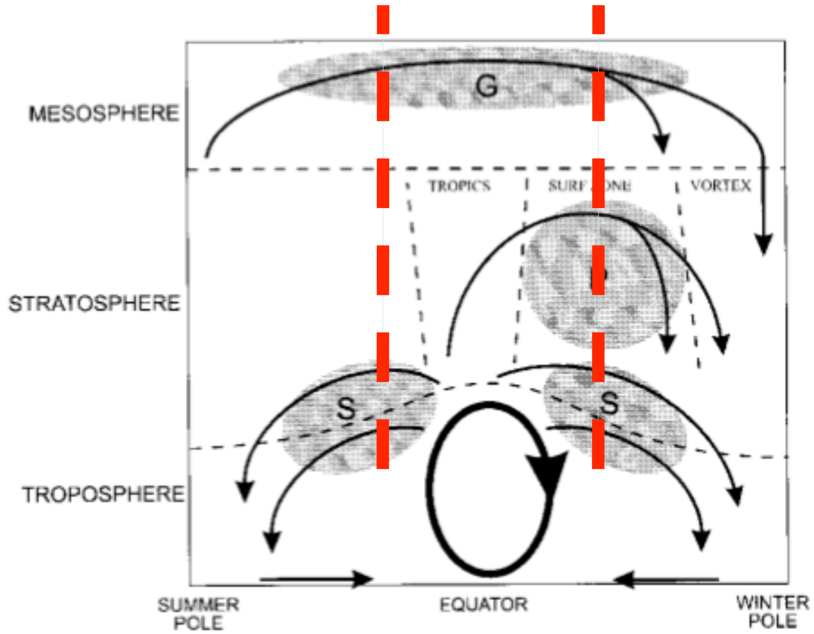
Time averaged BDC upwelling in tropics is controlled by time average wave force in subtropics

Annual cycle in wave-driven circulation

Rosenlof and Holton (1993)

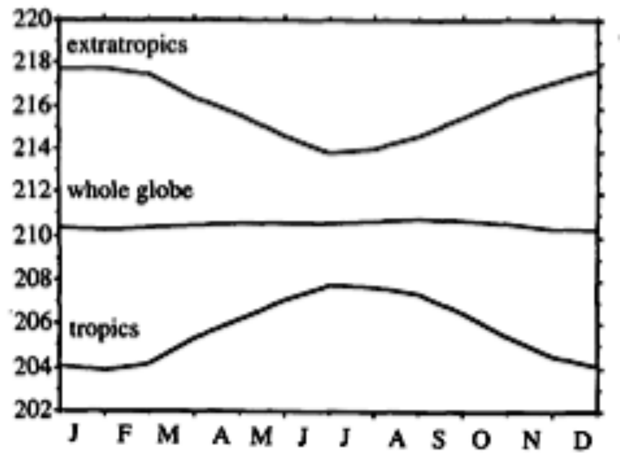
$$\overline{w}^*(\phi, z) = \frac{1}{a\rho_0(z)\cos\phi}\frac{\partial}{\partial\phi}\left[\int_z^\infty \frac{\nabla.\mathbf{F}}{2\Omega a\,\sin\phi}\Big|_{\phi=\text{const.}}\,dz'\right]$$

	UKMO	*Holton* [1990]
DJF	114.0	93.3
MAM	76.4	56.1
JJA	55.8	47.2
SON	70.3	62.4
Mean	79.1	64.8



Plumb (2002)

Yulaeva et al (1994)



$$\frac{\partial \overline{T}}{\partial t} + \underset{-\overline{Q}_{\mathrm{dyn}}}{\overline{w}^*\overline{S}} = \underset{\overline{Q}_{\mathrm{rad}}}{-\alpha(\overline{T} - T_0)}$$

Global Average

$$\frac{\partial \langle \overline{T} \rangle_{global}}{\partial t} + \cancel{\langle \overline{w}^* \overline{S} \rangle}_{global} = -\alpha(\langle \overline{T} \rangle_{global} - \langle T_0 \rangle_{global})$$

Driven by annual variation in ozone heating in tropical stratosphere?

Tropics - Extratropics

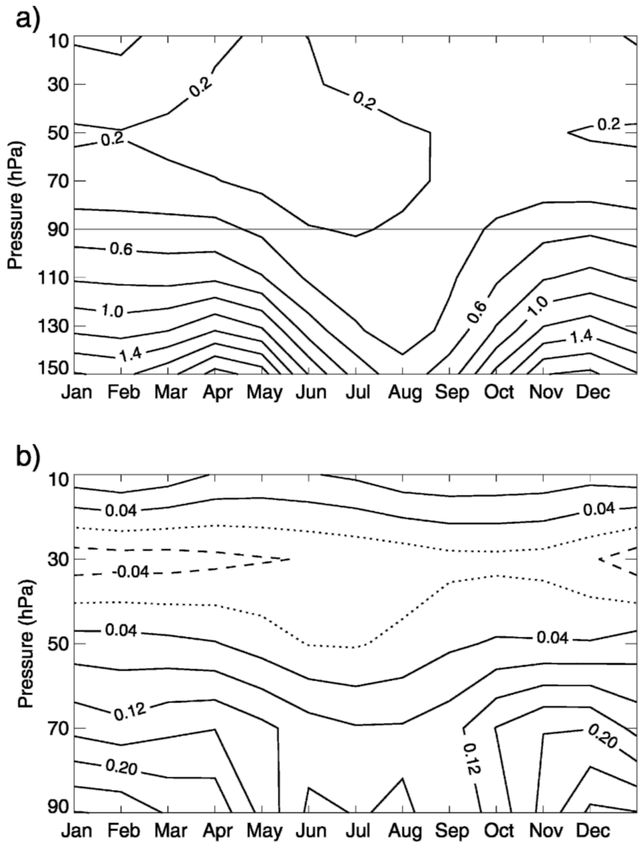
$$\frac{\partial \langle \overline{T} \rangle_{T-E}}{\partial t} + \langle \overline{w}^* \overline{S} \rangle_{T-E} = -\alpha(\langle \overline{T} \rangle_{T-E} - \langle T_0 \rangle_{T-E})$$

Dynamical response to annual variation in wave fluxes in extratropical stratosphere?

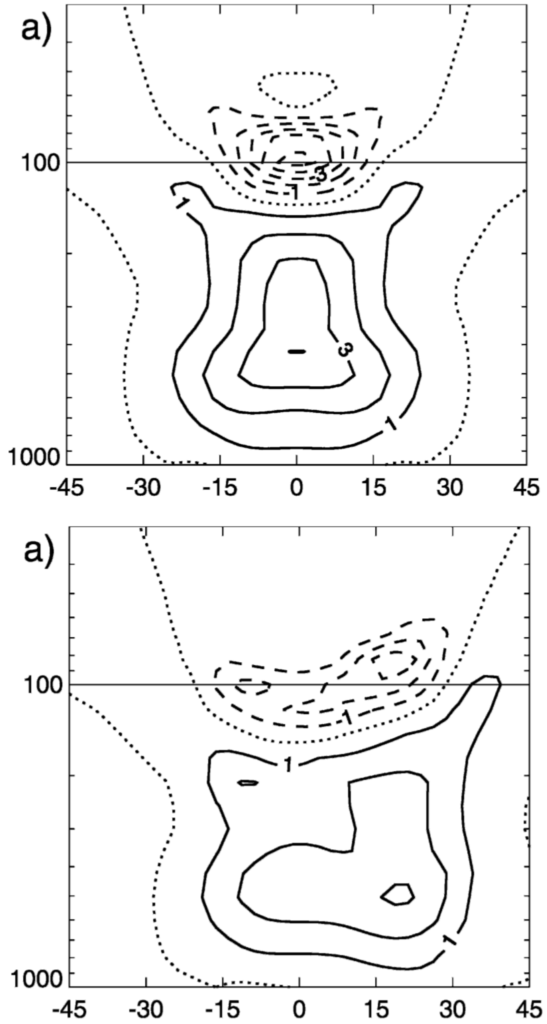
Role of low-latitude waves in $\nabla.\mathbf{F}$?

$\overline{\omega}^*$

$-\dfrac{\partial\overline{\omega}^*}{\partial p}$



Kerr-Munslow and Norton (2006)

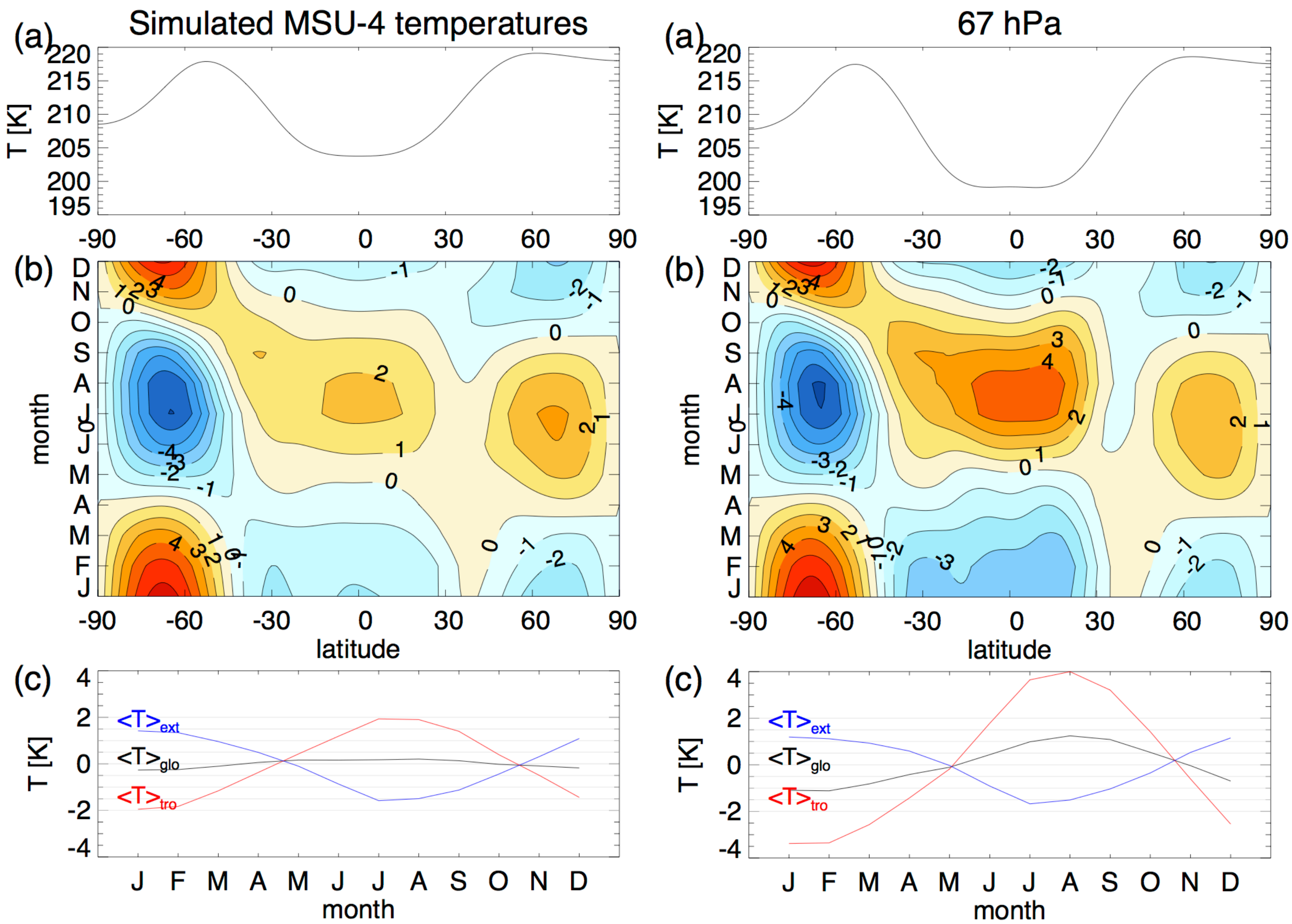


Equatorial localised heating

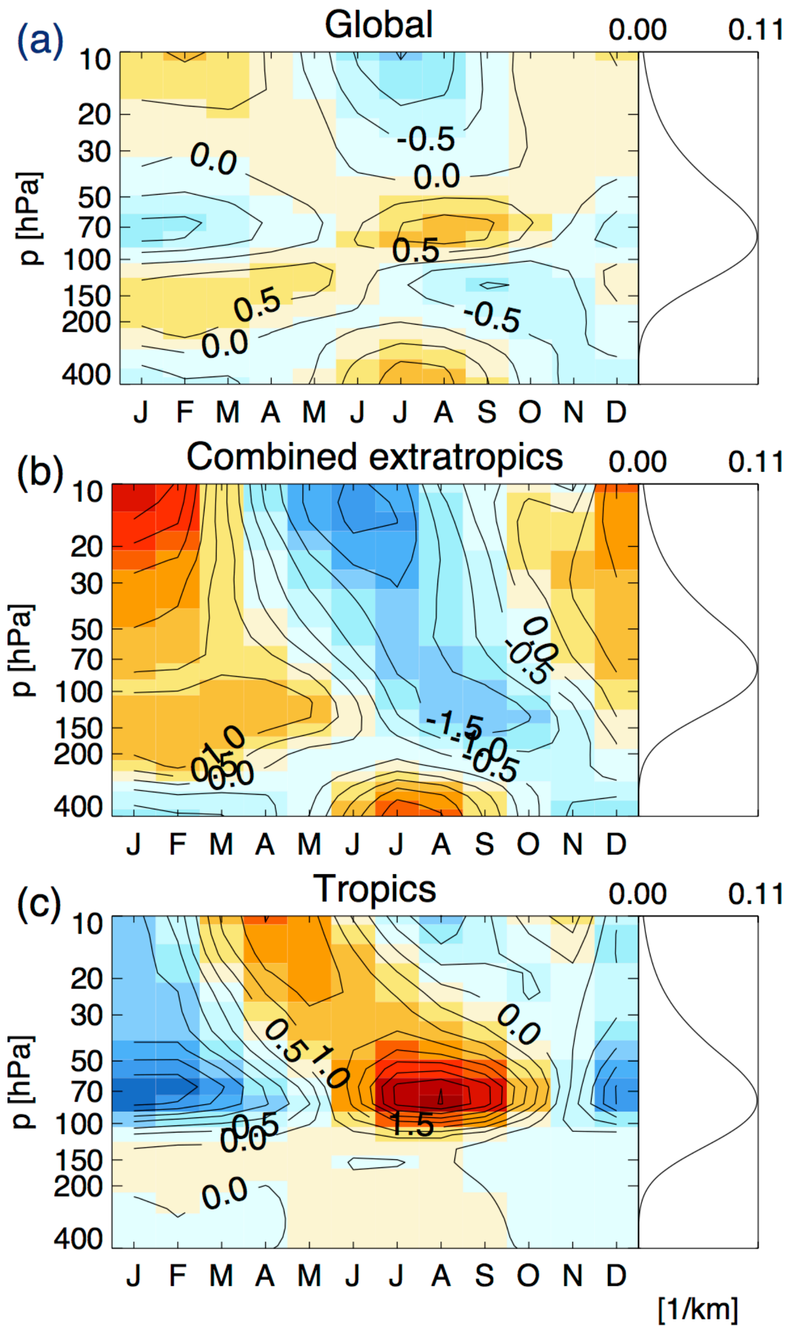
Off-equatorial localised heating

Norton (2006)

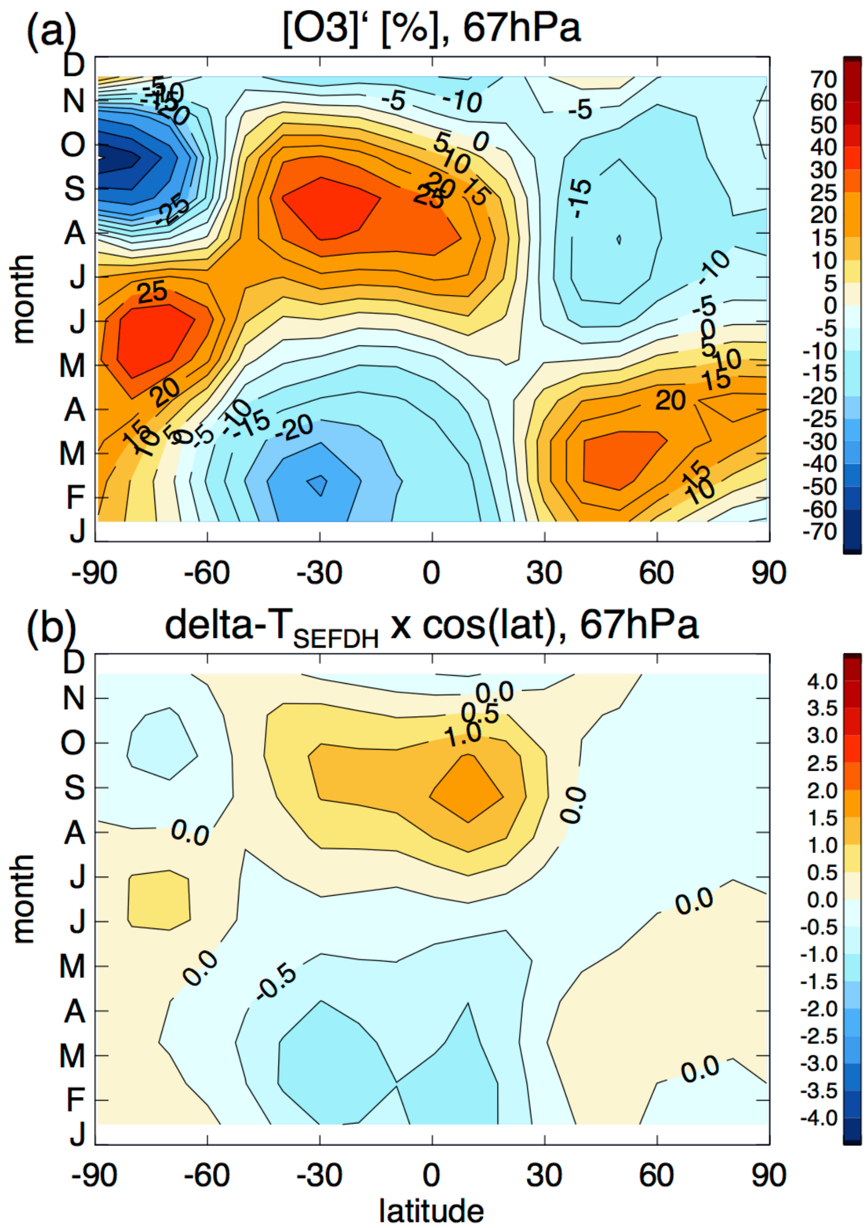
Fueglistaler, H and Forster (2011)



Fueglistaler et al (2011)



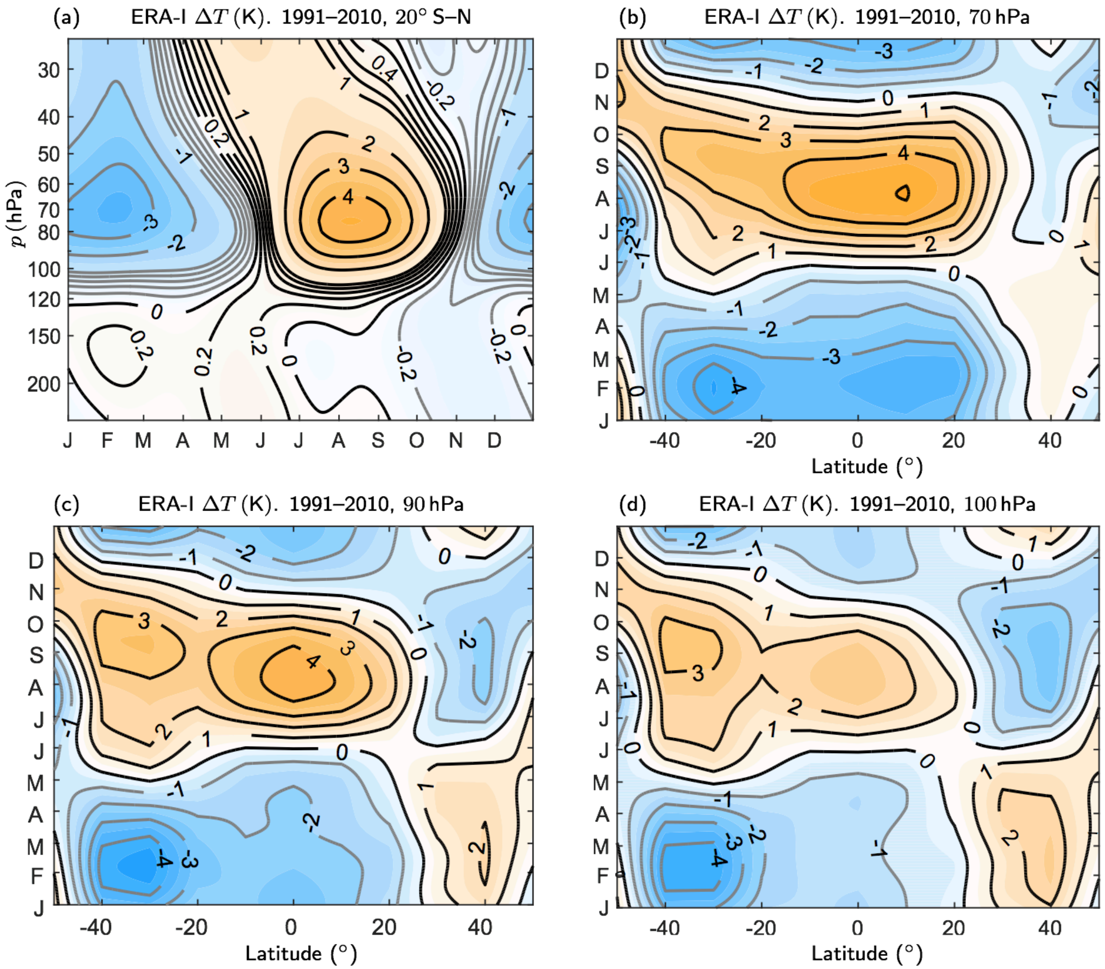
Ozone-driven temperature annual cycle



Fueglistaler et al (2011)

Re-examination of driving of annual cycle

Ming, Maycock, Hitchcock and H (2017)



amplitude largest at 70hPa

90-100 hPa relevant for dehydration

What physical processes determine amplitude and structure (vertical and horizontal)?

SEFDH calculation

$$\frac{\partial \overline{T}}{\partial t} + \overline{w}^* \overline{S} = Q_{\mathrm{rad}}(\overline{T}, \overline{\chi}_{\mathrm{O_3}}, \overline{\chi}_{\mathrm{H_2O}})$$

specified *t*-varying $\overline{T}^0 \quad \overline{\chi}^0_{\mathrm{O_3}} \quad \overline{\chi}^0_{\mathrm{H_2O}}$

$$\frac{\partial \overline{T}^0}{\partial t} = Q_{\mathrm{rad}}(\overline{T}^0, \overline{\chi}^0_{\mathrm{O_3}}, \overline{\chi}^0_{\mathrm{H_2O}}) + \overline{Q}^0_{\mathrm{dyn}}$$

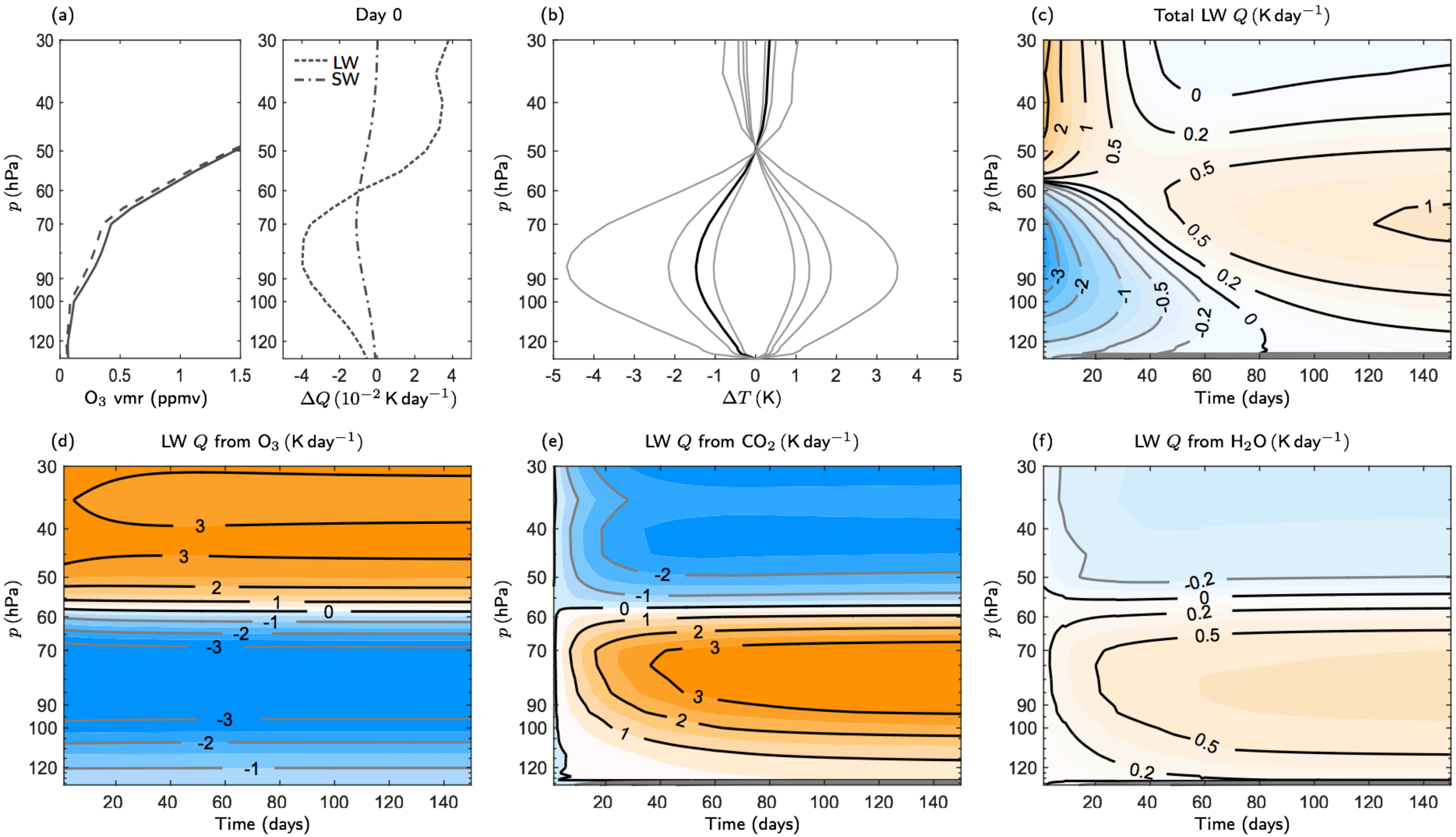
$$\longrightarrow \overline{Q}^0_{\mathrm{dyn}}$$

specified *t*-varying $\Delta\overline{\chi}^0_{\mathrm{O_3}} \quad \Delta\overline{\chi}^0_{\mathrm{H_2O}}$

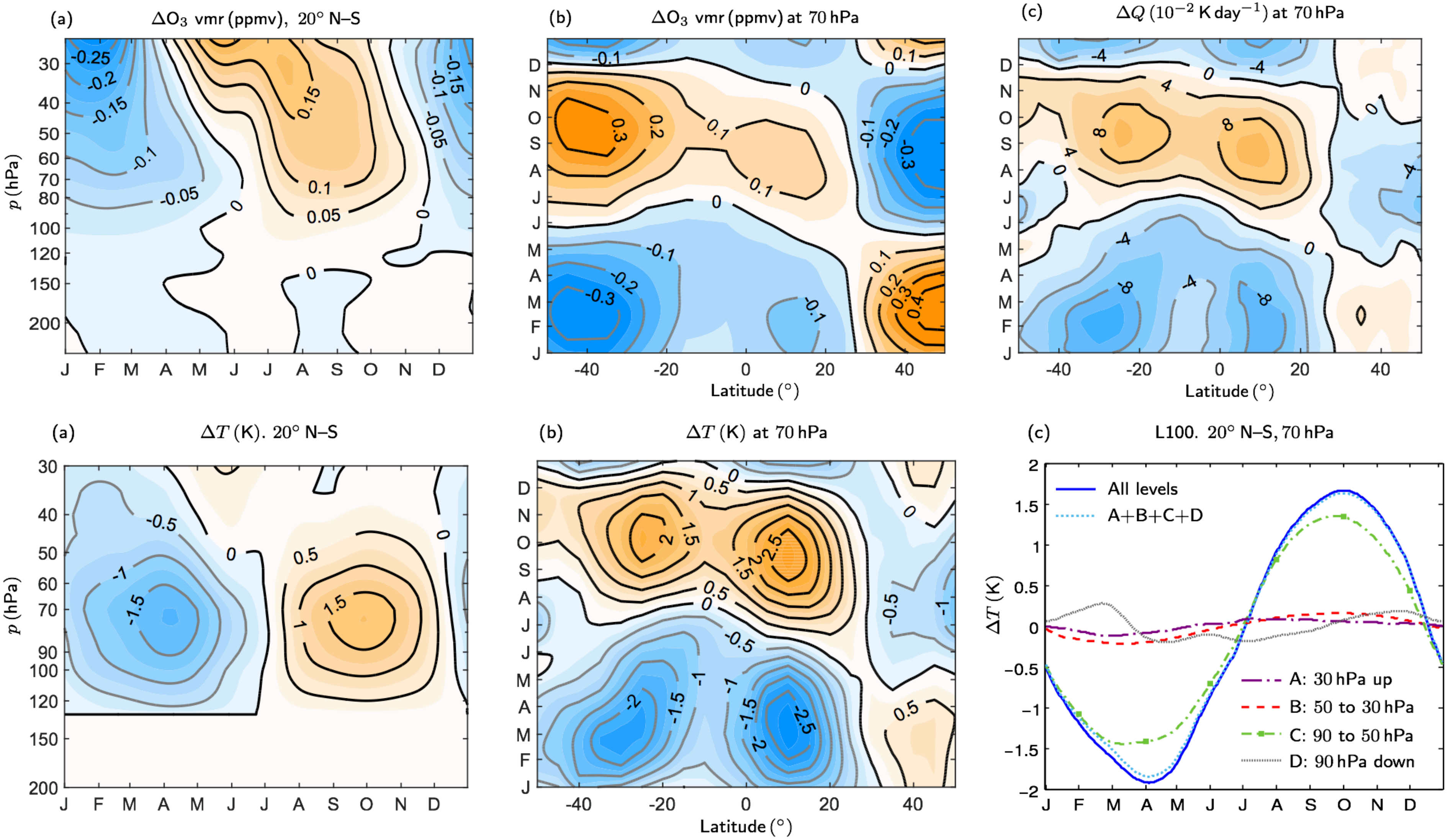
$$\frac{\partial(\overline{T}^0 + \Delta\overline{T})}{\partial t} = Q_{\mathrm{rad}}(\overline{T}^0 + \Delta\overline{T}, \overline{\chi}^0_{\mathrm{O_3}} + \Delta\overline{\chi}^0_{\mathrm{O_3}}, \overline{\chi}^0_{\mathrm{H_2O}} + \Delta\overline{\chi}^0_{\mathrm{H_2O}}) + \overline{Q}^0_{\mathrm{dyn}}$$

$$\longrightarrow \Delta\overline{T}$$

Effect of imposed $\Delta\overline{\chi}^{0}_{O_3}$

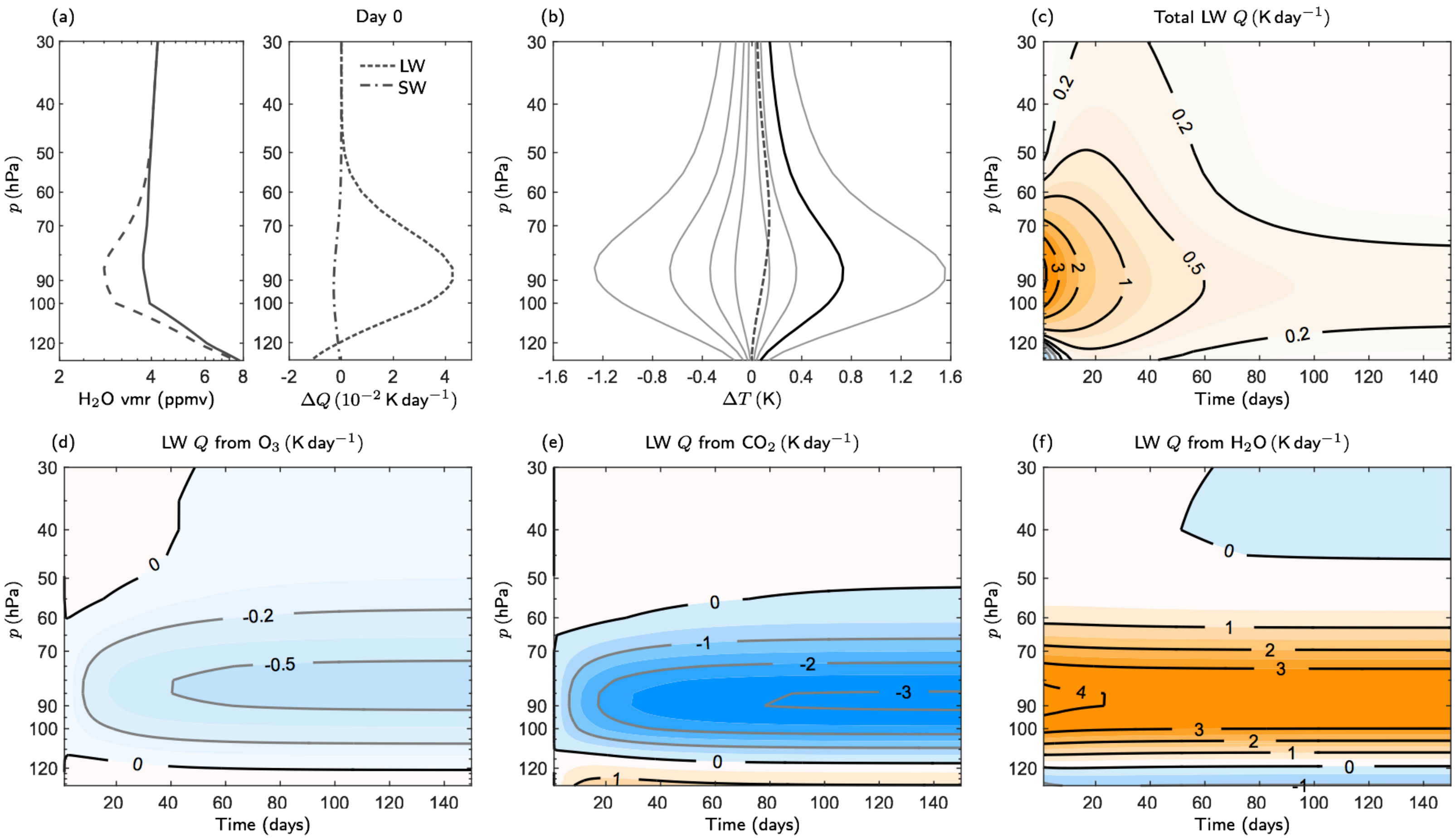


Ozone

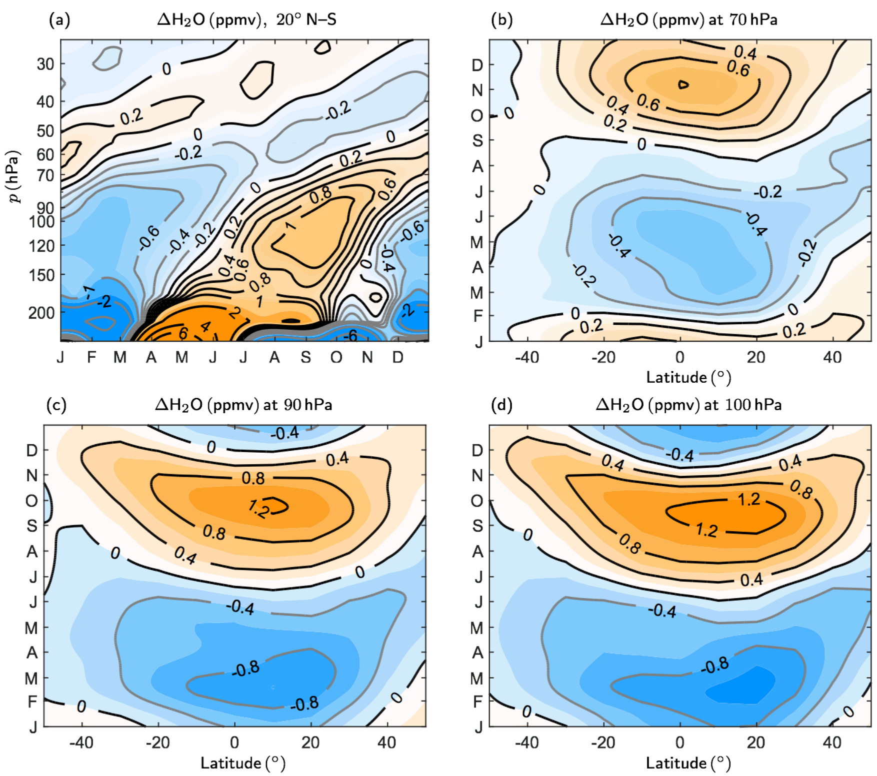


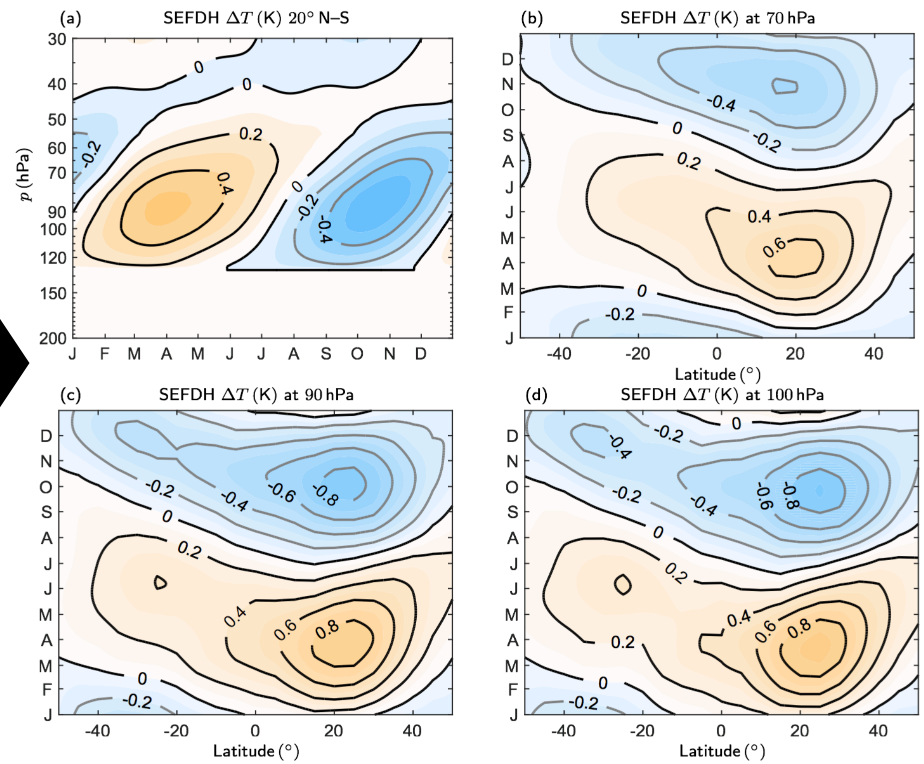
(a) ΔO_3 vmr (ppmv), 20° N–S
p (hPa)
(b) ΔO_3 vmr (ppmv) at 70 hPa
Latitude (°)
(c) ΔQ (10^{-2} K day^{-1}) at 70 hPa
Latitude (°)
(a) ΔT (K). 20° N–S
p (hPa)
(b) ΔT (K) at 70 hPa
Latitude (°)
(c) L100. 20° N–S, 70 hPa
ΔT (K)
All levels
A+B+C+D
A: 30 hPa up
B: 50 to 30 hPa
C: 90 to 50 hPa
D: 90 hPa down

Effect of imposed $\Delta\overline{\chi}^0_{\mathrm{H_2O}}$

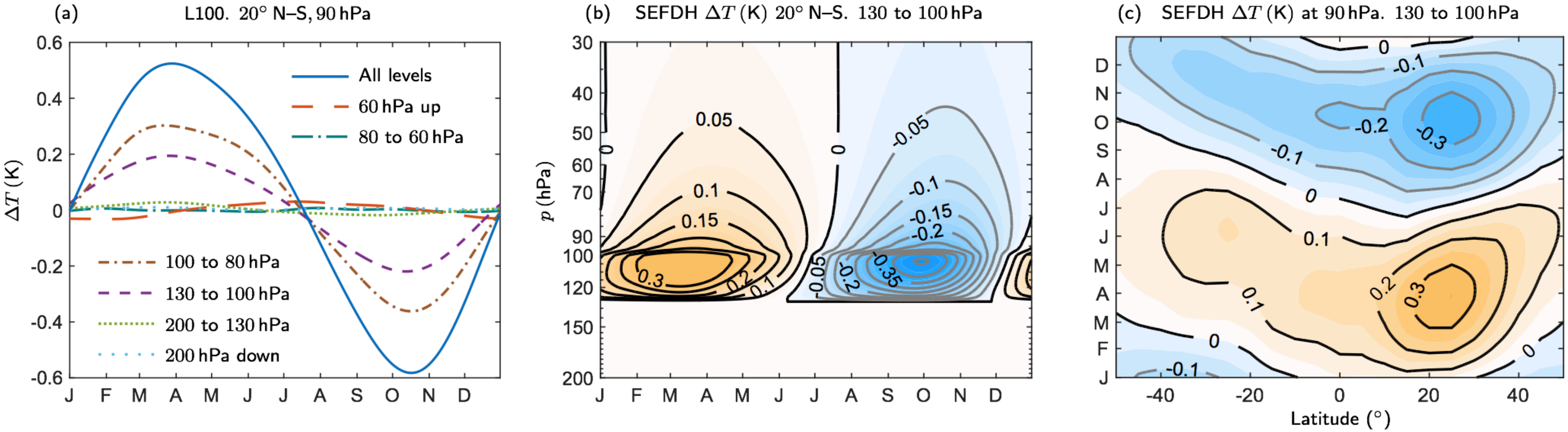


Water vapour





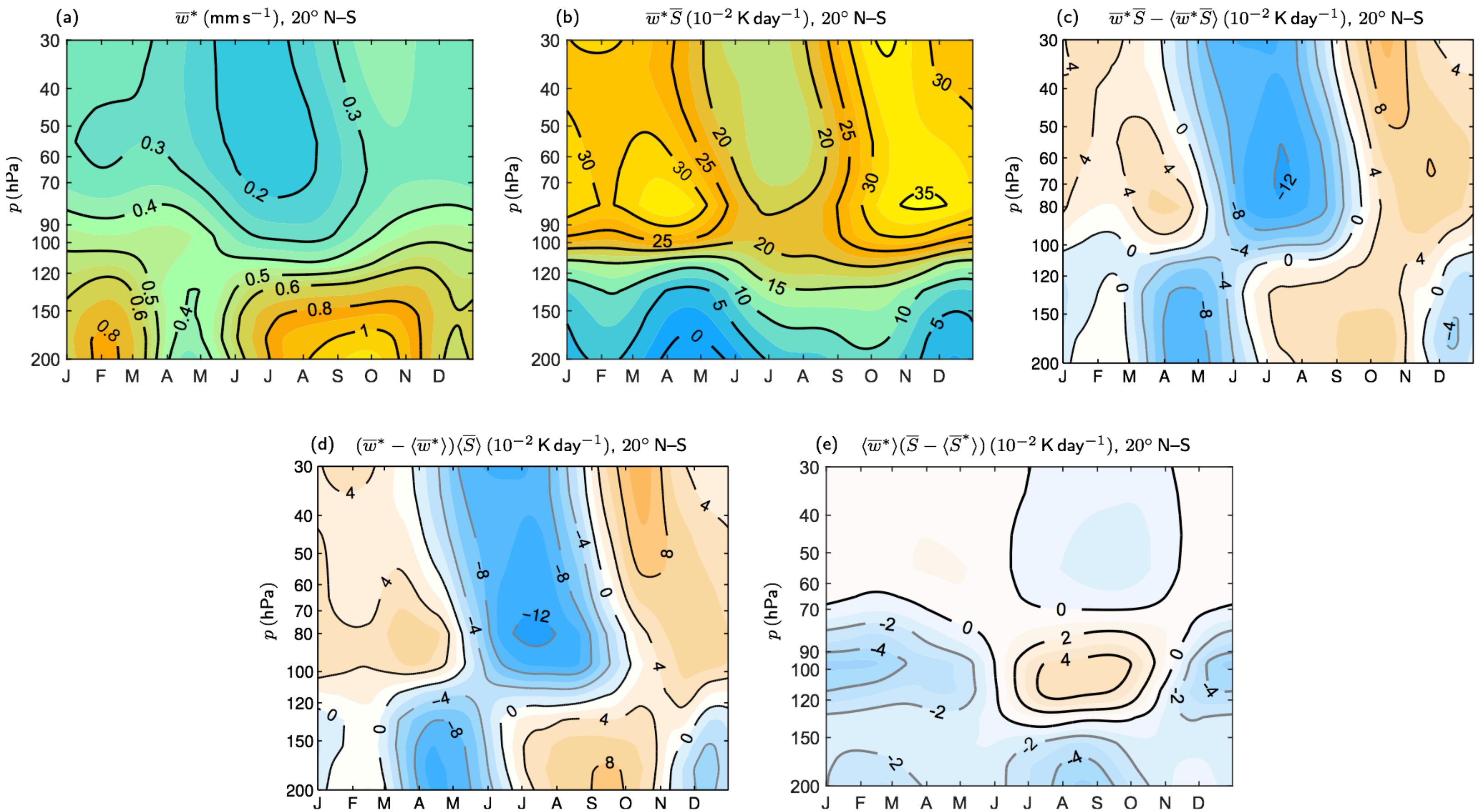
Water vapour – non-local effects in vertical



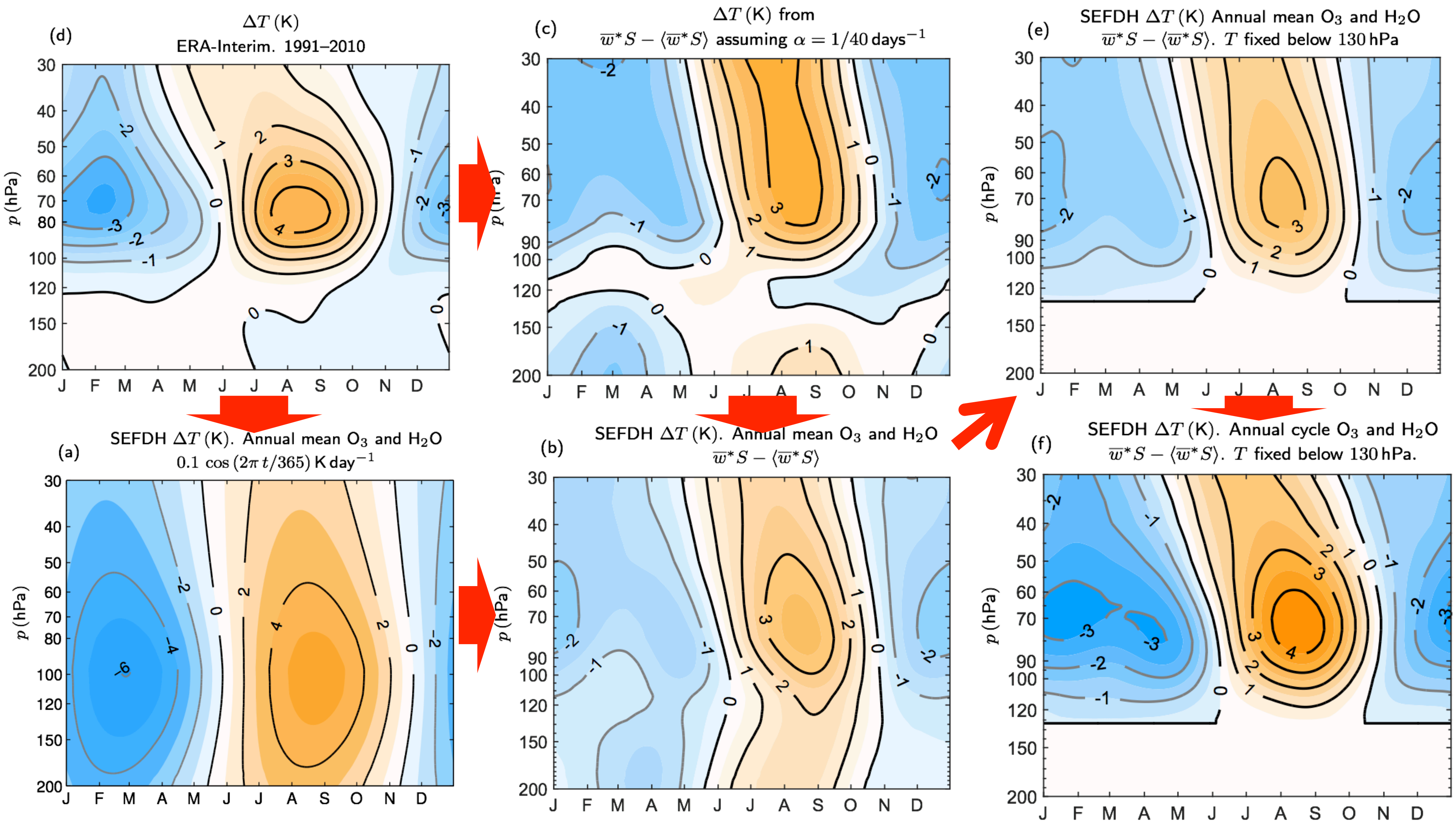
Temperature cycle driven by dynamical heating

$$\frac{\partial(\overline{T}^0 + \Delta\overline{T})}{\partial t} = Q_{\mathrm{rad}}(\overline{T}^0 + \Delta\overline{T}, \overline{\chi}^0_{\mathrm{O_3}}, \overline{\chi}^0_{\mathrm{H_2O}}) + \overline{Q}^0_{\mathrm{dyn}} + \Delta\overline{Q}_{\mathrm{dyn}}$$

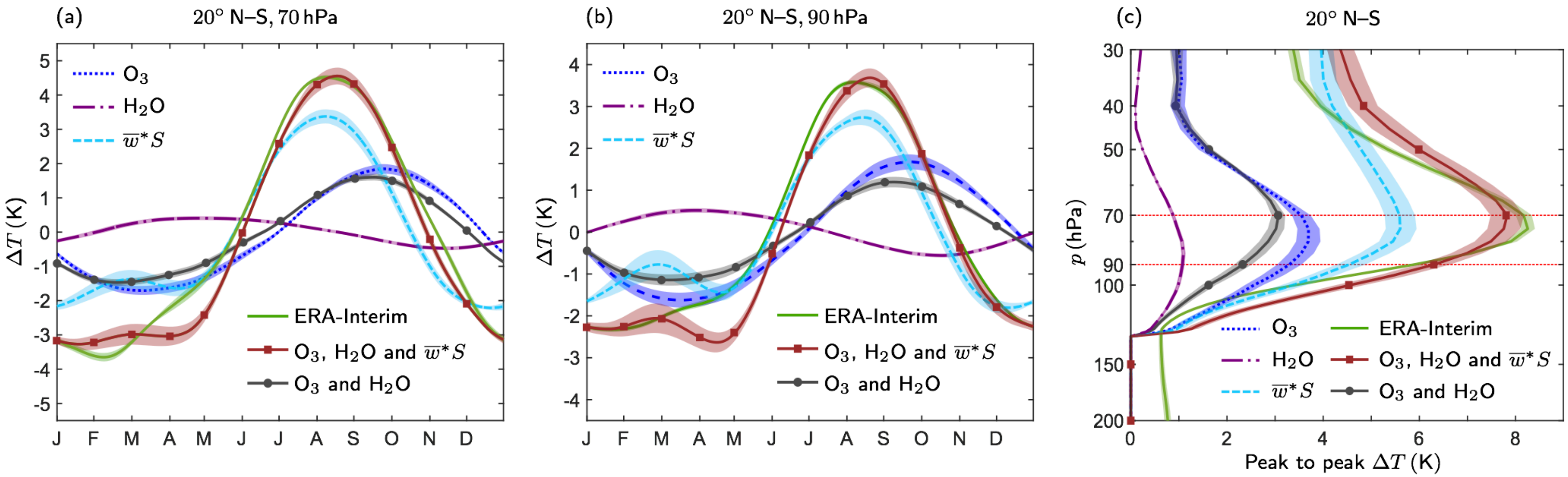
$\Delta\overline{Q}_{\mathrm{dyn}}$?



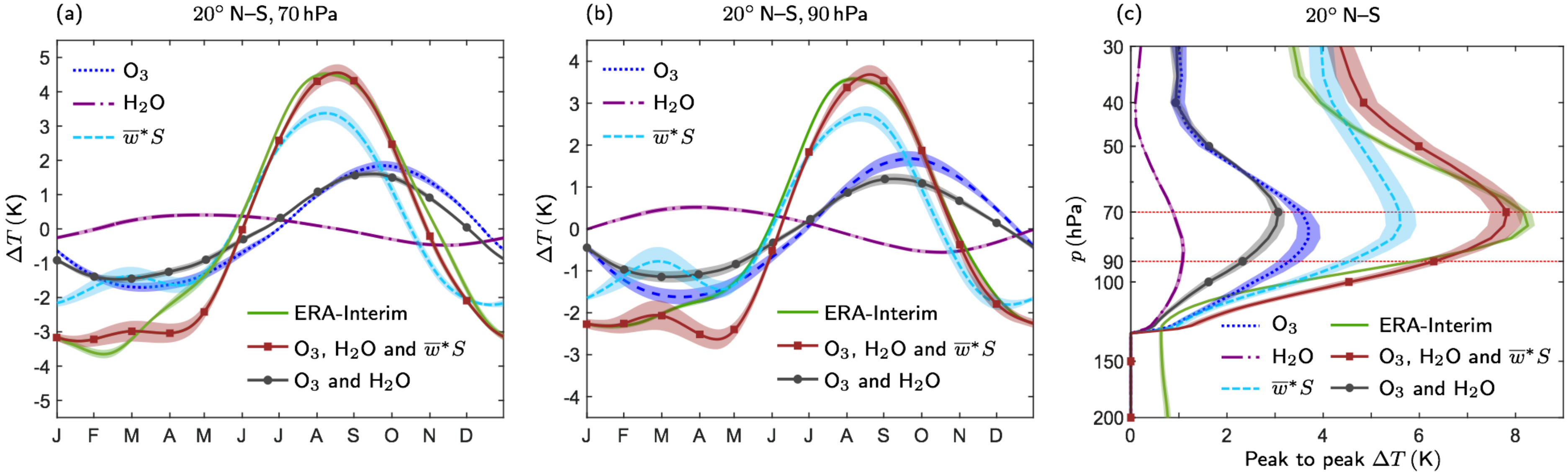
$\Delta\overline{T}$ driven by dynamical heating



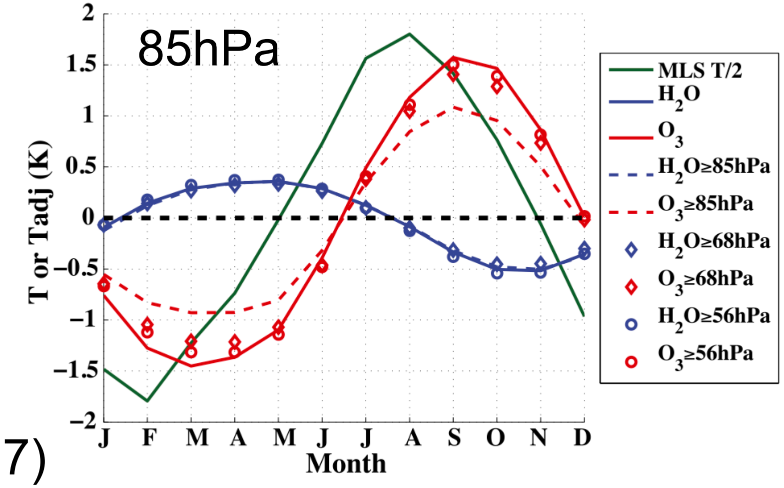
$$\frac{\partial \Delta \overline{T}}{\partial t} = \Delta Q_{\mathrm{rad}}[\Delta T] + \Delta Q_{\mathrm{rad}}[\Delta \overline{\chi}^{0}_{\mathrm{O_3}}] + \Delta Q_{\mathrm{rad}}[\Delta \overline{\chi}^{0}_{\mathrm{H_2O}}] + \Delta \overline{Q}_{\mathrm{dyn}}$$

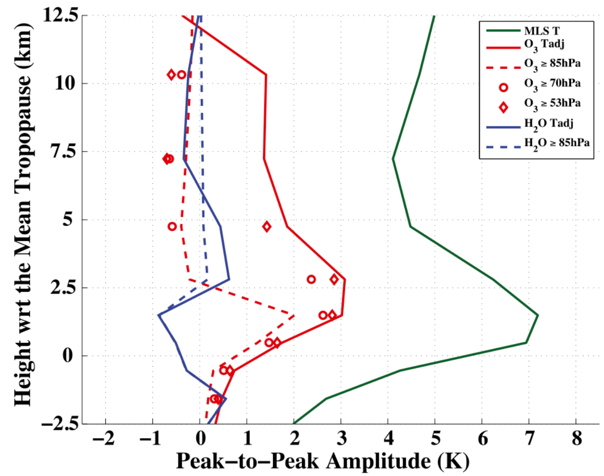


Ming el al (2017)



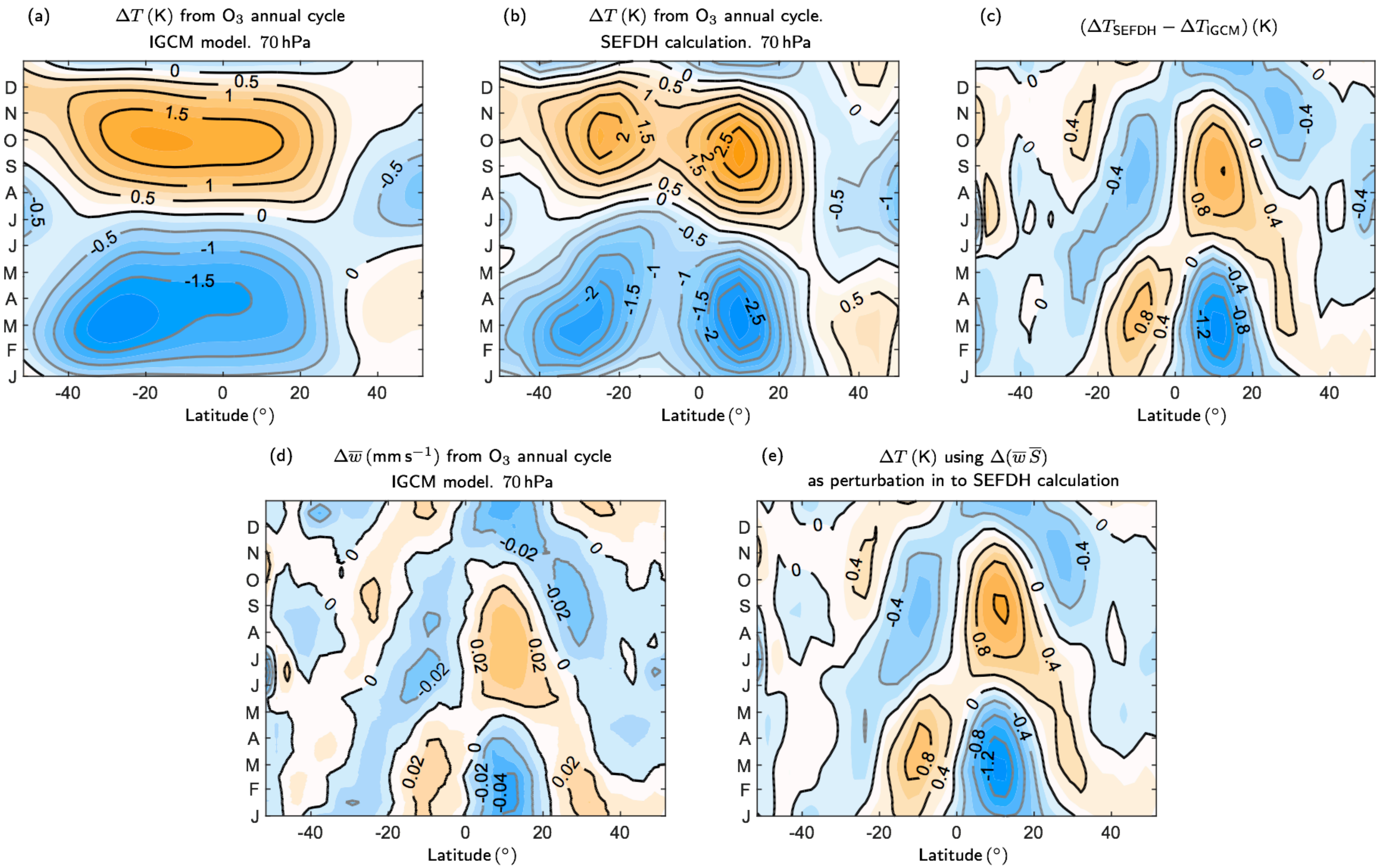
Gilford and Solomon (2017)





Relax SEFDH assumption

Radiation code + zonally symmetric dynamics



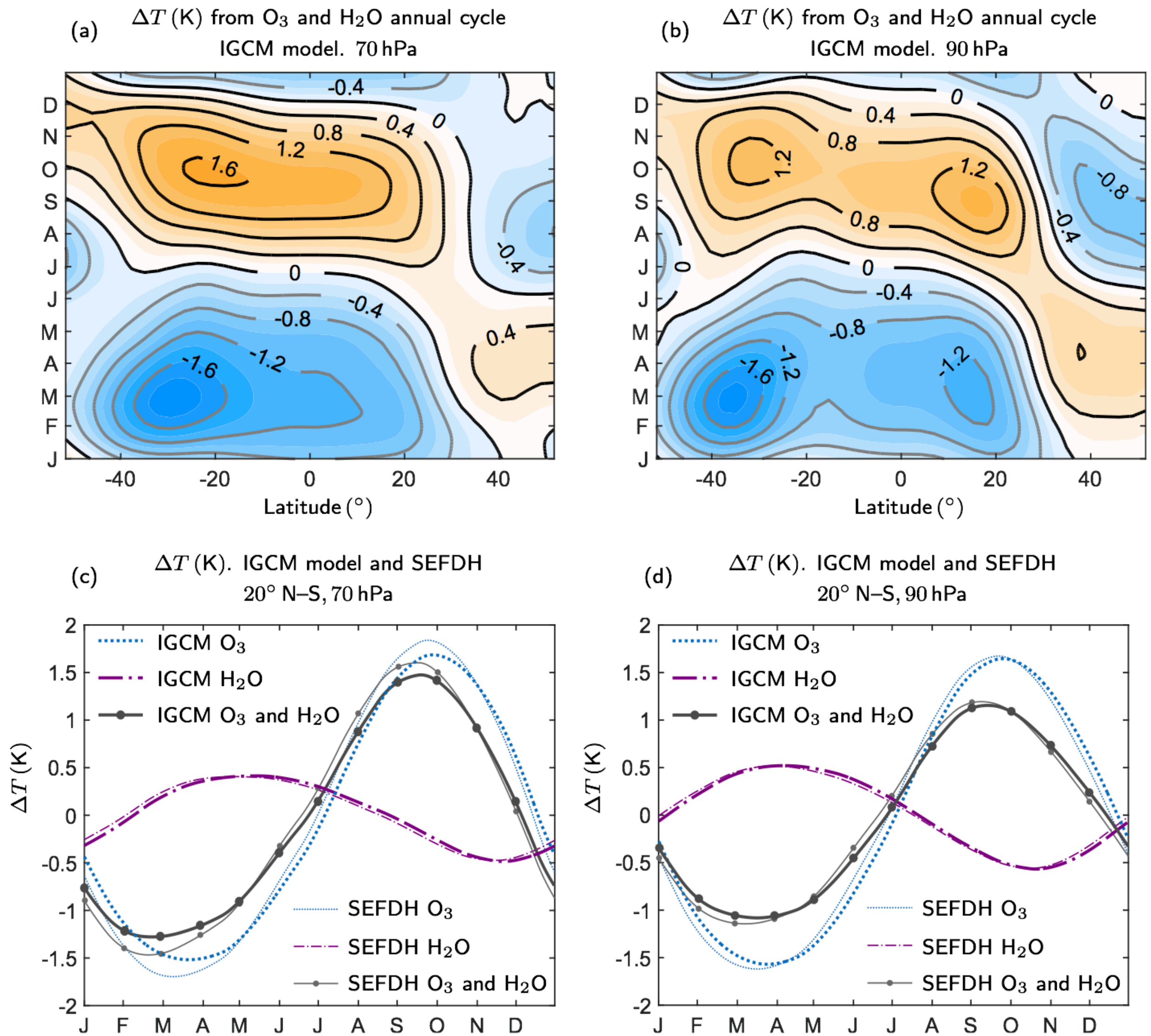
$$\partial_t\overline{u} + \frac{1}{a\ \cos\ \phi}\,\overline{v}^*\,\partial_\phi\left(\overline{u}\ \cos\ \phi\right) + \overline{w}^*\,\partial_z\overline{u} - f\,\overline{v}^* = \overset{0}{\cancel{\frac{1}{\rho_0\, a\ \cos\ \phi}\nabla\cdot\vec{F}}}, \quad (1)$$

$$f\,\partial_z\overline{u} + \frac{R}{H}\,\frac{1}{a}\,\partial_\phi\overline{T} = 0, \quad (2)$$

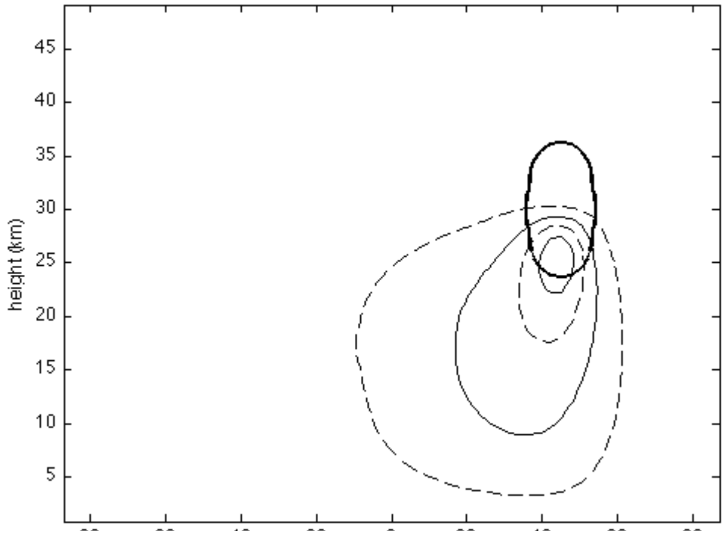
$$\frac{1}{a\ \cos\ \phi}\,\partial_\phi\left(\overline{v}^*\ \cos\ \phi\right) + \frac{1}{\rho_0}\,\partial_z\left(\rho_0\overline{w}^*\right) = 0, \quad (3)$$

$$\partial_t\overline{T} + \frac{1}{a}\,\overline{v}^*\,\partial_\phi\overline{T} + \overline{S}\,\overline{w}^* = \Delta\overline{Q}_{\mathrm{rad}}[\overline{T}, \Delta\overline{\chi}_{\mathrm{O_3}}, \Delta\overline{\chi}_{\mathrm{H_2O}}]. \quad (4)$$

Effect on tropical average 20N-20S

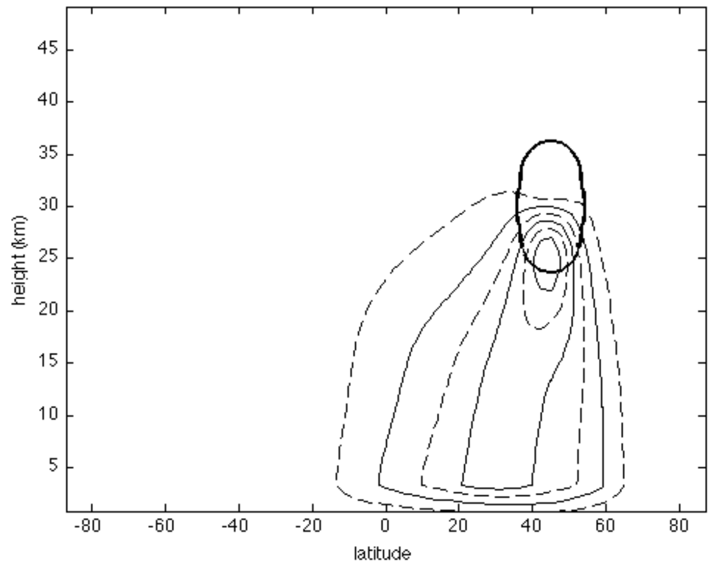


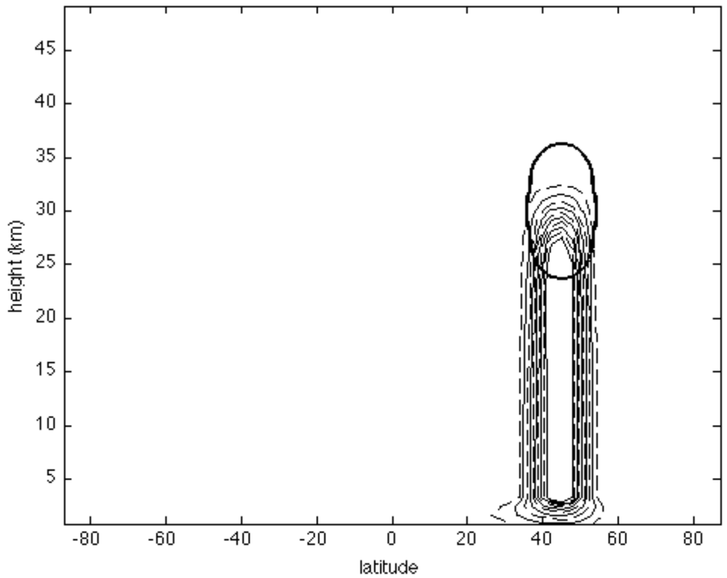
Meridional circulation response on different timescales



rapid variation

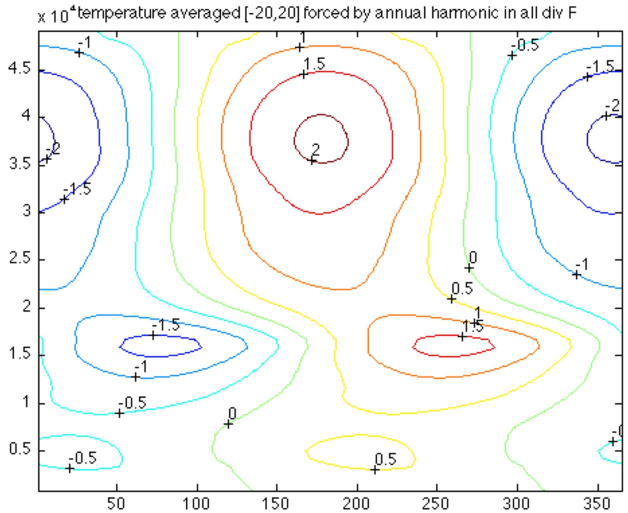
annual variation



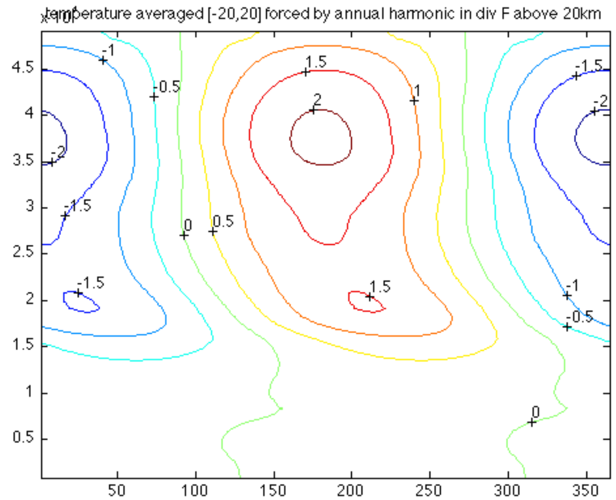


slow variation

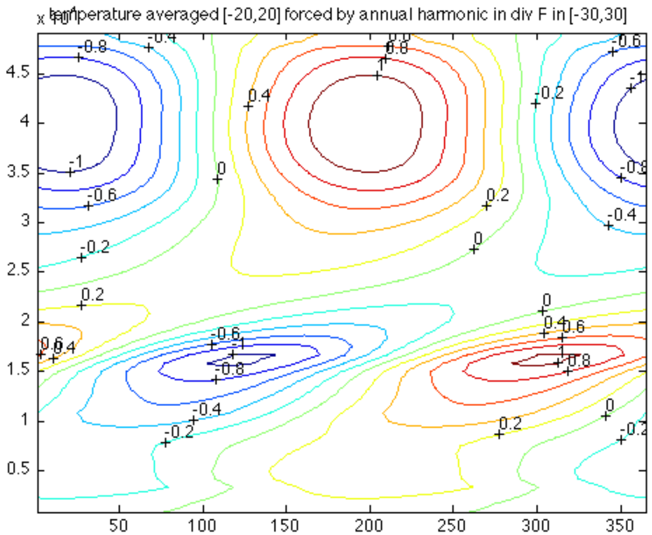
$\Delta\overline{T}$ driven by $\nabla.\mathbf{F}$ from different regions



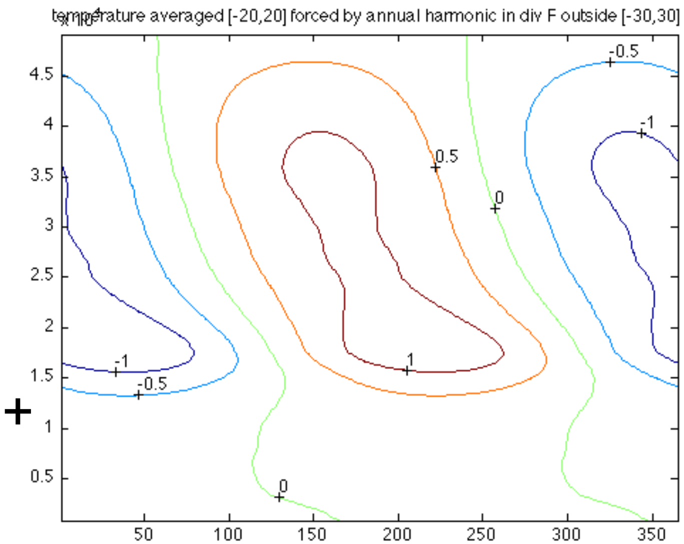
all



$z > 20$km



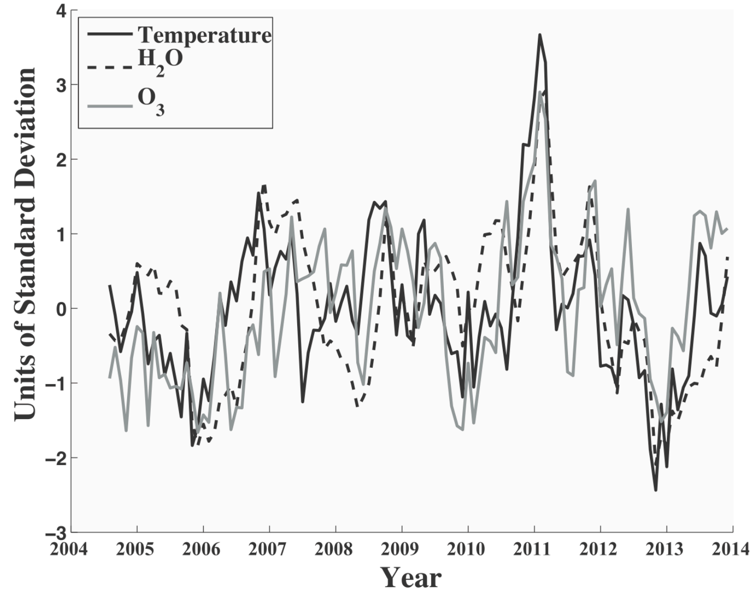
[-30 ,30]

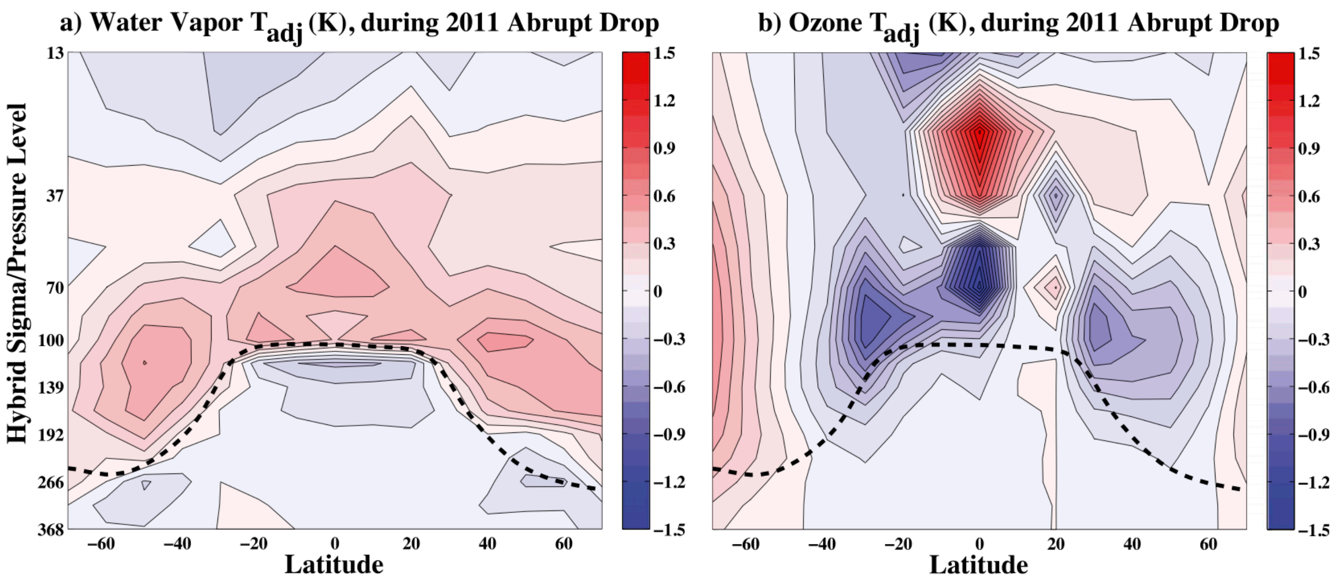


[-90 ,-30] +
[30,90]

2011 'water vapour drop'

Gilford et al (2016)





Summary

1. Annual cycle in tropical tropopause temperatures is driven both by dynamical effects (response to wave force) and by radiative effects (response to variations in ozone and water vapour)

2. Dynamical effects – non-locality of response to wave force needs to be taken into account. Wave forces due to waves propagating from extratropics and from tropics are likely to be important.

3. Radiative effects – SEFDH calculations give useful insight into tropical average, but not into latitudinal structure.

4. Similar considerations apply to longer term variations, e.g. interannual variations.

5. Calculations presented are for *given* change in wave force or *given* change in chemical species – but in reality these are determined by feedbacks and must be understood as part of the response as a whole.