Energy deposition of vertically propagating waves: The role of thermal tides for the global circulation in the mesopause region

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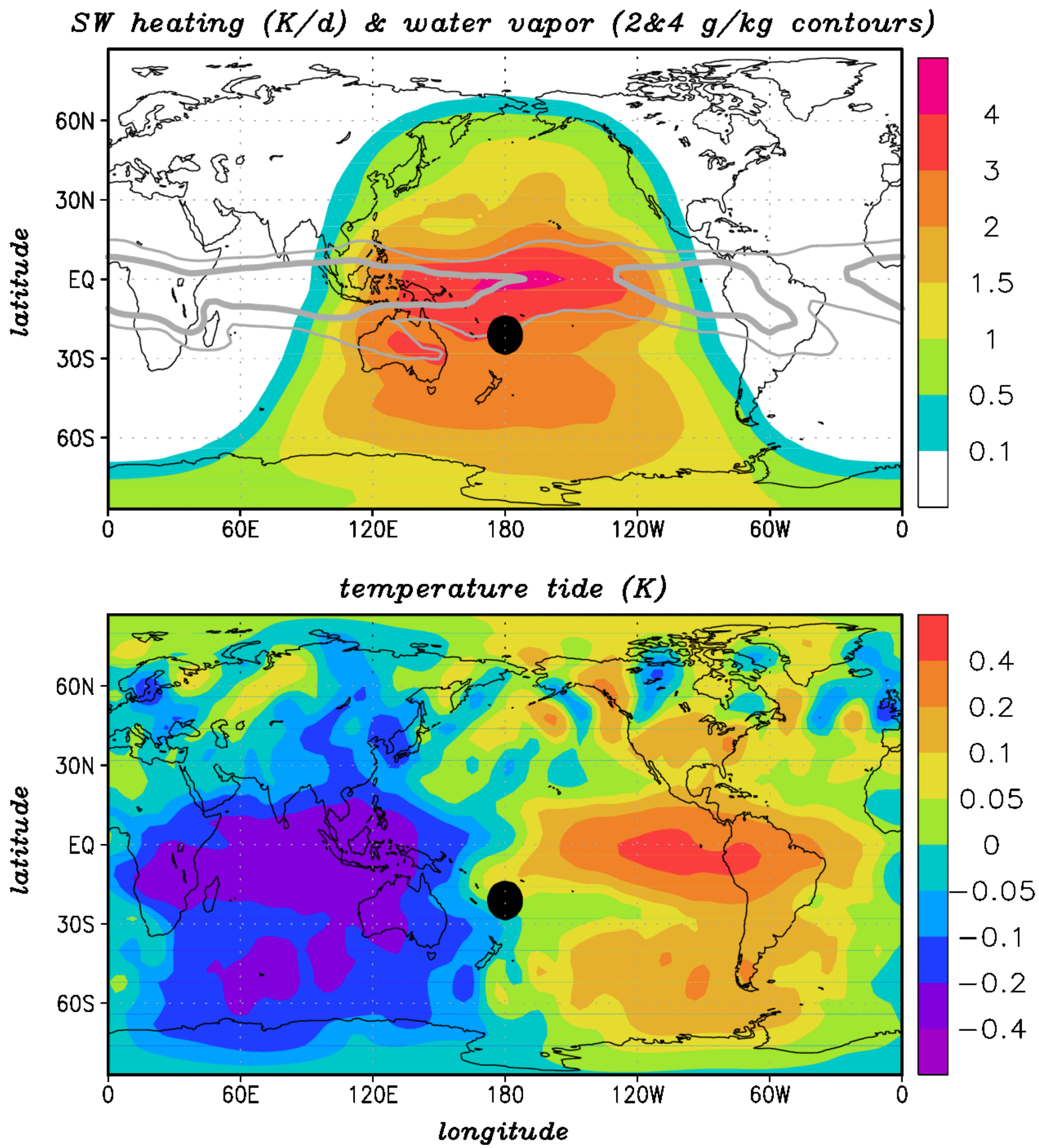
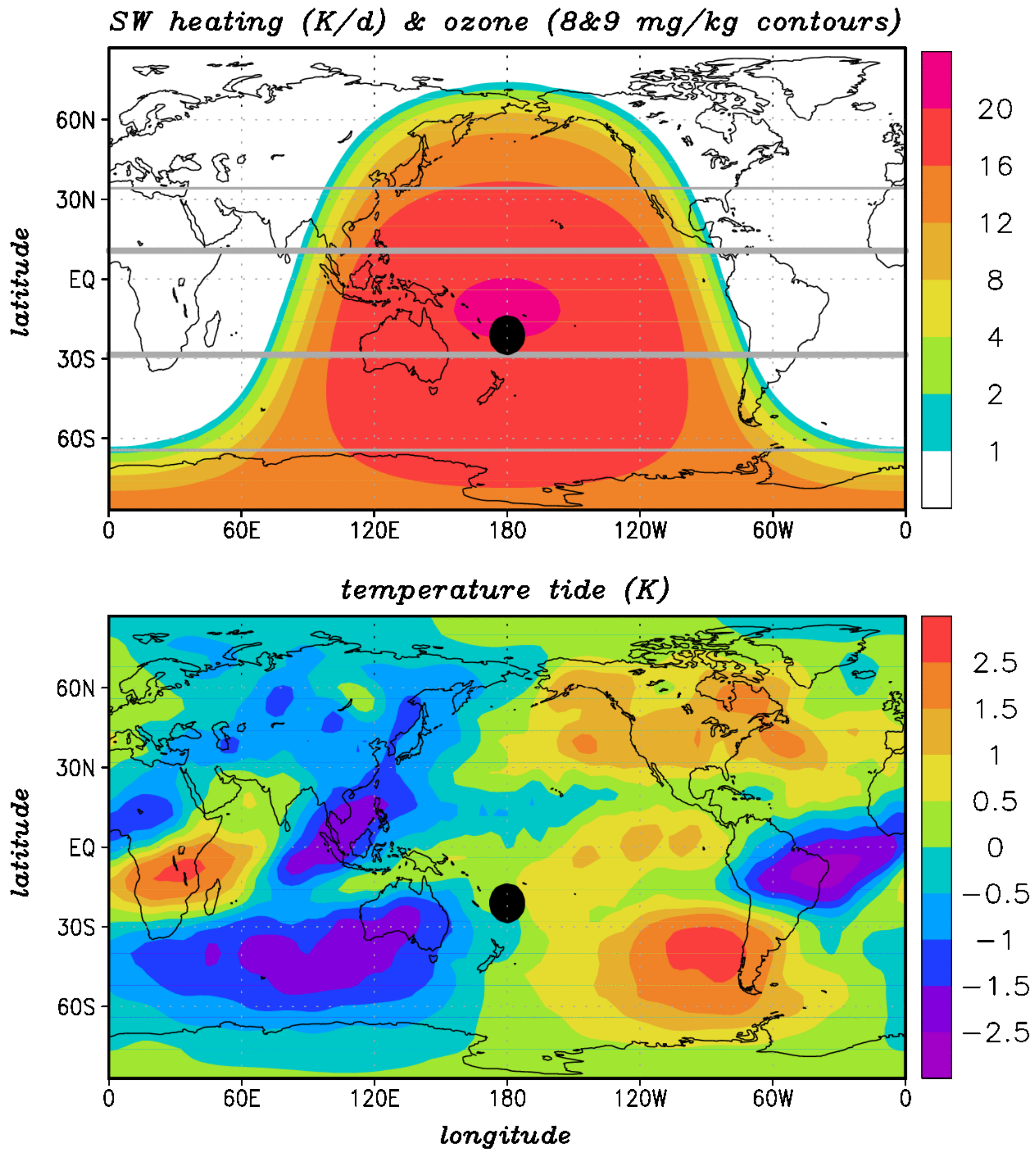
All results are based on an idealized climate with conventional resolution (resolved Rossby waves and thermal tides, parameterized gravity waves), including explicit computation of radiation, moisture cycle, and the surface budget (Becker et al., 2015, JASTP).

WTD, August 31 – September 3, 2015

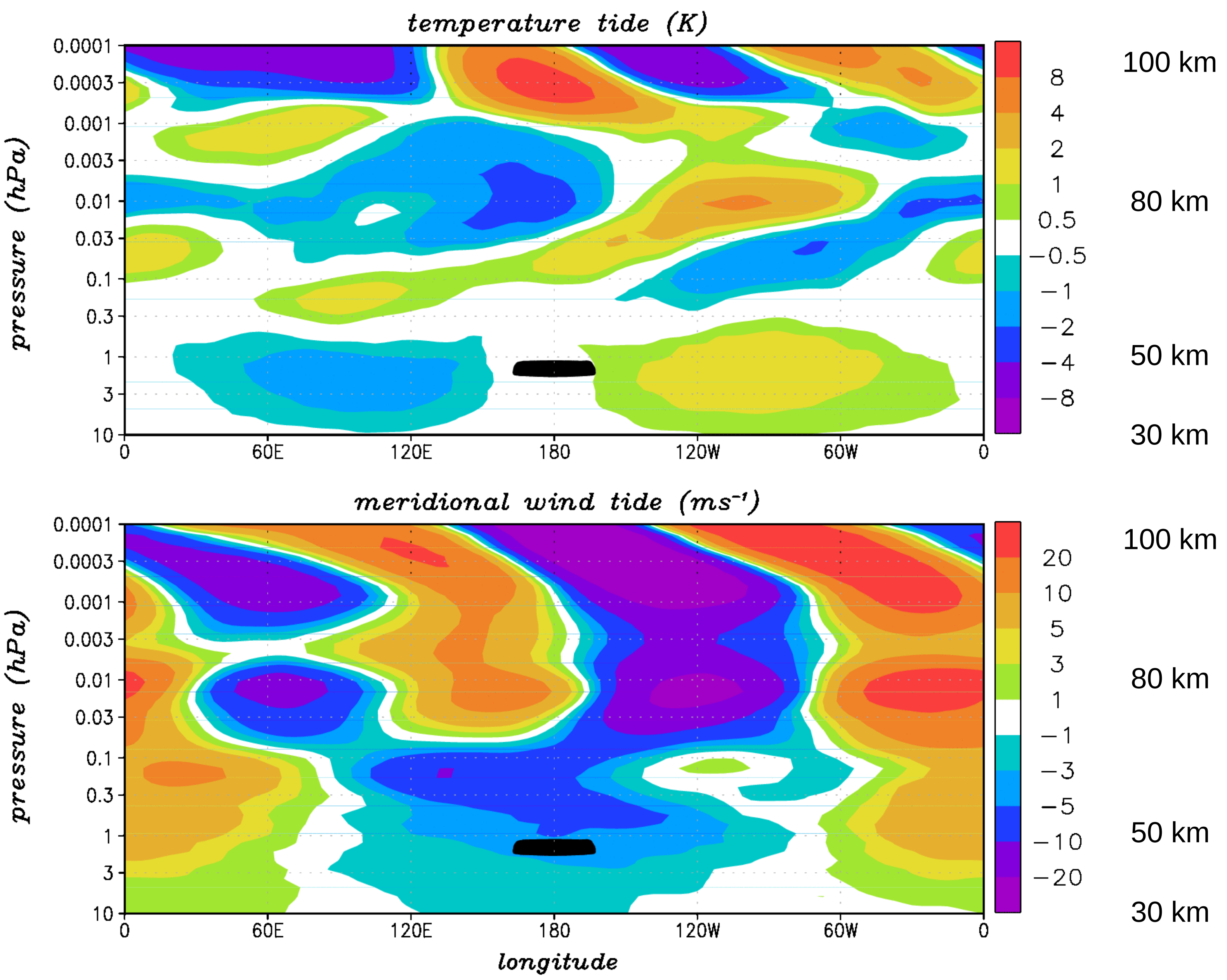
Generation of thermal tides:
Absorption of short-wave (SW) radiation by tropospheric water vapor
(mean daily cycle in January, 550 hPa ~ 4 km height)



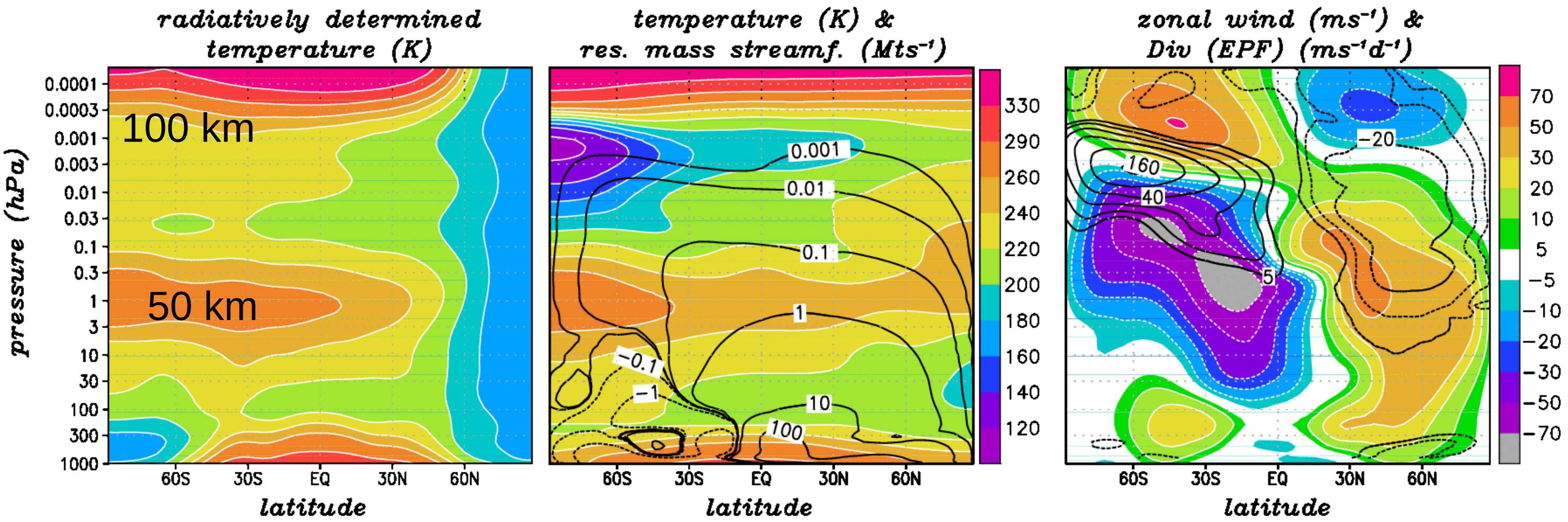
Generation of thermal tides:
Absorption of short-wave (SW) radiation by stratospheric ozone
(mean daily cycle January, 1 hPa ~ 50 km height)



Resulting thermal tides in austral summer at 60°S



Wave driving of the general circulation of the lower and middle atmosphere during January



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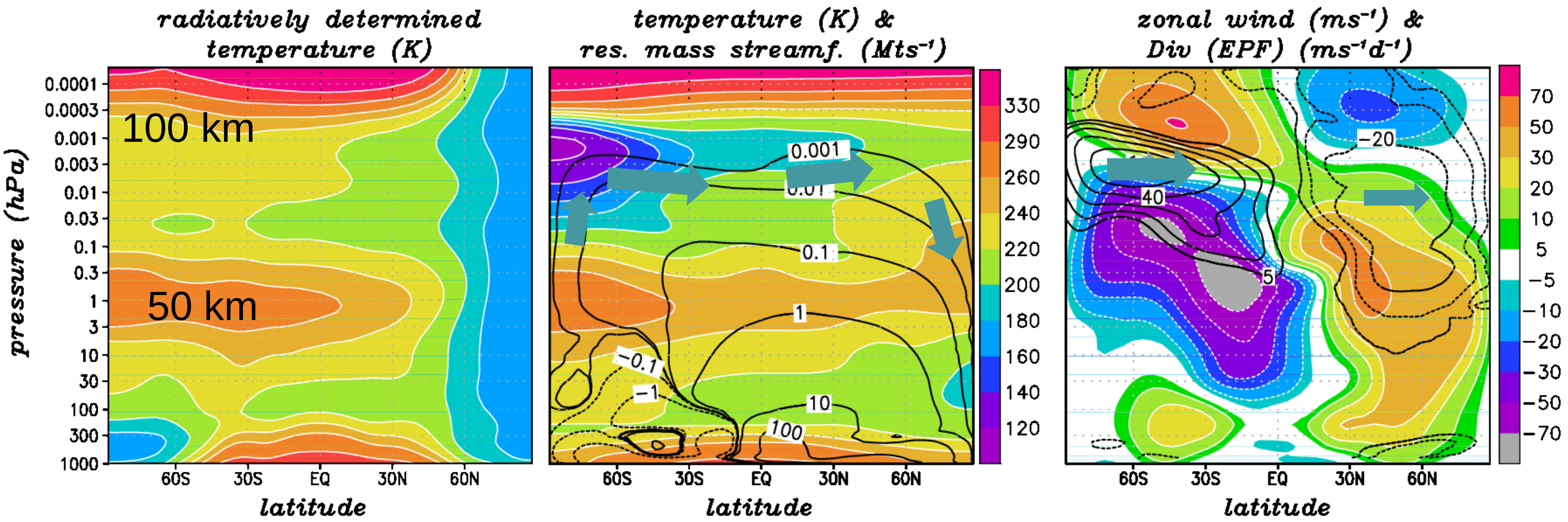

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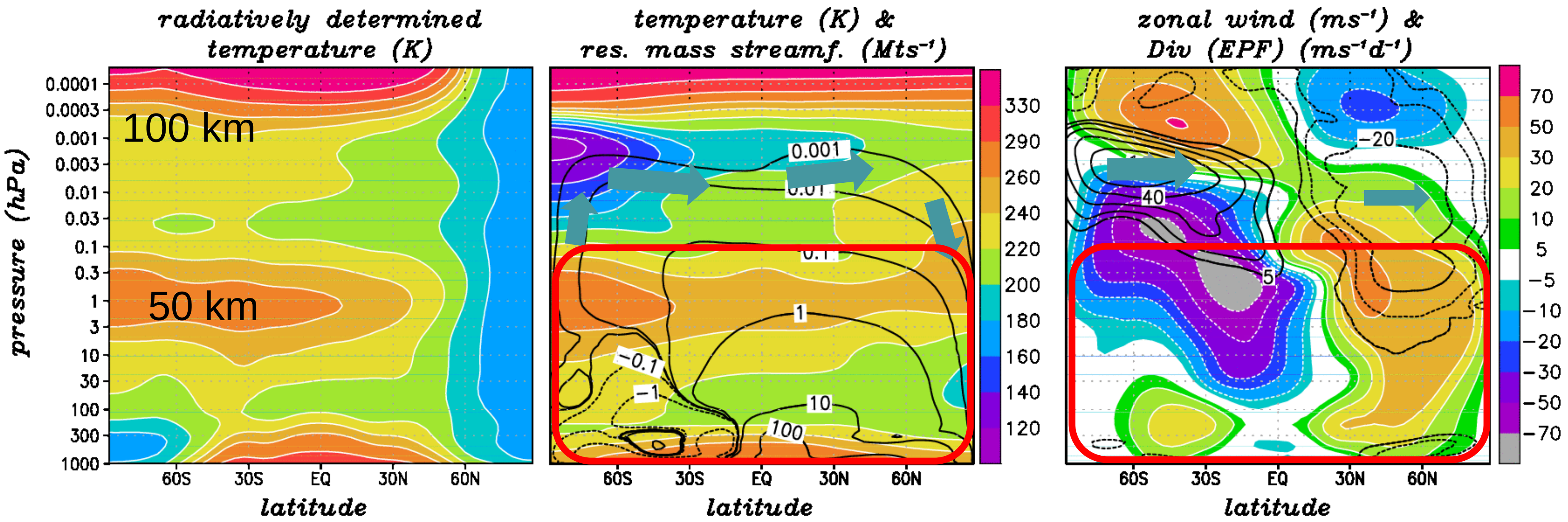

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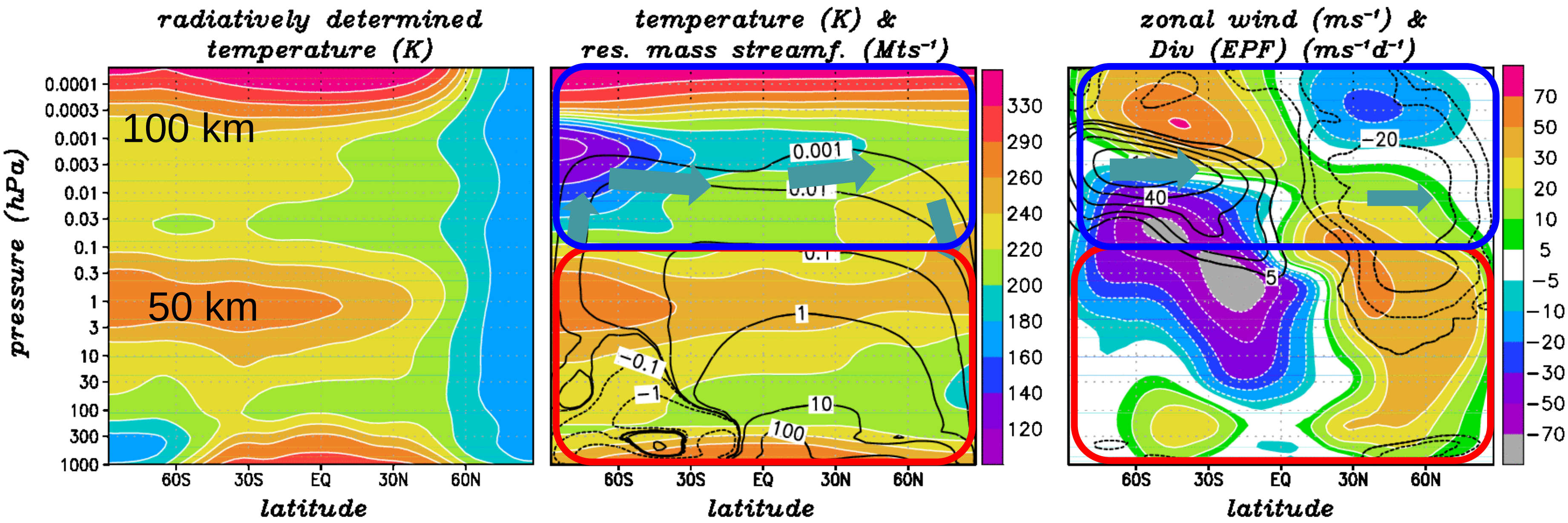
Wave driving of the general circulation of the lower and middle atmosphere during January



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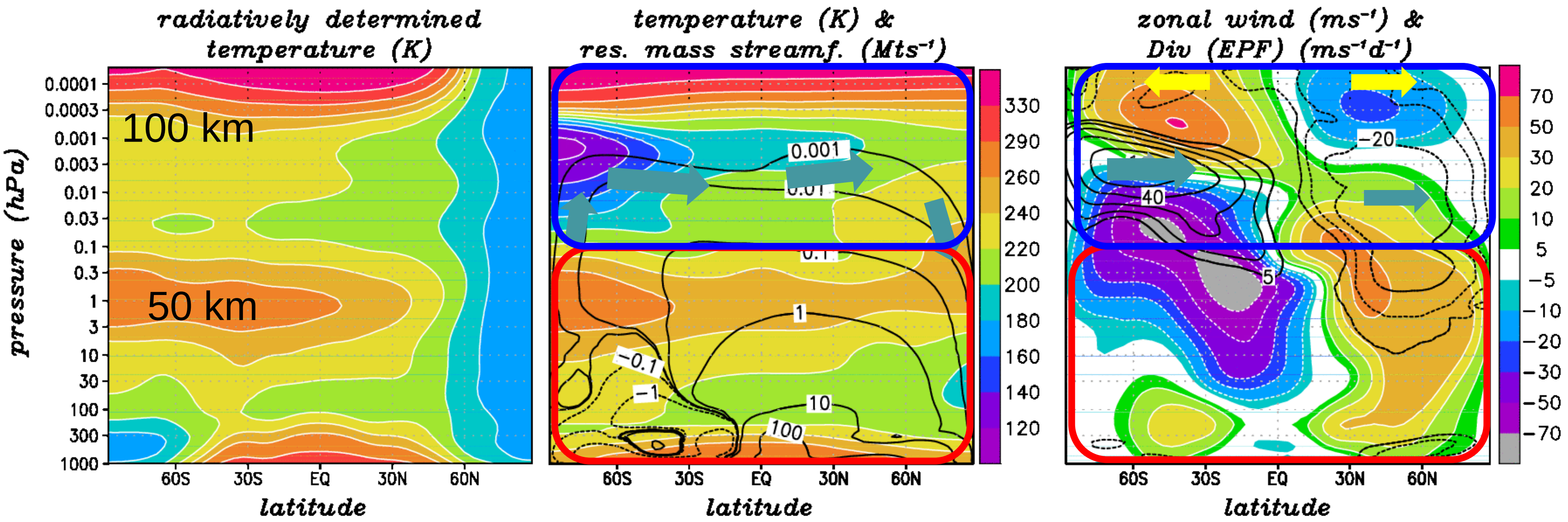

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- **Tides drive poleward circulation branches in the lower thermosphere.**

Wave driving in the TEM picture

(Andrews & McIntyre, 1976, JAS; Dunkerton, 1978, JAS)

$$[X] = \text{zonal mean of } X = [X] + X^*$$

$$v_{res} = [v] + \partial_p \frac{[T^* v^*]}{\frac{R}{c_p\, p}[T] - \partial_p [T]} = [v] + (\text{merid. Stokes drift}) / \rho$$

$$\omega_{res} = [\omega] - \frac{1}{a \cos\phi} \partial_\phi \left(\frac{\cos\phi\, [T^* v^*]}{\frac{R}{c_p\, p}[T] - \partial_p [T]} \right) = [\omega] - g\, (\text{vert. Stokes drift})$$

zonal momentum equation in the transformed Eulerian mean (TEM):

$$\partial_t [u] = (f + [\xi])\, v_{res} - \omega_{res}\, \partial_p [u] + \text{Div (EPF)} + (\text{mom. diff.})$$

$$\text{Div (EPF)} \approx \text{Div (qgEPF)} + (\text{GW drag})$$

$$\text{Div (qgEPF)} = -\frac{1}{a \cos^2\phi} \partial_\phi \left(\cos^2\phi\, [u^* v^*] \right) - \partial_p \frac{f\, [T^* v^*]}{\frac{R}{c_p\, p}[T] - \partial_p [T]}$$

$$\text{GW drag} = -\partial_p [u^* \omega^*]$$

Wave driving and causality in the temporal mean

- Turbulent diffusion is essential to induce Div (EPF) $\neq 0$ (non-acceleration theorem).

- The residual circulation is driven by waves:

$$0 \approx (f + [\xi])\, v_{res} - \omega_{res}\, \partial_p [u] + \text{Div (EPF)}$$
$$0 = \frac{1}{a \cos\phi} \partial_\phi (\cos\phi\, v_{res}) + \partial_p\, \omega_{res}$$

- Thinking of the radiative heating in terms of $-(T - T_E)/\tau$ and neglecting all small-scale thermal effects, the residual circulation induces deviations from the radiatively determined state T_E via the balance between adiabatic and radiative heating:

$$0 \approx (c_p\, \rho)^{-1}\, \omega_{res} - ([T] - T_E)/\tau$$

- Thermal wind balance determines the zonal wind from the thermal structure:

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The TEM picture does not include the **direct contributions of the waves to the sensible heat budget**. For example, the turbulent dissipative heating due to breaking gravity is a frist-order effect on the mean flow in the mesopause region.

Reynolds average of the primitive equations (PE):

subgrid-scale turbulence represented by anisotropic diffusion in quasi-stationary approximation

$$\begin{aligned}\partial_t \mathbf{v} &= \mathbf{v} \times (f + \xi)\,\mathbf{e}_z - w\,\partial_z \mathbf{v} - \nabla \frac{\mathbf{v}^2}{2} - \frac{\nabla p}{\rho} \\ &\quad + \frac{1}{\rho}\partial_z(\rho K_z \partial_z \mathbf{v}) + \frac{1}{\rho}\nabla(\rho K_h \nabla \cdot \mathsf{S}_h) \\ \mathsf{S}_h &= \{(\nabla + \mathbf{e}_z/a) \circ \mathbf{v}\} + \{(\nabla + \mathbf{e}_z/a) \circ \mathbf{v}\}^T\end{aligned}$$

$$\begin{aligned}c_p\, d_t T &= \frac{d_t p}{\rho} + Q_{rad} + Q_{lat} \\ &\quad + \frac{c_p}{\rho}\partial_z\Big(\rho \frac{T}{\Theta}\frac{K_z}{P_r}\partial_z \Theta\Big) + \frac{c_p}{\rho}\nabla \cdot \Big(\rho \frac{K_h}{P_r}\nabla T\Big) + K_z(\partial_z \mathbf{v})^2 + K_h|\mathsf{S}_h|^2\end{aligned}$$

(hydrostatic approximation and continuity equation as usual)

Reynolds average of the primitive equations (PE):

Subgrid-scale waves in prognostic single-column approximation,
small-scale turbulence represented by anisotropic diffusion
in quasi-stationary approximation (Becker, 2004, JASTP)

$$\partial_t \mathbf{v} = \mathbf{v} \times (f + \xi)\, \mathbf{e}_z - w\, \partial_z \mathbf{v} - \nabla \frac{\mathbf{v}^2}{2} - \frac{\nabla p}{\rho} + \frac{1}{\rho} \partial_z (\rho K_z \partial_z \mathbf{v} - \mathbf{F}) + \frac{1}{\rho} \nabla (\rho K_h \nabla \cdot \mathsf{S}_h)$$

$$c_p\, d_t T = \frac{d_t p}{\rho} + Q_{rad} + Q_{lat} + \frac{c_p}{\rho} \partial_z \left(\rho \frac{T}{\Theta} \left(\frac{K_z}{P_r} \partial_z \Theta - F_\Theta \right)\right) - \frac{g\, F_\Theta}{\Theta} + \frac{c_p}{\rho} \nabla \cdot \left(\rho \frac{K_h}{P_r} \nabla T\right) + K_z (\partial_z \mathbf{v})^2 + K_h |\mathsf{S}_h|^2 + K_z \overline{(\partial_z \mathbf{v}')^2} + K_h \overline{|\mathsf{S}'_h|^2}$$

$$\overline{d_t \kappa} = -\frac{1}{\rho} \mathbf{F} \cdot \partial_z \mathbf{v} - \frac{\partial_z F_p}{\rho} + \frac{g\, F_\Theta}{\Theta} - K_z \overline{(\partial_z \mathbf{v}')^2} - K_h \overline{|\mathsf{S}'_h|^2}$$

$$\mathbf{F} = \rho\, \overline{\mathbf{v}' w'}, \quad F_p = \overline{p' w'}, \quad F_\Theta = \overline{\Theta' w'}, \quad \kappa = \mathbf{v}'^2 / 2$$

$$c_p\, \rho\, \overline{T' w'} = F_p + c_p\, \rho\, (T / \Theta)\, F_\Theta$$

Reynolds average of the primitive equations (PE):

Subgrid-scale waves in quasi-stationary single-column approximation,

small-scale turbulence represented by anisotropic diffusion

in quasi-stationary approximation (Becker, 2004, JASTP)

$$\partial_t \mathbf{v} = \mathbf{v} \times (f + \xi)\,\mathbf{e}_z - w\,\partial_z \mathbf{v} - \nabla \frac{\mathbf{v}^2}{2} - \frac{\nabla p}{\rho} + \frac{1}{\rho}\partial_z(\rho K_z \partial_z \mathbf{v} - \mathbf{F}) + \frac{1}{\rho}\nabla(\rho K_h \nabla \cdot \mathsf{S}_h)$$

$$c_p\, d_t T = \frac{d_t p}{\rho} + Q_{rad} + Q_{lat} + \frac{c_p}{\rho}\partial_z\left(\rho\frac{T}{\Theta}\left(\frac{K_z}{P_r}\partial_z\Theta - F_\Theta\right)\right) + \frac{c_p}{\rho}\nabla\cdot\left(\rho\frac{K_h}{P_r}\nabla T\right) \boxed{-\frac{1}{\rho}\mathbf{F}\cdot\partial_z\mathbf{v} - \frac{\partial_z F_p}{\rho}} + K_z(\partial_z\mathbf{v})^2 + K_h|\mathsf{S}_h|^2$$

$$\boxed{E = -\frac{1}{\rho}\mathbf{F}\cdot\partial_z\mathbf{v} - \frac{\partial_z F_p}{\rho} = K_z\overline{(\partial_z\mathbf{v}')^2} + K_h\overline{|\mathsf{S}'_h|^2} - \frac{g\,F_\Theta}{\Theta}}$$

$$\mathbf{F} = \rho\,\overline{\mathbf{v}'w'}, \quad F_p = \overline{p'w'}, \quad F_\Theta = \overline{\Theta'w'}, \quad c_p\,\rho\,\overline{T'w'} = F_p + c_p\,\rho\,(T/\Theta)\,F_\Theta$$

Wave-mean flow interaction theorems (quasi-stationary)

- ideal and quasi-linear gravity waves:

$$\begin{aligned} \mathbf{F} &= \text{const} \\ F_{\ominus} &= 0 \\ \mathbf{v}\cdot\mathbf{F} + F_p &= \text{const} \\ -\rho^{-1}(\partial_z F_p + \mathbf{F}\cdot\partial_z\mathbf{v}) &= E = 0 \end{aligned}$$

- wave damping of upward propagating gravity waves:

$$\begin{aligned} -\rho^{-1}\partial_z\mathbf{F} &\propto \mathbf{c}_I \\ F_{\ominus} &\leq 0 \\ -\rho^{-1}(\partial_z F_p + \mathbf{F}\cdot\partial_z\mathbf{v}) &= E > 0 \end{aligned}$$

Extension to inertial gravity waves

$$\mathbf{F} \rightarrow \mathbf{F}(1 - {\omega_I}^2/f^2)$$

Implications

- Two forms of the direct contribution of vertically propagating waves to the large-scale sensible heat budget, i.e., the energy deposition:

$$E = -\frac{1}{\rho}\mathbf{F}\cdot\partial_z\mathbf{v} - \frac{\partial_z F_p}{\rho} = K_z\,\overline{(\partial_z\mathbf{v}')^2} + K_h\,\overline{|\mathsf{S}'_h|^2} - \frac{g\,F_\Theta}{\Theta}$$

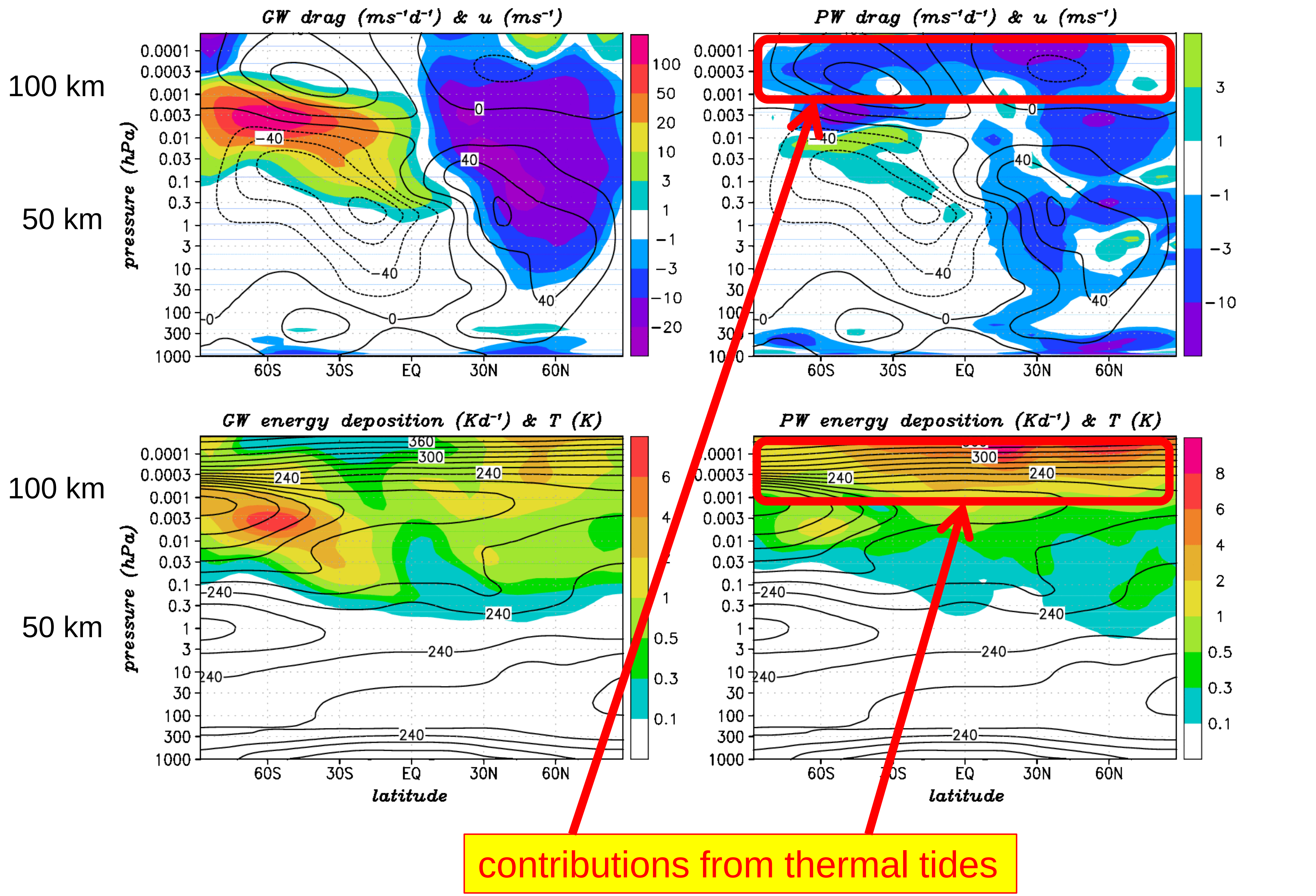
- The first identity may be used for parameterized waves.

- Only the second identity applies when the waves are resolved. Hence, in order to account for the energy deposition (in addition to the EPF divergence), the waves must be damped by (harmonic and anisotropic) momentum diffusion and the associated frictional heating (shear production) must be included in the thermodynamic equation of motion.

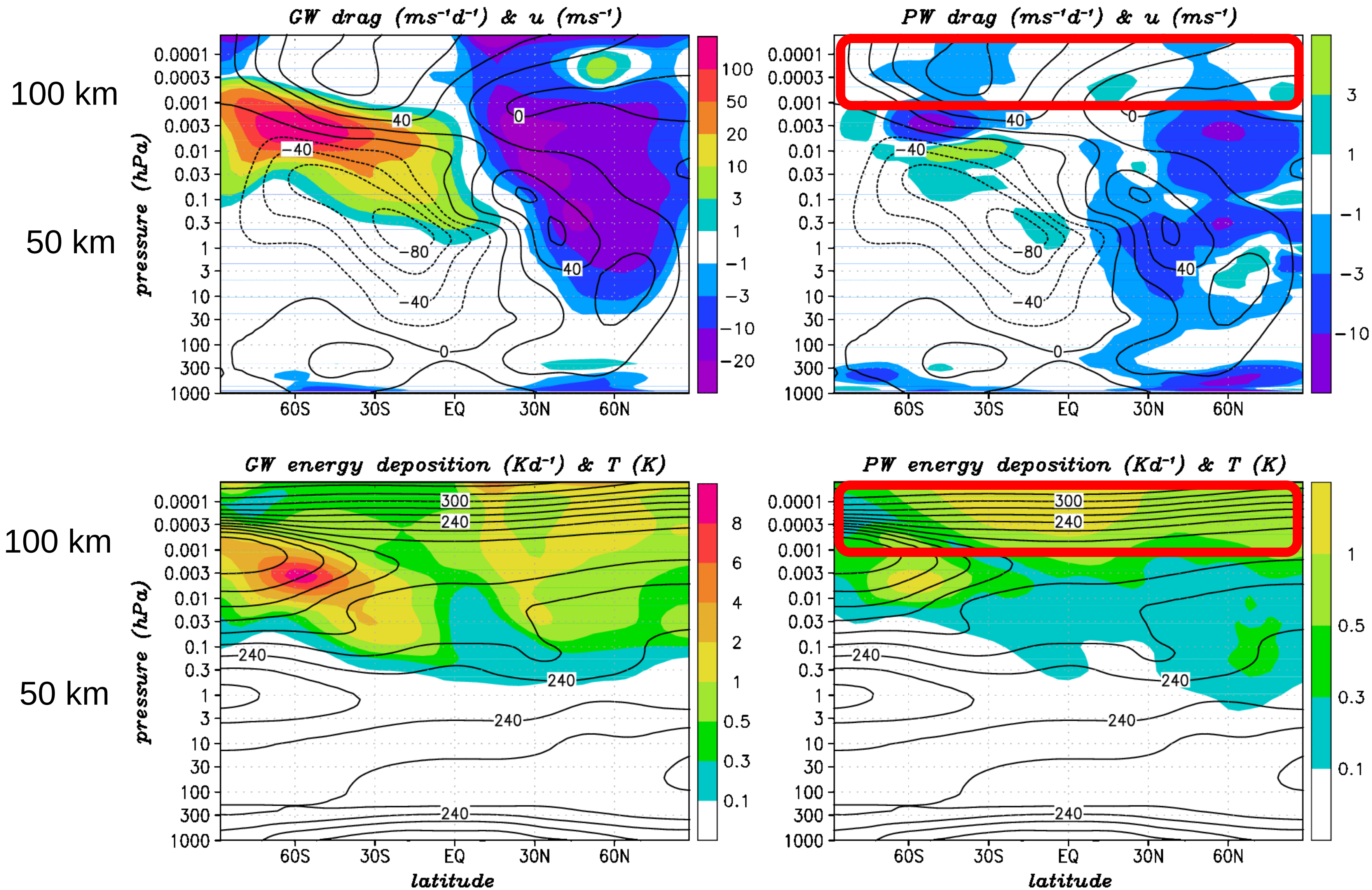
- Since the frictional heating is generally incomplete or flawed in atmospheric circulation models, also the energy deposition of resolved waves propagating from lower to higher altitudes (e.g., thermal tides, Rossby waves) is basically ignored.

The Kühlungsborn Mechanistic general Circulation Model (KMCM) includes subgrid-scale parameterization with consistent energetics.

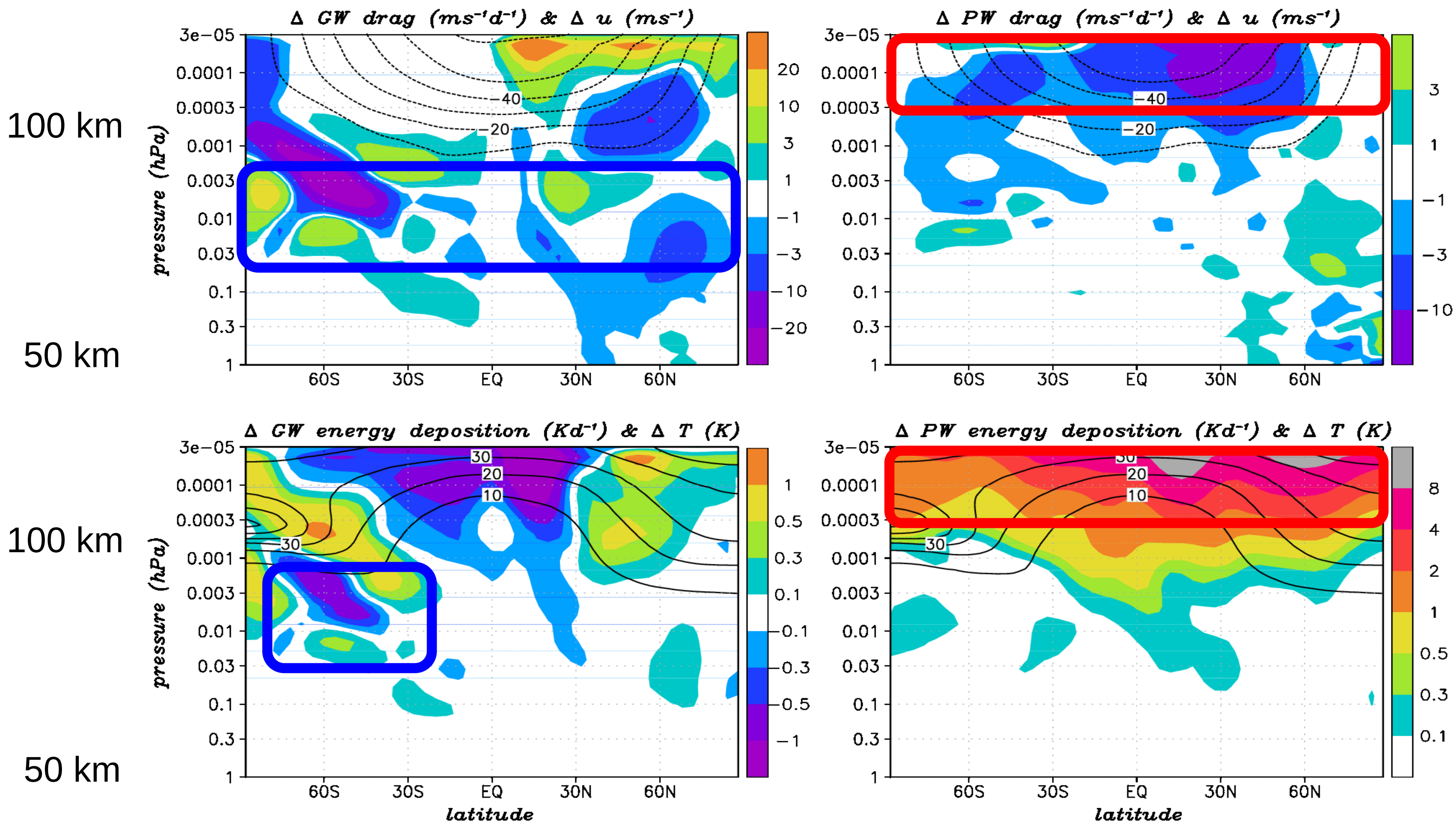
Control simulation



Simulation without tides: $Q_{rad} \rightarrow [Q_{rad}]$



Model response to forcing of thermal tides by short-wave radiation



- downward shift of the mesospheric GW drag and GW energy deposition

- westward acceleration, substanital energy desposition, and poleward circulation cells (maximum heating at high latitudes) in the lower thermosphere

Conclusions and speculation

The periodic Doppler-shifting of zonally propagating GWs due to thermal tides results in a significant downward shift (and reduction per unit mass) of the GW drag and GW energy desposition in the upper mesosphere.

Thermal tides exert a westward drag in the thermosphere, inducing poleward flow and adiabatic heating in the polar lower thermosphere.

The energy deposition of thermal tides is substantial, but basically ignored in GCMs extending into the thermosphere. In the present model it is dominated by frictional heating due to horizontal momentum diffusion.

The relevance of energy (and momentum) deposition in atmospheric flow results from the exponential decrease of density with altitude while the momentum and energy extracted from lower altitudes due to wave generation is negligible. Energy (and momentum) deposition may nevertheless be relevant also in oceanic flow when the wave generation represents a significant wave-mean flow interaction.