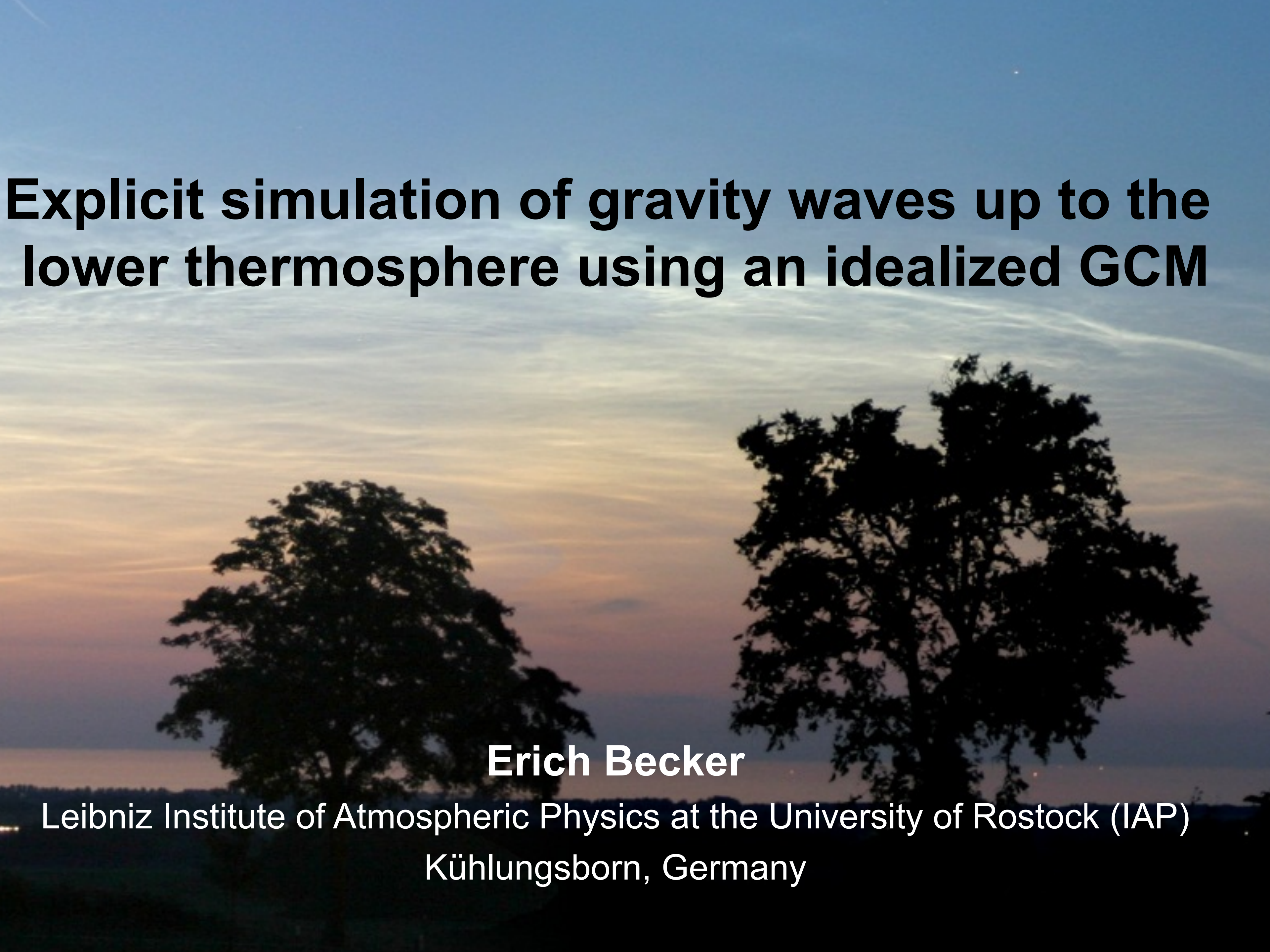

Explicit simulation of gravity waves up to the lower thermosphere using an idealized GCM

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Why a GW resolving GCM?

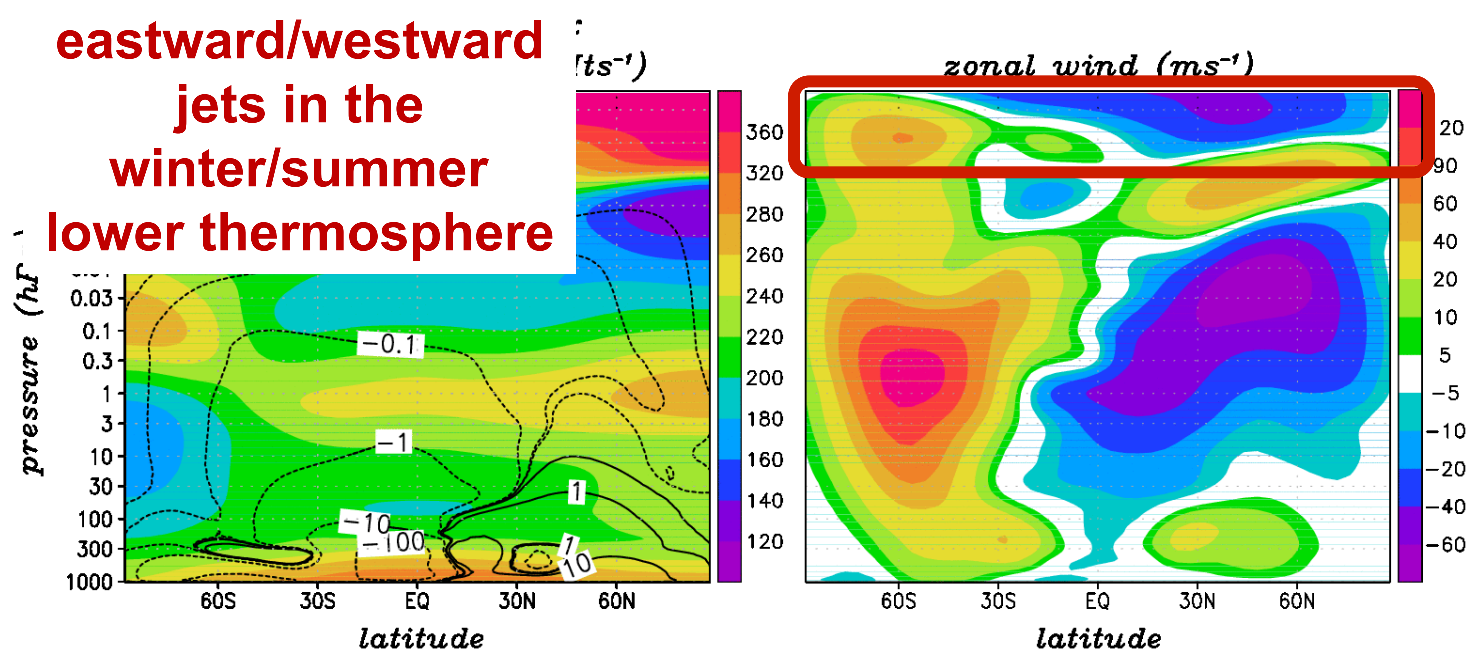
Current GW parameterizations do a good job in providing the GW drag that is required in the mesosphere (non-orographic GWs) and winter stratosphere (orographic GWs), but are subject to the **strong assumptions of single column dynamics and a quasi-stationary GW energy equation**.

- Interaction with resolved waves and parameterized turbulent diffusion is generally questionable.
- Continuous sources for *non-orographic waves* cannot be specified, only *launch-level parameters.*
- Intermittency is difficult to include.
- Parameterized GWs do not participate in the horizontal energy cascade (and in the Lorenz energy cycle).

Kühlungsborn Mechanistic general Circulation Model (KMCM)

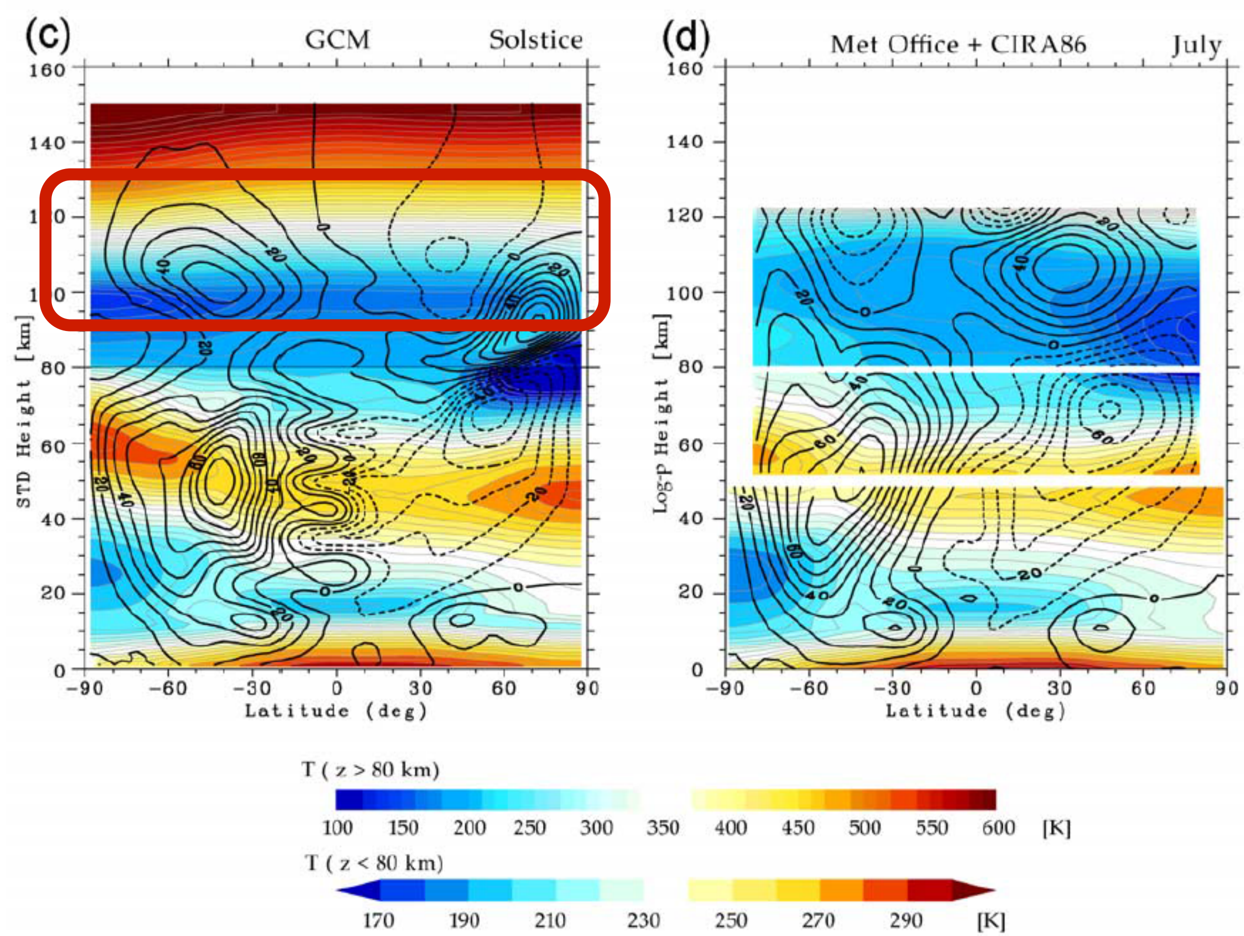
- hydrostatic spectral GCM (Simmons & Burridge, 1981, MWR); T120L190 or T240L190 (up to ~130 km, level spacing ~600 m up to 100 km)
- tracer transport based on the spectral method (Schlutow et al., 2014, JGR)
- radiative transfer and tropospheric moisture cycle, including a slab ocean, land-sea masks (Becker et al., 2015, JASTP); vertically varying heat capacity and gas constant, molecular diffusion, and ion drag
- Smagorinsky-type horizontal and vertical diffusion; both diffusion coefficients depend on the Richardson number; additional linear horizontal diffusion in the lower thermosphere

July climatology

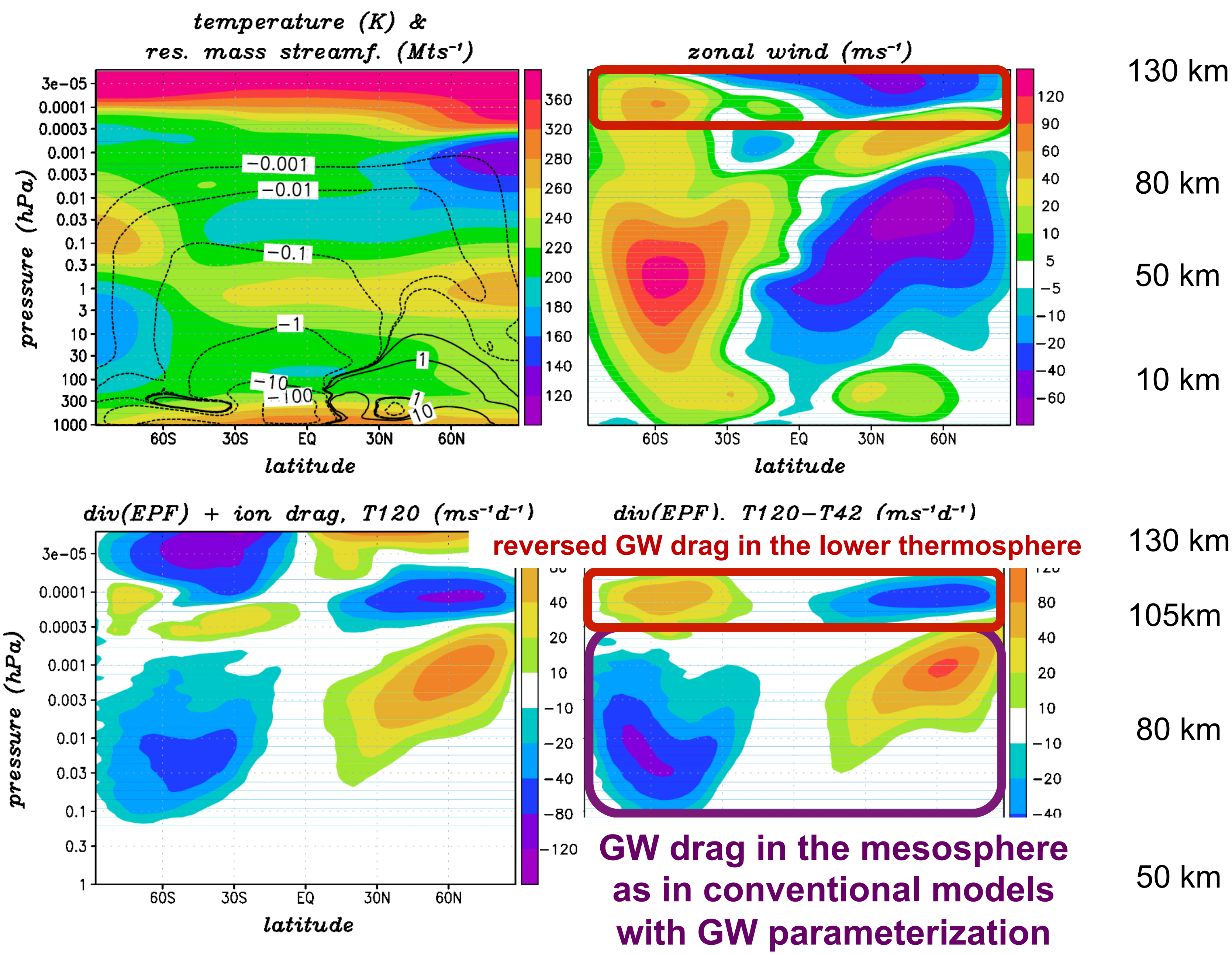


Another GW-resolving GCM with a realistic summer-to-winter-circulation in the upper mesosphere is the vertically extended KANTO model (Watanabe et al., 2008, JGR) called JAGUAR (Watanabe and Miyahara, 2009, JGR) which is a fully comprehensive spectral GCM with T213L270 resolution.

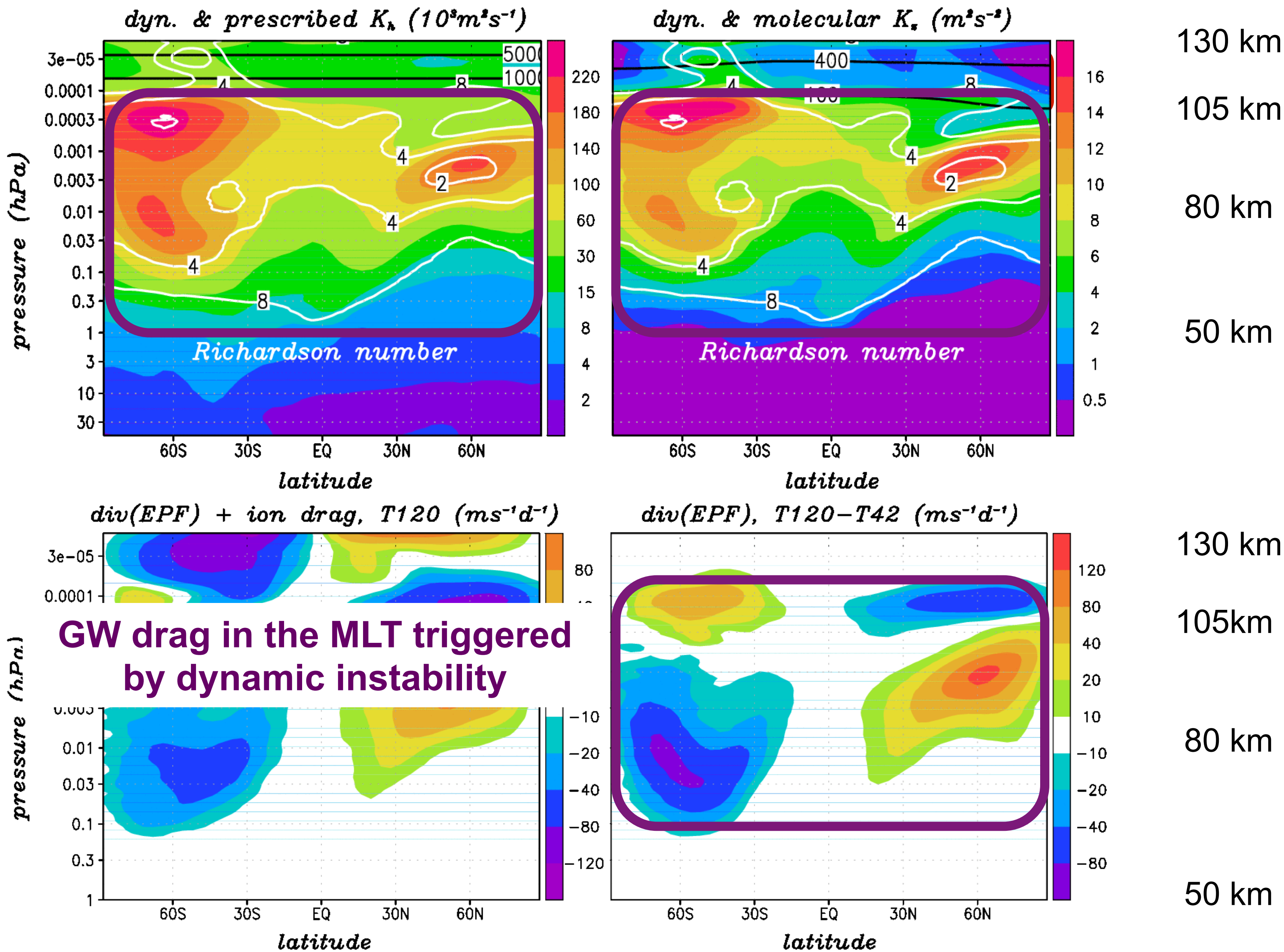
eastward/westward jets in the winter/summer lower thermosphere



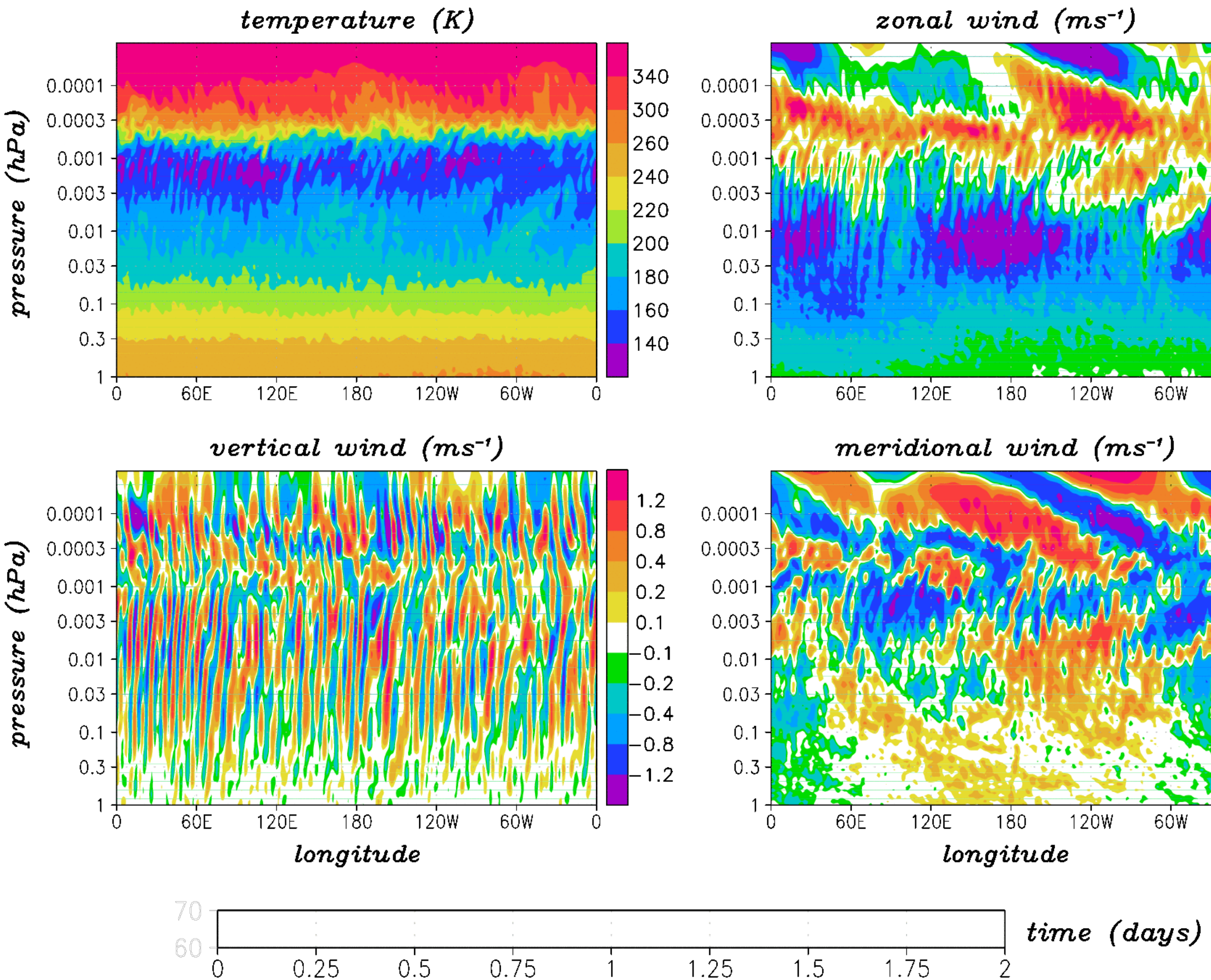
Zonal-mean climatology and wave driving, July, KMCM T120L190



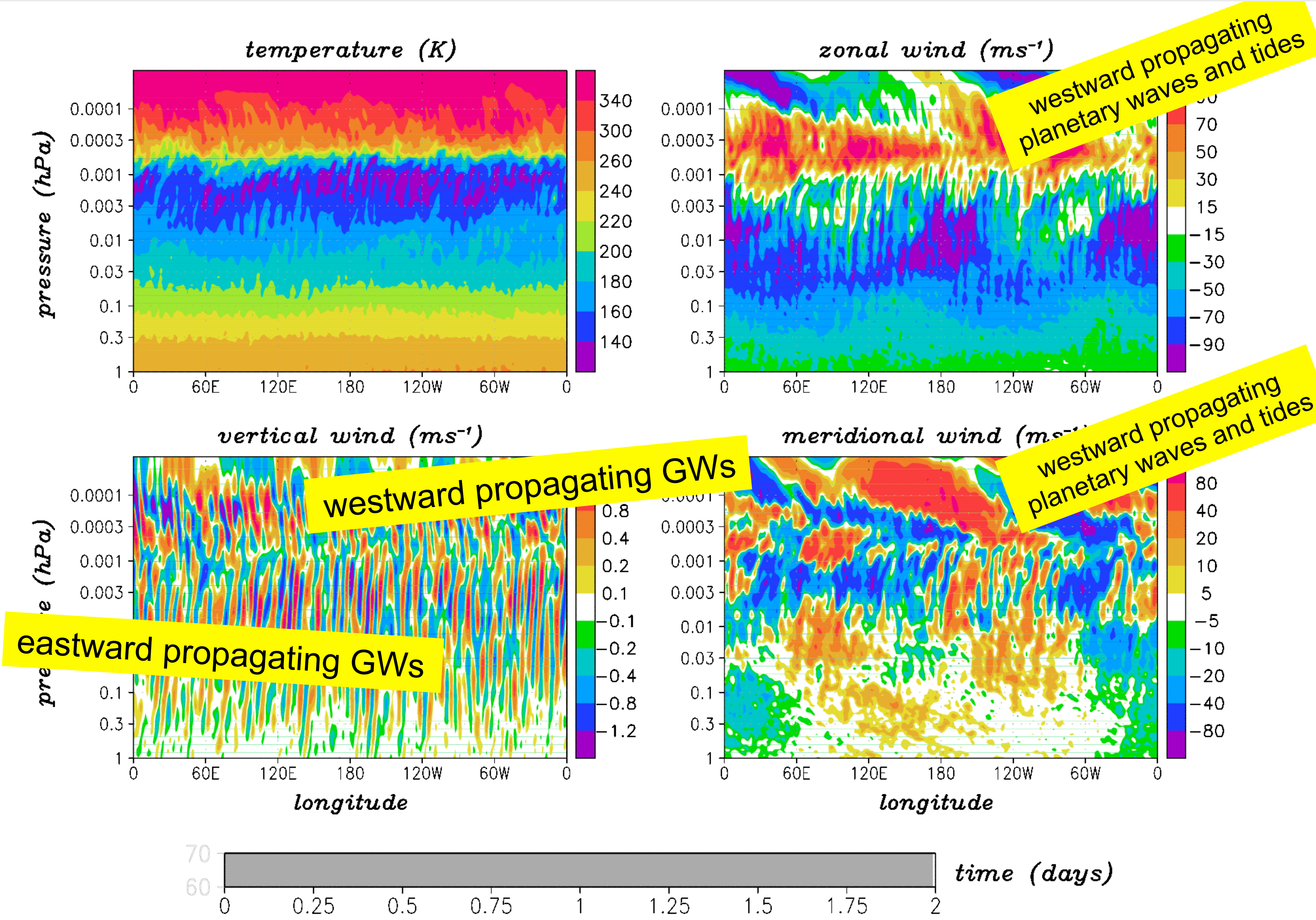
Diffusion scheme and wave driving, July, KMCM T120L190



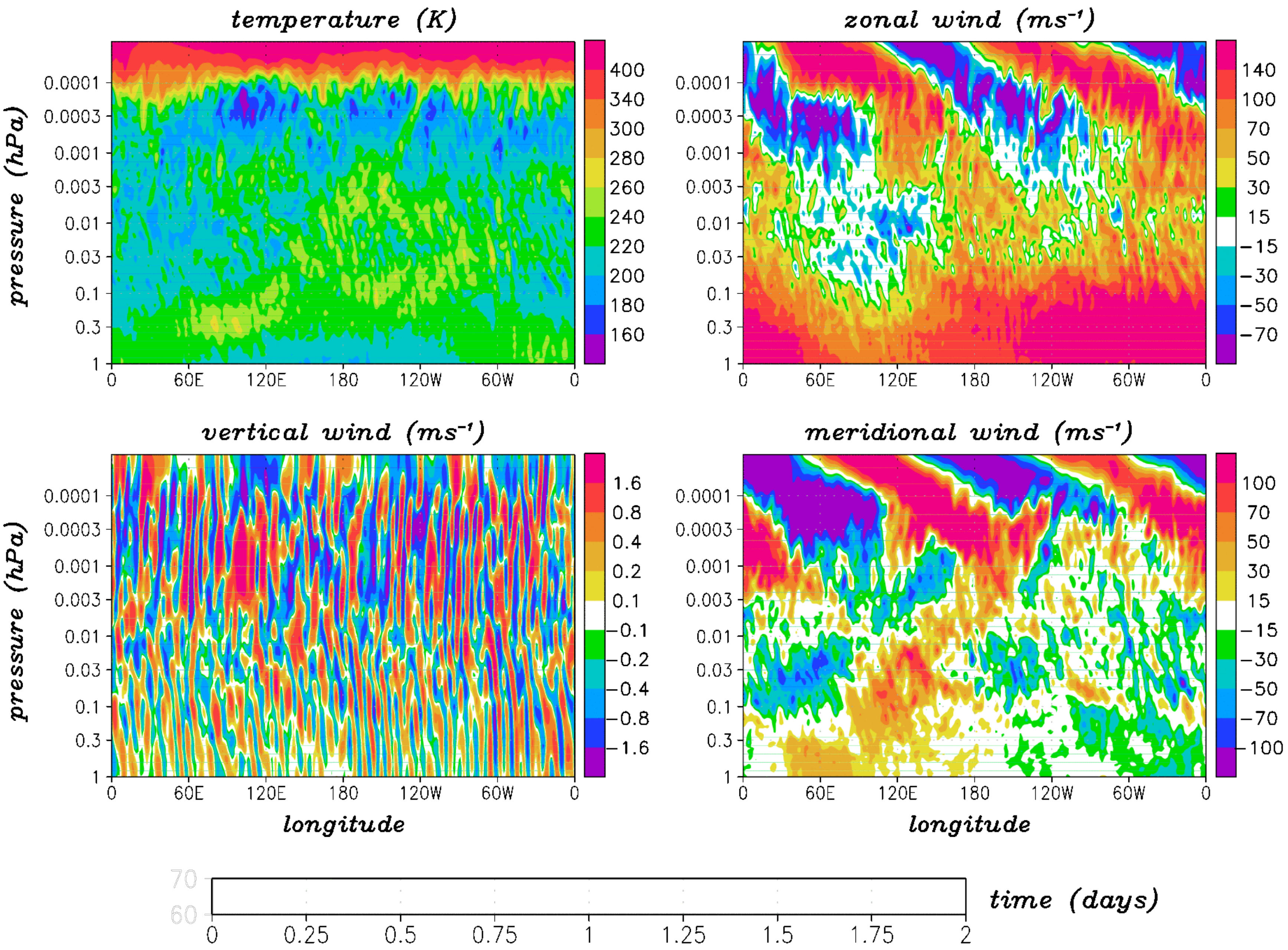
Variability in the MLT at 55°N during July



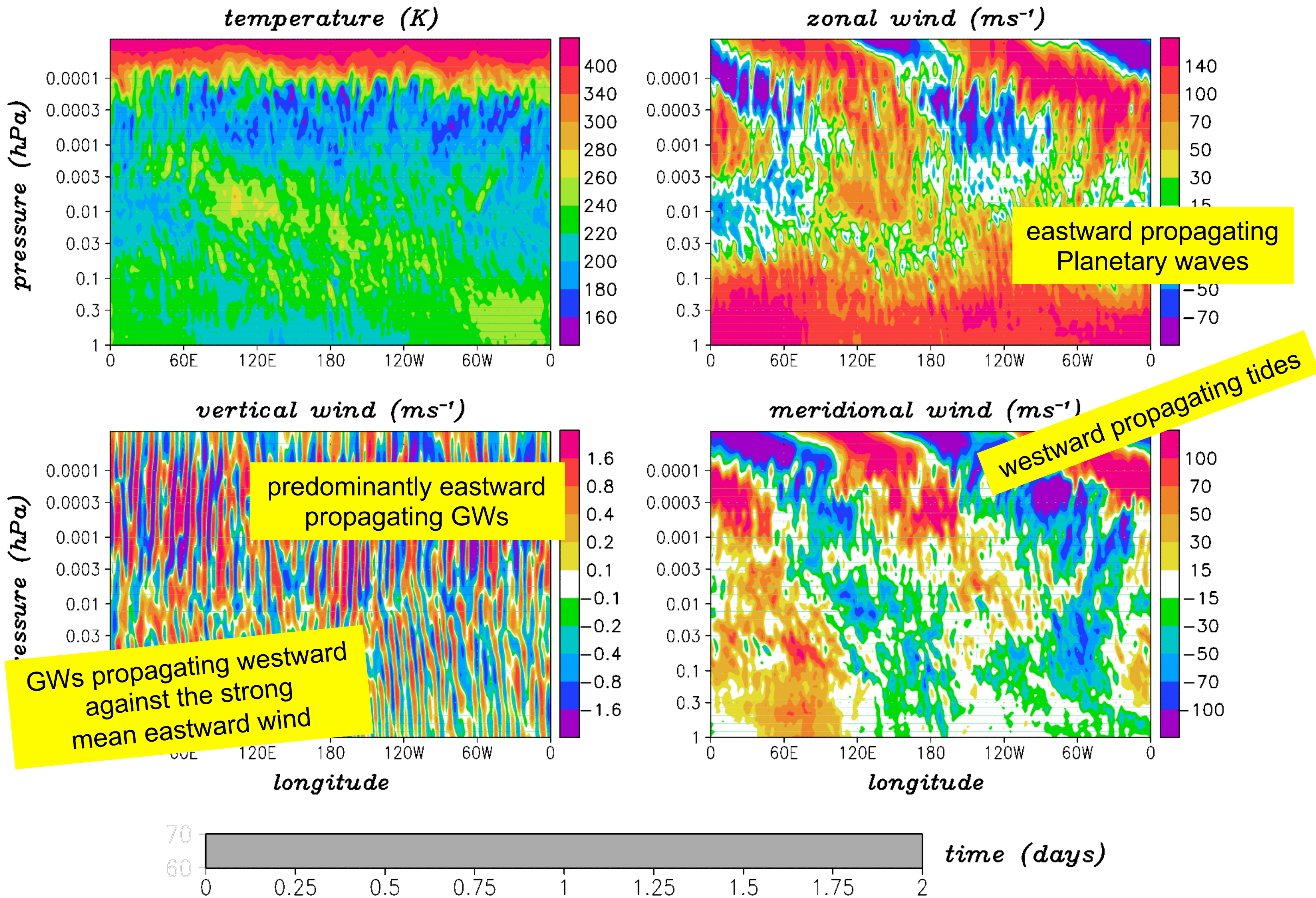
Variability in the MLT at 55°N during July



Variability in the MLT at 55°S during July



Variability in the MLT at 55°S during July



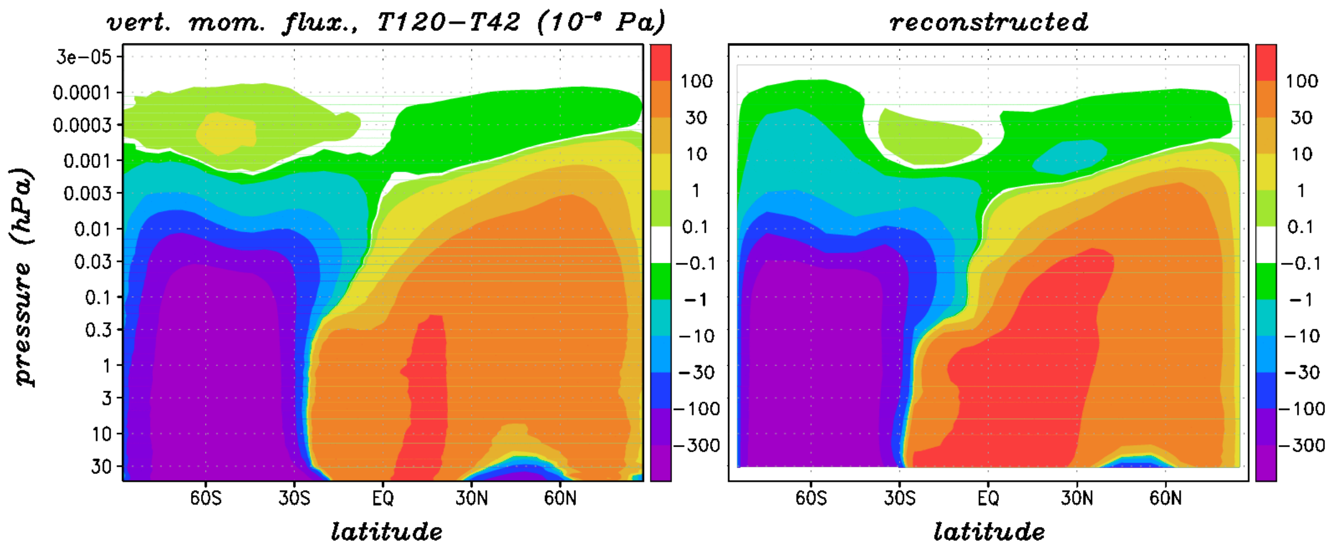
Simple wavenumber-frequency analysis to explore the nature of the reversed GW momentum flux in the lower thermosphere: Secondary GWs?

Assumptions: Zonal propagation, mid-frequency approximation

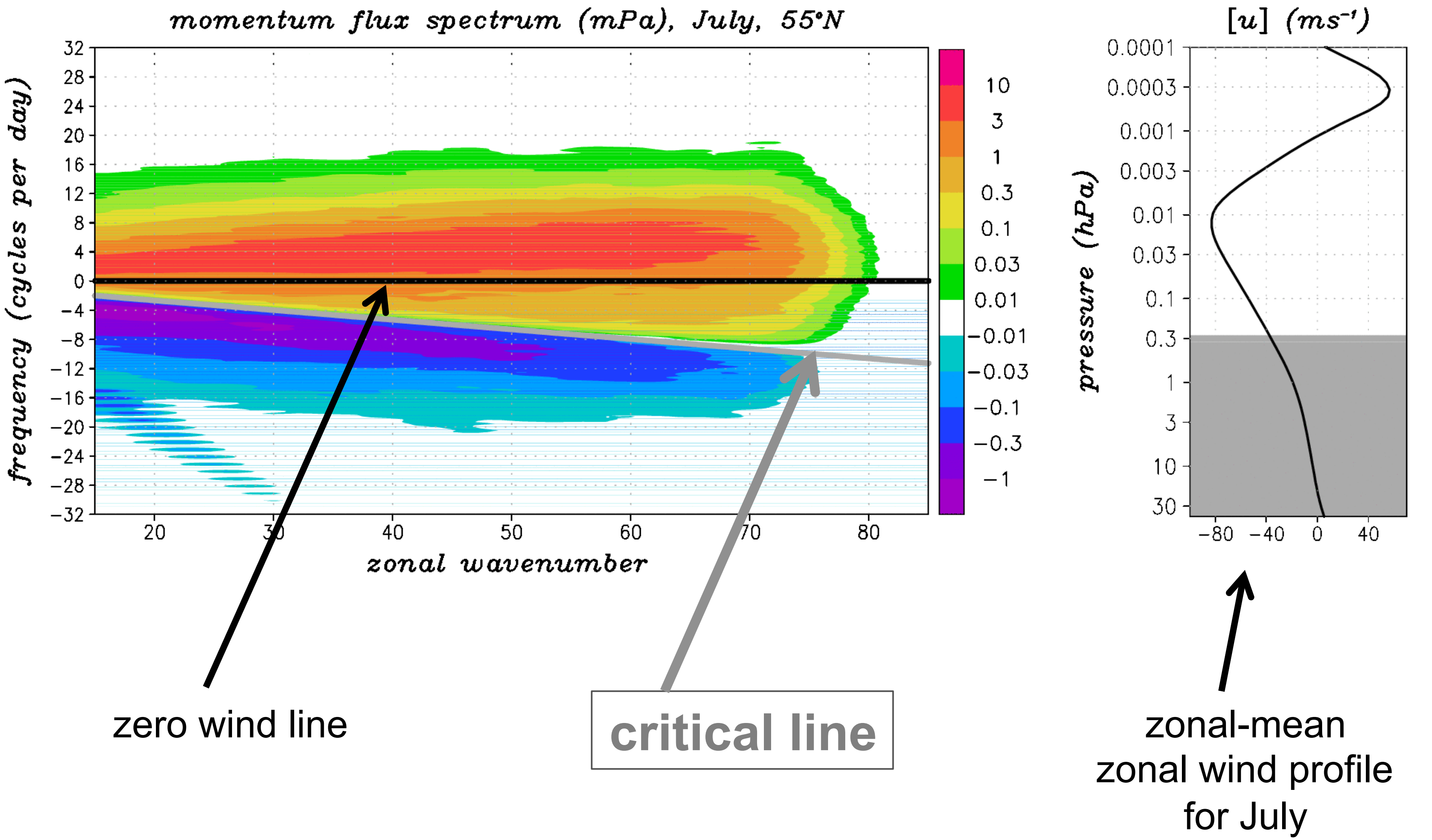
(It's better to be approximately right than precisely wrong)

$$
\begin{aligned}
u' &= \mathrm{Re}\left(\sum_m \sum_j \hat{u}_{mj}(\phi,p)\, \mathrm{e}^{i(m\lambda-\omega_j t)}\right) \\
w' &= -\mathrm{Re}\left(\frac{m}{a\cos\phi}\,\frac{U-c_{mj}(\phi)}{N}\sum_m \sum_j \hat{u}_{mj}(\phi,p)\, \mathrm{e}^{i(m\lambda-\omega_j t)}\right) \\
c_{mj}(\phi) &= \omega_j\, a \cos\phi \,/\, m
\end{aligned}
$$

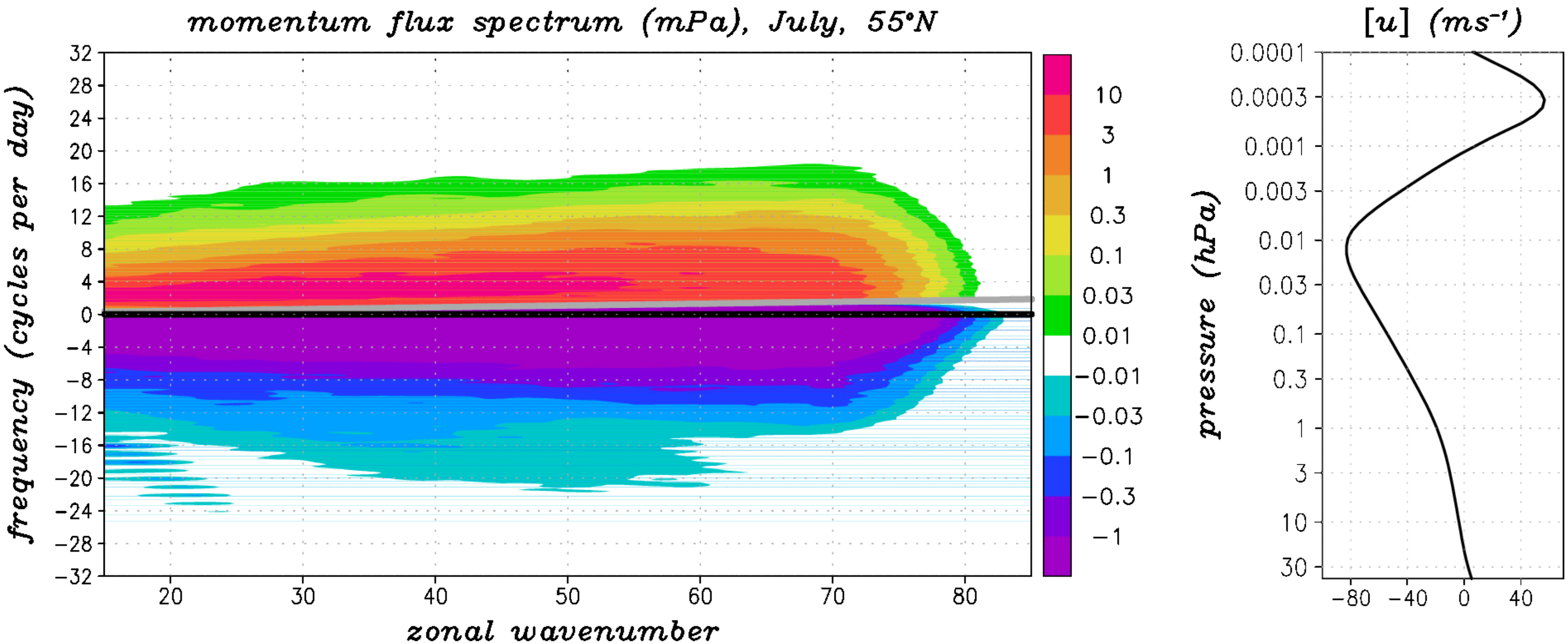
$$
\boxed{\rho\,\overline{u'w'} = -\frac{\rho}{2}\sum_m \sum_j \frac{m}{a\cos\phi}\,\frac{U-c_{mj}(\phi)}{N}\,\left|\,\hat{u}_{mj}(\phi,p)\,\right|^2}
$$



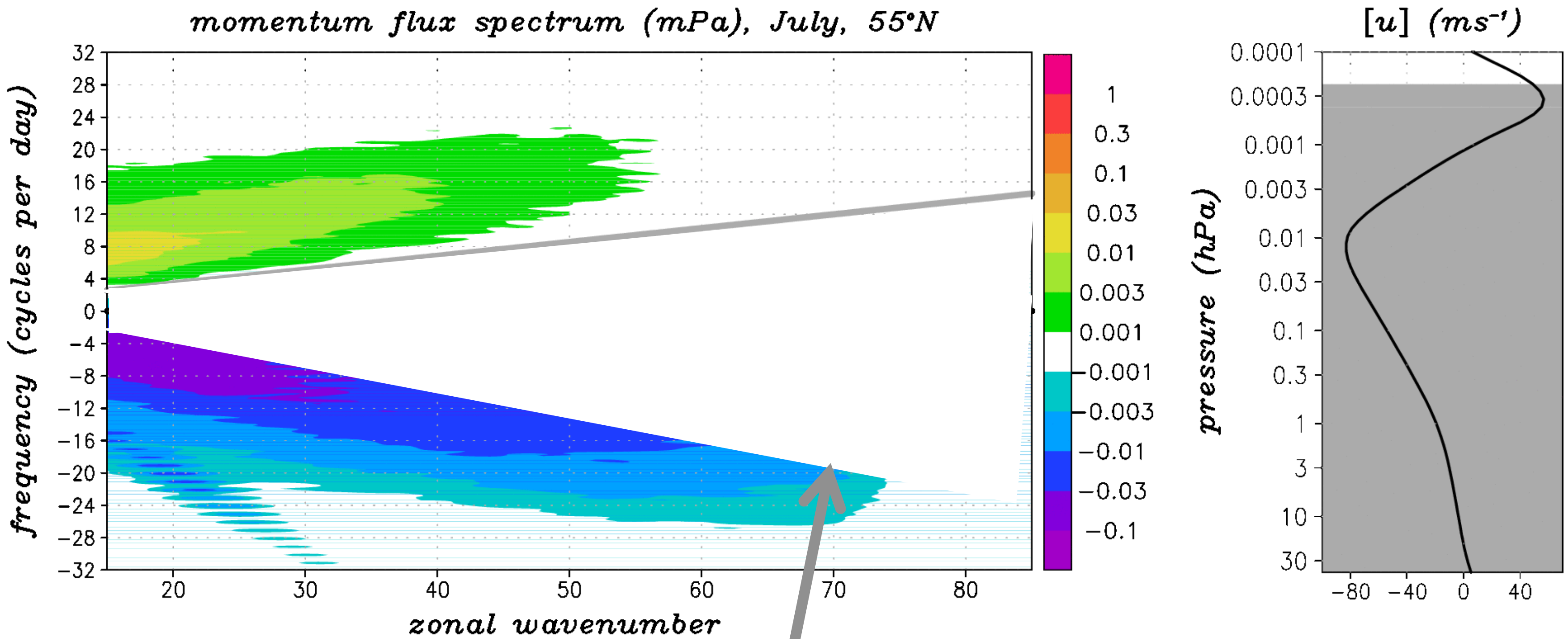
Vertical evolution of the GW momentum flux spectrum (July, 55°N)



Vertical evolution of the GW momentum flux spectrum (July, 55°N)



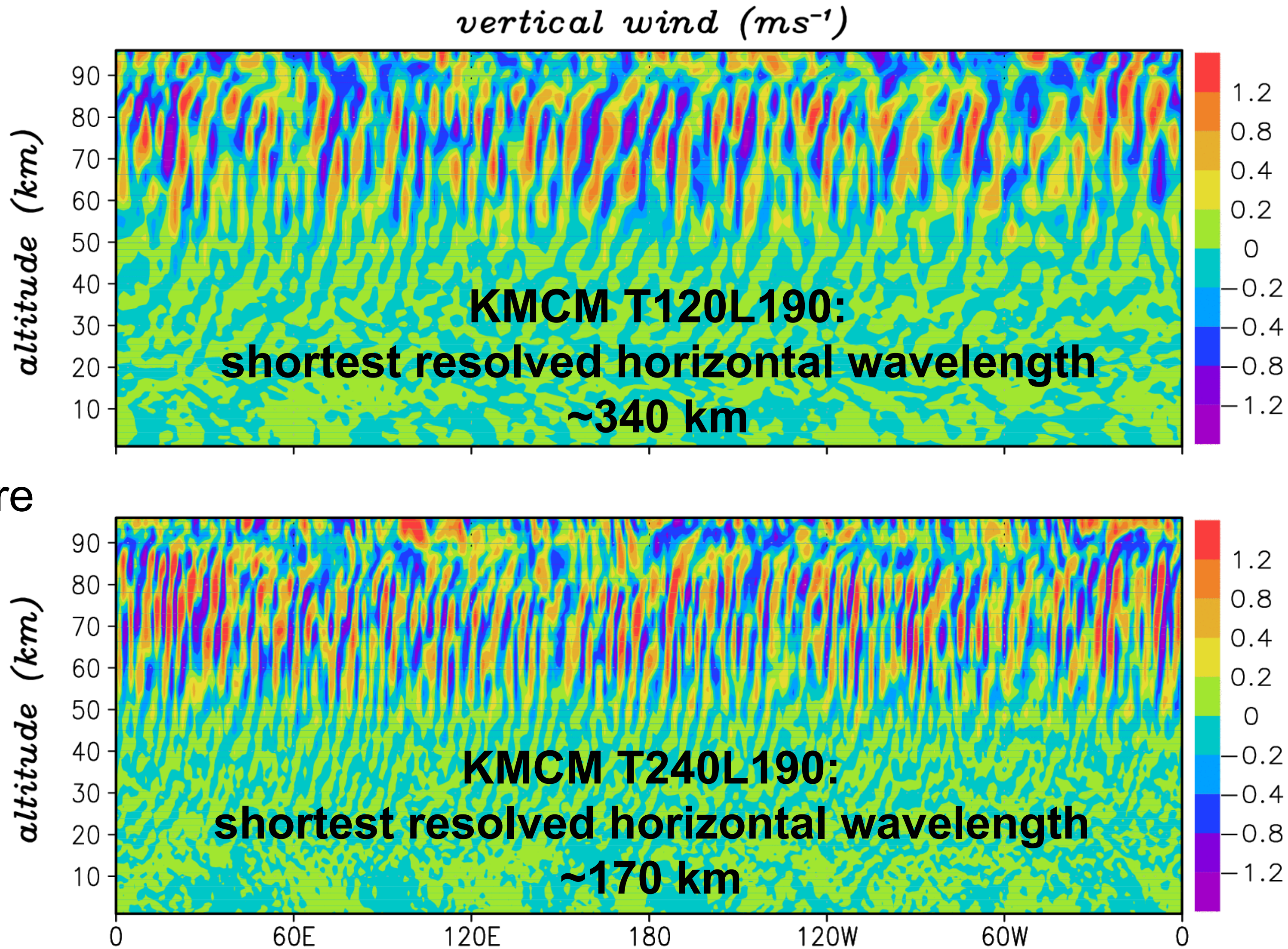
Vertical evolution of the GW momentum flux spectrum (July, 55°N)



GW modes supposed to be absorbed at critical levels

Resolution dependence of the simulated GW scales (former model version)<

summer
hemisphere
55°



For higher resolution, the simulated gravity waves have smaller spatial scales (and higher frequencies).

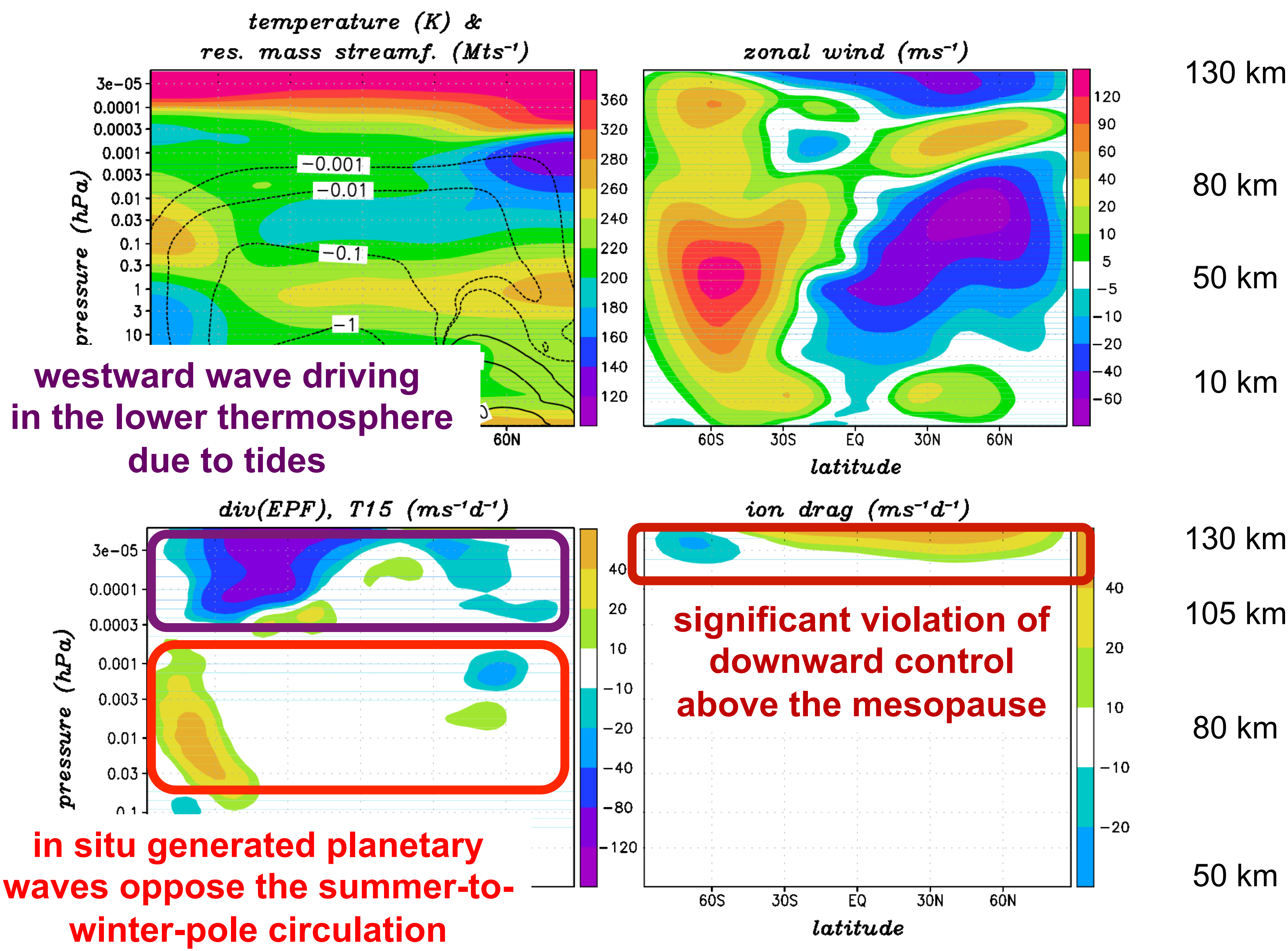
Conclusions

- A GW-resolving (spectral) GCM with a Smagorinsky-type diffusion scheme that adjusts to dynamic instability (for vertical and horizontal diffusion) yields realistic non-orographic GW drag in the MLT.

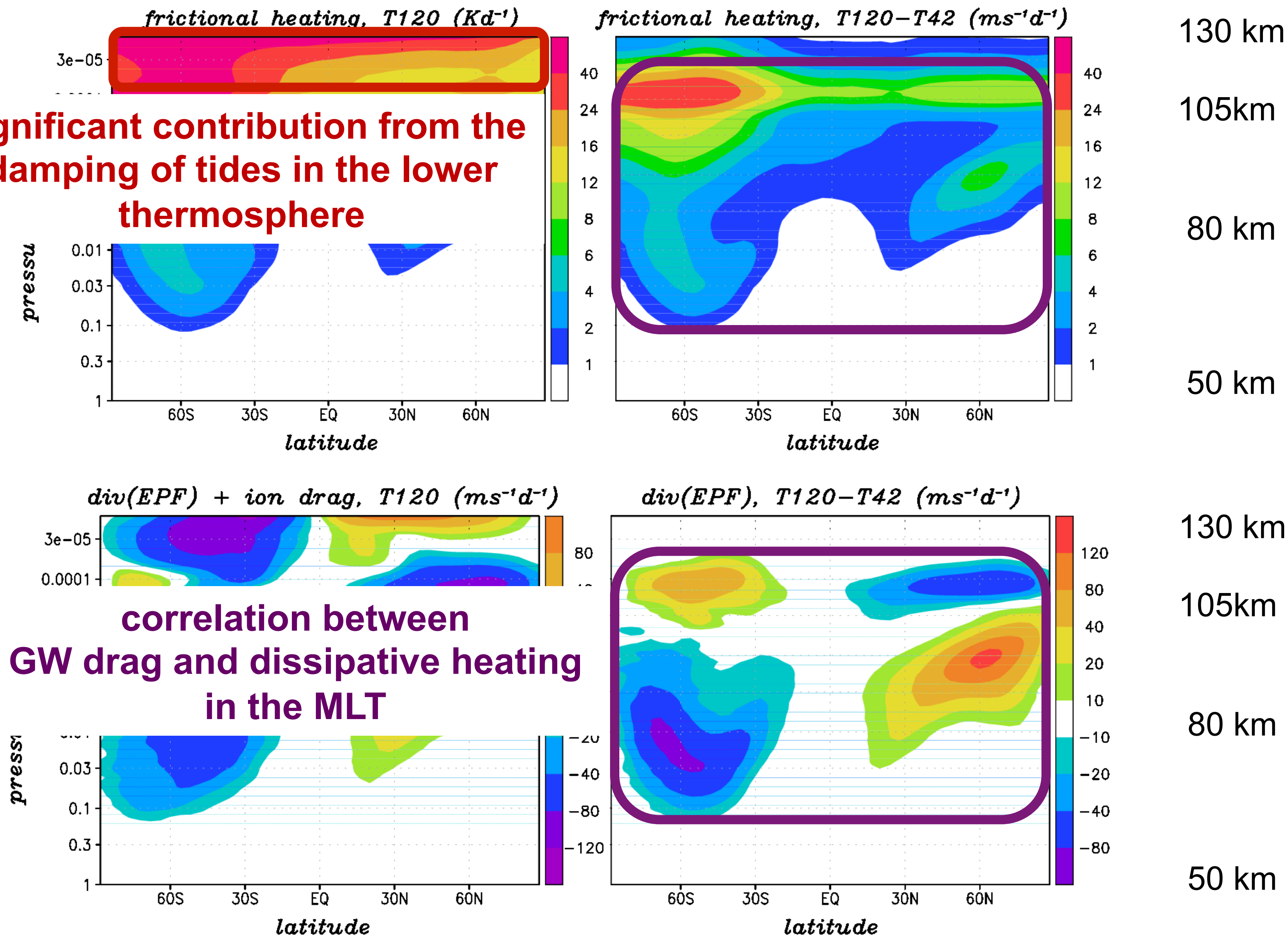
- **GW attenuation at critical levels at lower altitudes where the GW amplitudes are small is not resolved for a vertical level spacing of a few 100 m.** The simulated reversal of the momentum flux above the mesopause is spurious.

- The simulated GW scales are resolution-dependent (general issue of non-convergence of circulation models with respect to numerical resolution).

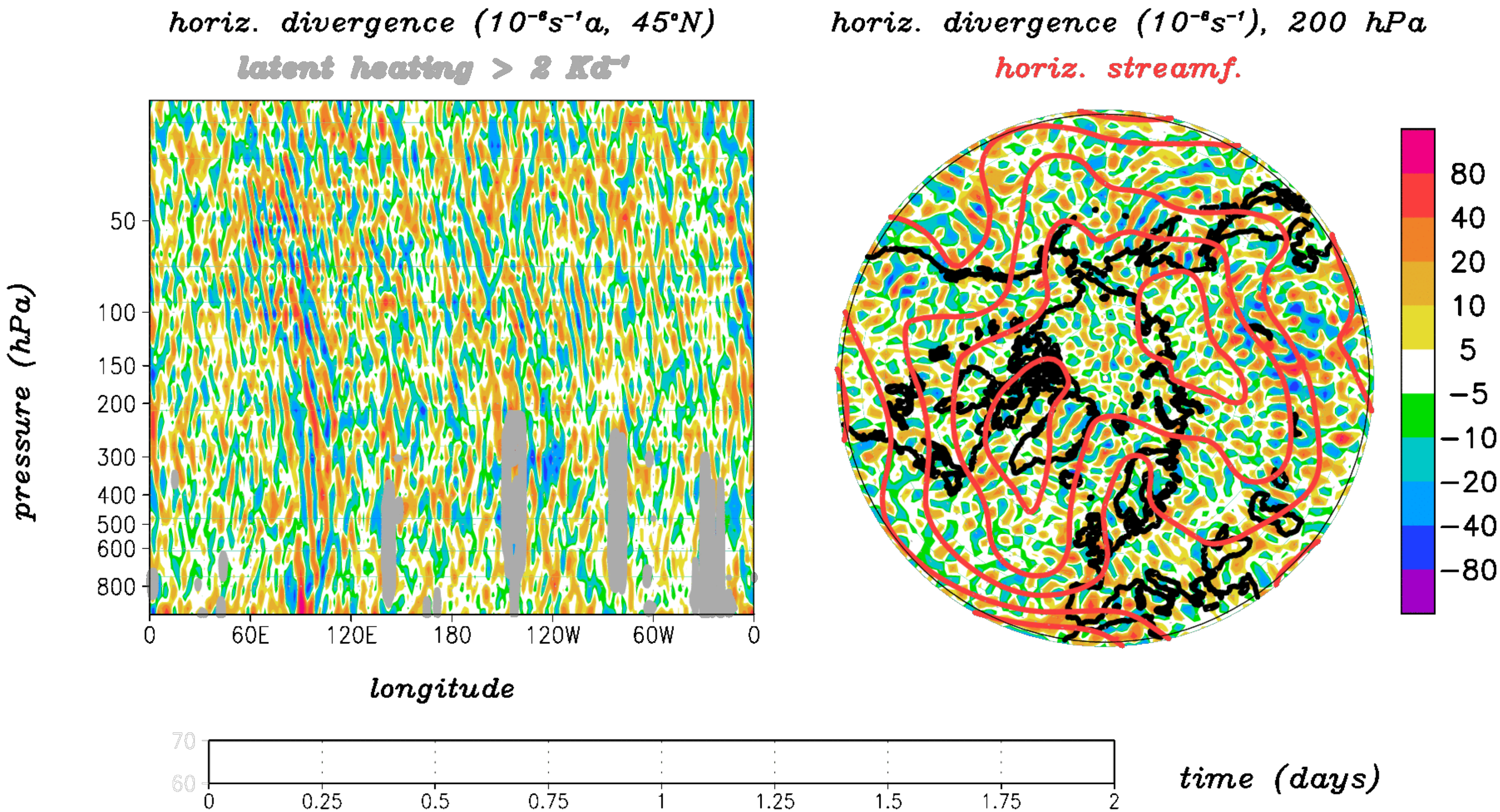
Zonal-mean climatology and wave driving, July, KMCM T120L190



Frictional heating and wave driving, July, KMCM T120L190



Tropospheric GW activity:
Arbitrary 2-day time interval during July



Subgrid-scale diffusion: Classical anisotropic Smagorinsky Model extended by a Richardson criterion (Becker, 2009, JAS)

$$(\partial_t \mathbf{v})_{diff} = \rho^{-1} \nabla_h (\rho K_h \mathbf{S}_h) + \rho^{-1} \partial_z (\rho K_z \partial_z \mathbf{v})$$

$$\mathbf{S}_h = \{ (\nabla + \mathbf{e}_z / a) \circ \mathbf{v} \} + \{ (\nabla + \mathbf{e}_z / a) \circ \mathbf{v} \}^T - \mathbf{1} \nabla \cdot \mathbf{v}$$

$$(\partial_t c_p T)_{diff} = \frac{c_p}{\rho} \nabla_h (\rho K_h \nabla_h T) + \frac{c_p}{\rho} \partial_z (\rho \frac{T}{\Theta} K_z \partial_z \Theta) + K_h | \mathbf{S}_h |^2 + K_z (\partial_z \mathbf{v})^2$$

$$K_h = l_h^2 |\mathbf{S}_h| (1 + \alpha F(R_i)) \gg K_z = l_z^2 |\partial_z \mathbf{v}| F(R_i)$$

$$F(R_i) = \begin{cases} \sqrt{1 - 18 R_i} & R_i < 0 \\ (1 + 9 R_i)^{-1}, & R_i \geq 0 \end{cases}$$

$$R_i = N^2 / (\partial_z \mathbf{v})^2 \quad \rightarrow \quad R_i - \frac{1}{4} \quad \text{for} \quad p < 100\,\text{hPa}$$

3 free parameters: 2 mixing lengths and α (Prandtl numbers are assumed to be 1)

Dynamical Smagorinsky Model
(Schaefer-Rolffs et al-, 2014, Met. Z.)

$$(\partial_t \mathbf{v})_{diff} = \rho^{-1}\nabla_h(\rho K_h \mathbf{S}_h) + \rho^{-1}\partial_z(\rho K_z \partial_z \mathbf{v})$$

$$\mathbf{S}_h = \{(\nabla + \mathbf{e}_z/a)\circ \mathbf{v}\} + \{(\nabla + \mathbf{e}_z/a)\circ \mathbf{v}\}^T - \mathbf{1}\,\nabla\cdot\mathbf{v}$$

$$(\partial_t c_p T)_{diff} = \frac{c_p}{\rho}\nabla_h\left(\rho\frac{T}{\Theta}K_{h\Theta}\nabla_h\Theta\right) + \frac{c_p}{\rho}\partial_z\left(\rho\frac{T}{\Theta}K_{z\Theta}\partial_z\Theta\right) + K_h|\mathbf{S}_h|^2 + K_z(\partial_z\mathbf{v})^2$$

$$K_h = l_h^2|\mathbf{S}_h| \gg K_z = l_z^2|\partial_z\mathbf{v}|$$

$$\tilde{X} = \text{average of } X \text{ over the smallest resolved scales}$$

$$l_h^2 = \left|\widetilde{\mathbf{v}\circ\mathbf{v}} - \tilde{\mathbf{v}}\circ\tilde{\mathbf{v}} - \frac{1}{2}\mathbf{1}(\widetilde{\mathbf{v}^2} - \tilde{\mathbf{v}}^2)\right|\,\left|\left(\frac{\tilde{\Delta}}{\Delta}\right)^2|\widetilde{\mathbf{S}_h}|\widetilde{\mathbf{S}_h} - |\widetilde{\mathbf{S}_h|\mathbf{S}_h}\right|^{-1}$$

$$l_z \propto l_h^{1/3}$$

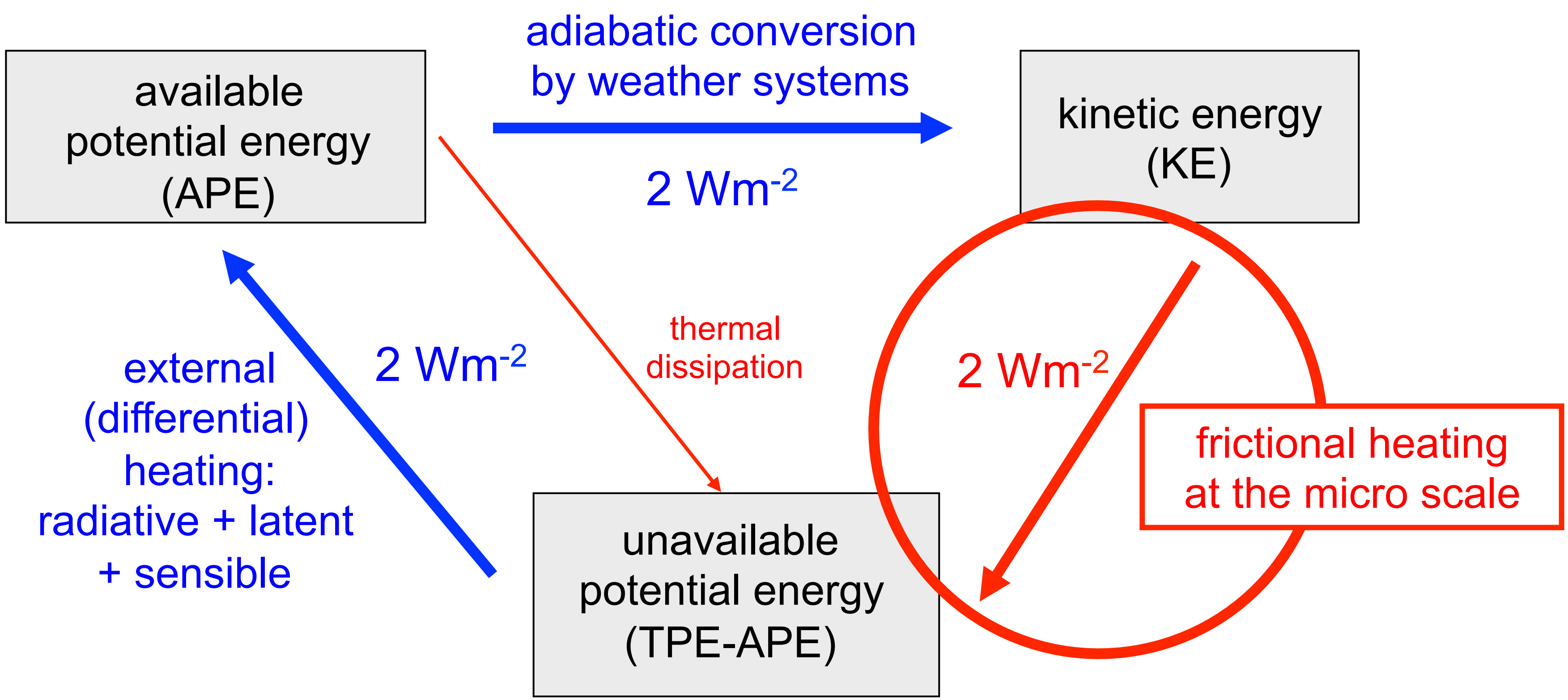
$$K_{h\Theta} = l_{h\Theta}^2|\mathbf{S}_h| \gg K_{z\Theta} = l_{z\Theta}^2|\partial_z\mathbf{v}|$$

free parameters:
grid scale, filter scale, …

$$l_{h\Theta}^2 = \left|\widetilde{\Theta\mathbf{v}} - \tilde{\Theta}\tilde{\mathbf{v}}\right|\,\left|\left(\frac{\tilde{\Delta}}{\Delta}\right)^2|\widetilde{\mathbf{S}_h}|\,\widetilde{\nabla\Theta} - |\widetilde{\mathbf{S}_h|\,\nabla\Theta}\right|^{-1}$$

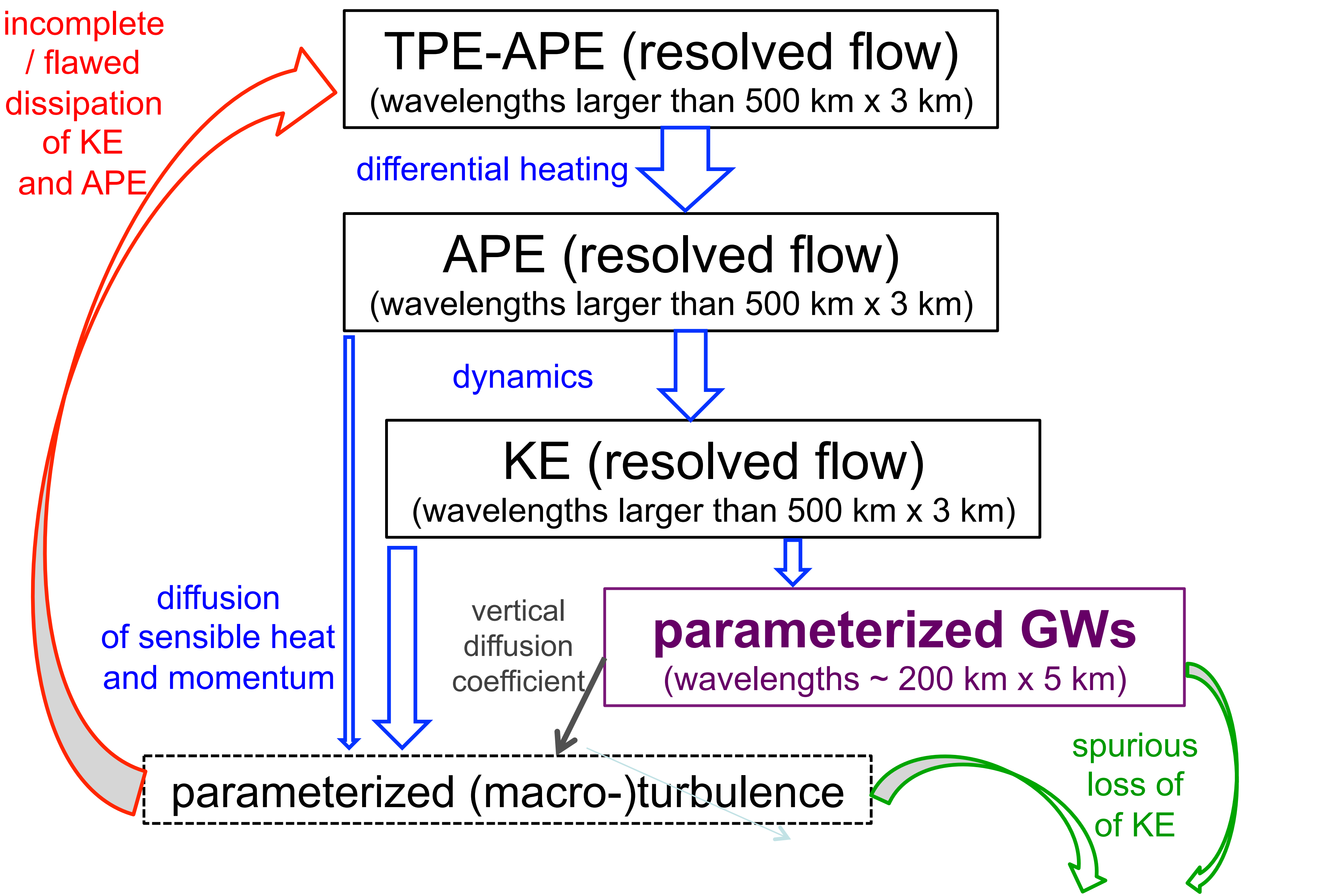
$$l_{z\Theta} \propto l_{h\Theta}^{1/3}$$

Lorenz energy cycle

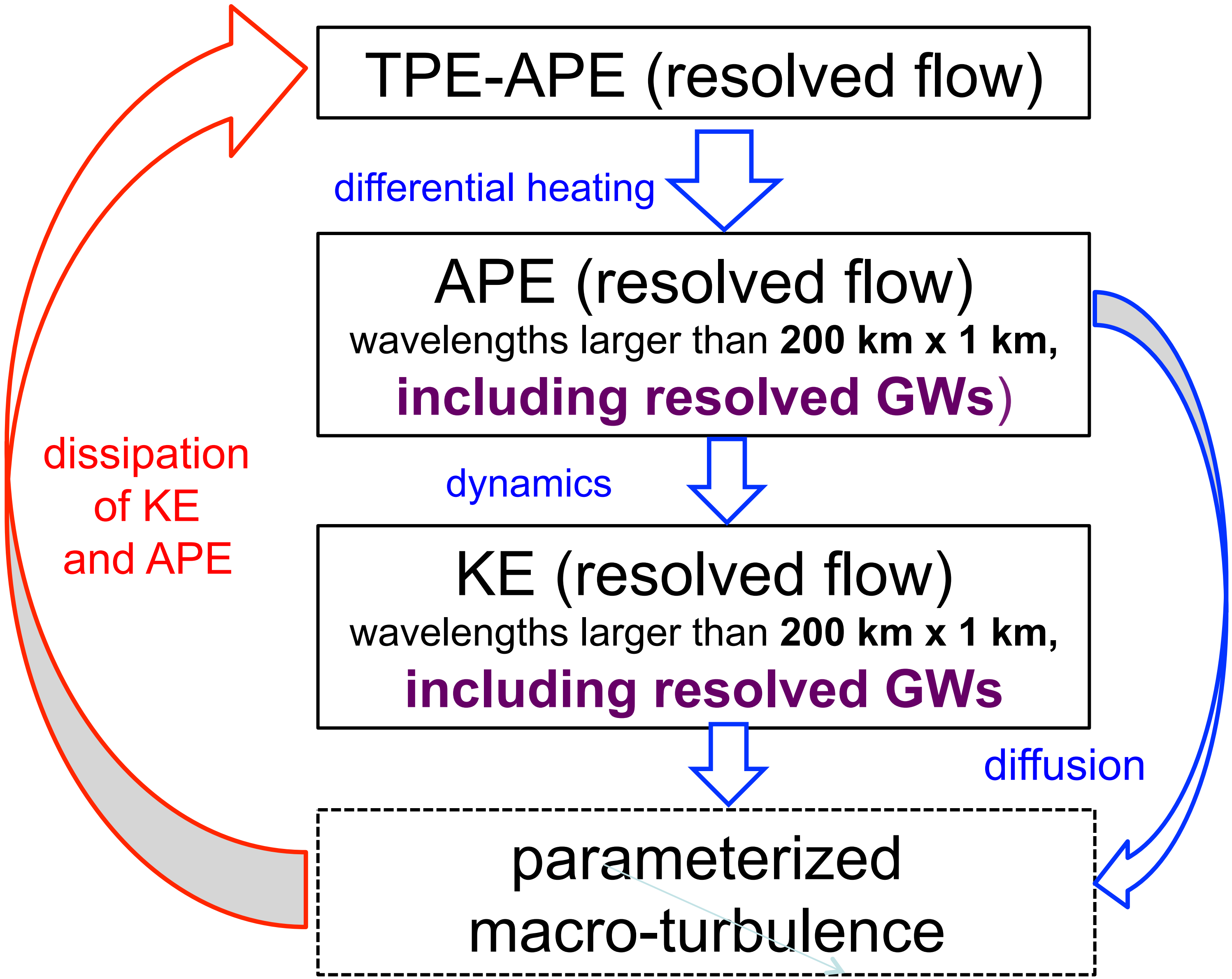


- frictional heating essential for entropy and energy budgets:
  net diabatic heating of the atmosphere = frictional heating (Lorenz, 1967)
- frictional heating occurs at the end of energy cascades through the mesoscales (including GWs) and turbulence
- relative importance of thermal dissipation?

Energy transfers in conventional atmospheric models



Energy transfers in a GW-resolving GCM with consistent subgrid-scale diffusion

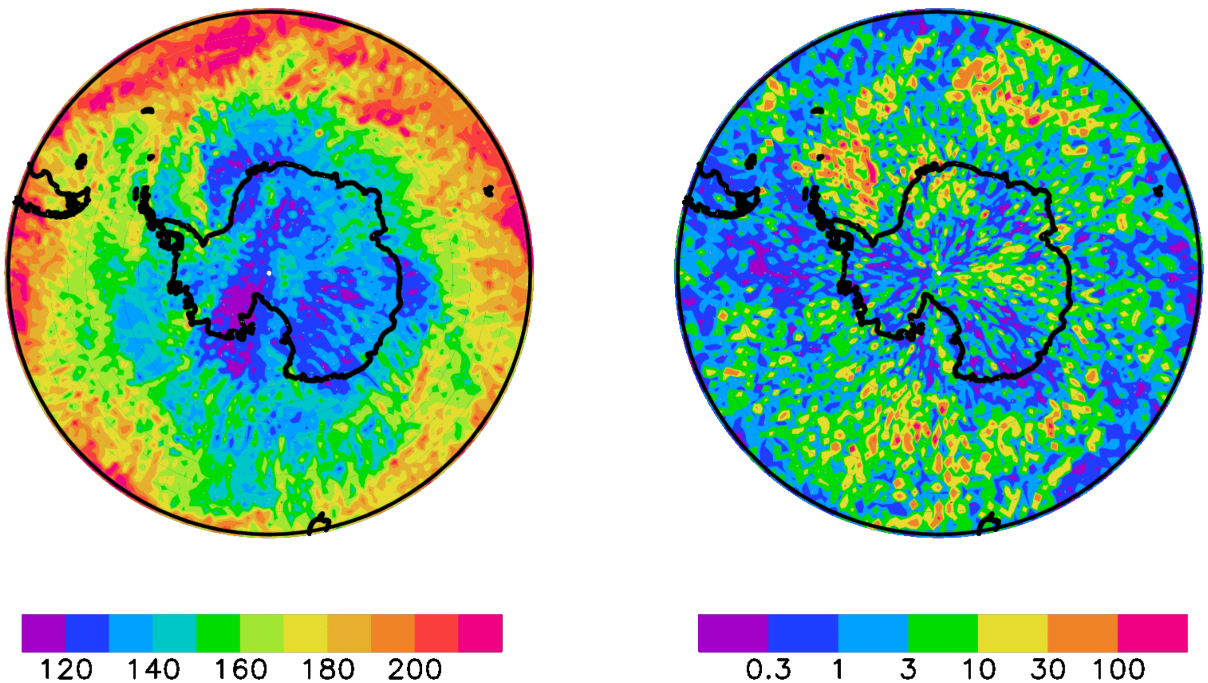


Why a gravity-wave resolving GCM?

GW parameterizations miss elementary aspects of the mesoscales in the real atmosphere:

- Wave effects are highly intermittent (temporally and spatially)

snapshot of temperature (K) and dissipation (K/d) around 85 km (January)



- **Parameterized GWs do not participate in the horizontal energy cascade, nor do they participate in the Lorenz energy cycle** (except for the surface friction due to orographic GWs).