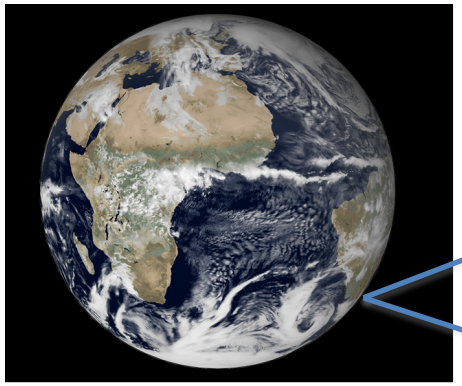
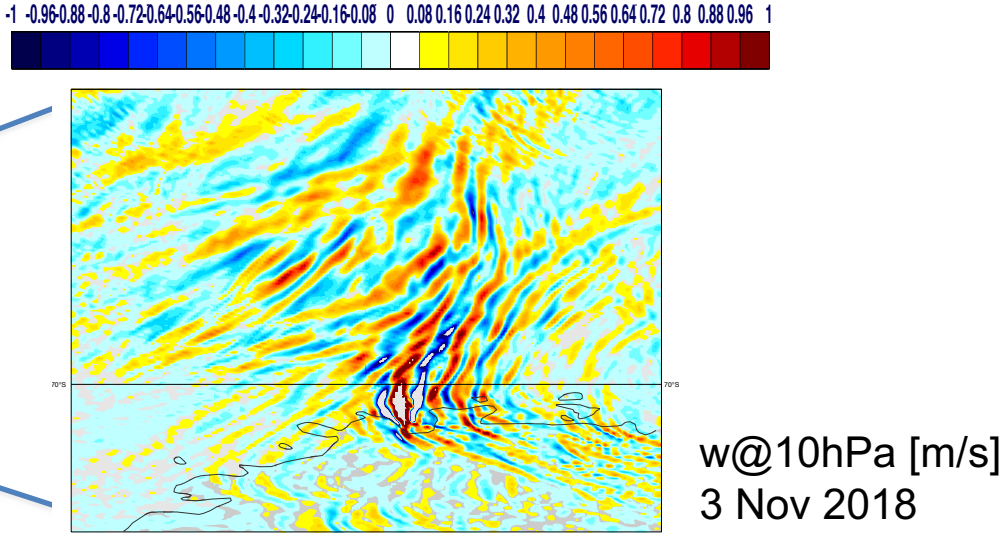
Resolved gravity waves in the stratosphere: Impact of horizontal resolution increase from O(10 km) to O(1 km)





w@10hPa [m/s]
3 Nov 2018

Inna Polichtchouk, Nils Wedi,
Young-Ha Kim, Annelize van Niekerk

ECMWF Annual Seminar, 12-16 Sep 2022

ECMWF | OAK RIDGE National Laboratory | LEADERSHIP COMPUTING FACILITY | JOHANN WOLFGANG GOETHE UNIVERSITÄT FRANKFURT AM MAIN | Met Office

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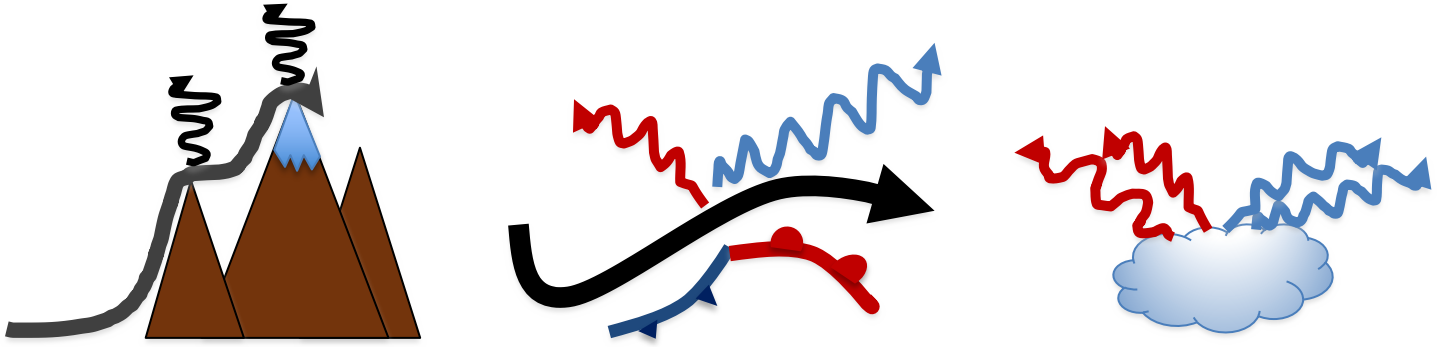
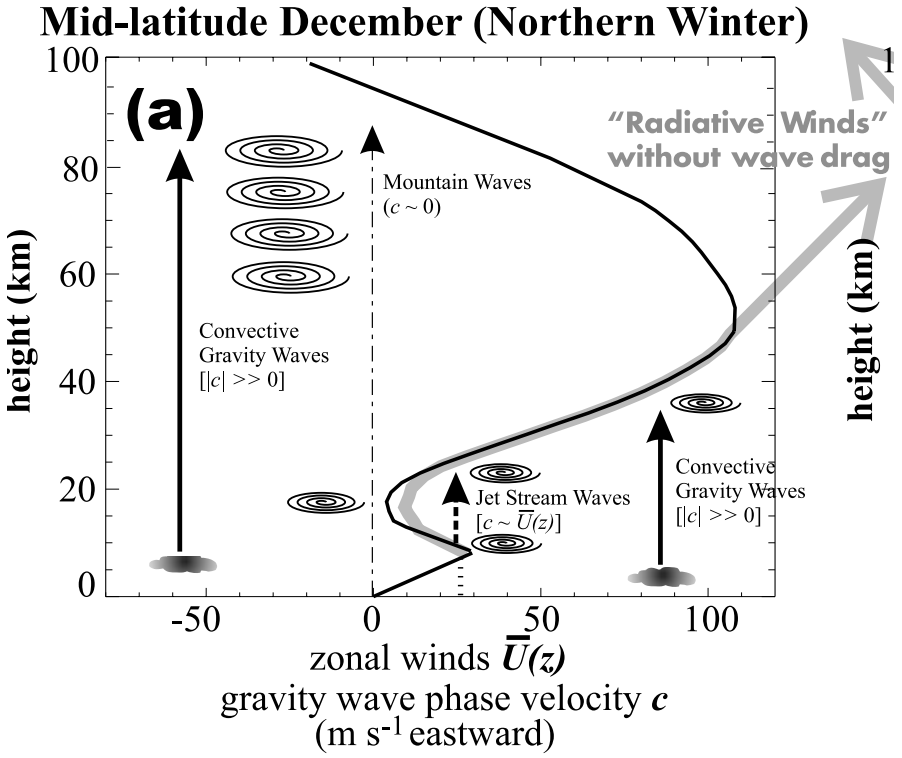
Background: Gravity waves

- GWs exist in any medium where density decreases with height. Restoring force gravity.
- Atmospheric GWs can be generated via different mechanisms, such as flow over orography, deep convective plumes and jets/fronts.
- Background wind and temperature determine generation, propagation and dissipation.
- In the stratosphere, horizontal wavelengths 10 km <λ_h < 3000 km → Resolution of most global models too coarse to represent the whole GW spectrum explicitly (also true for obs!) → **Parametrizations** of GWs needed.

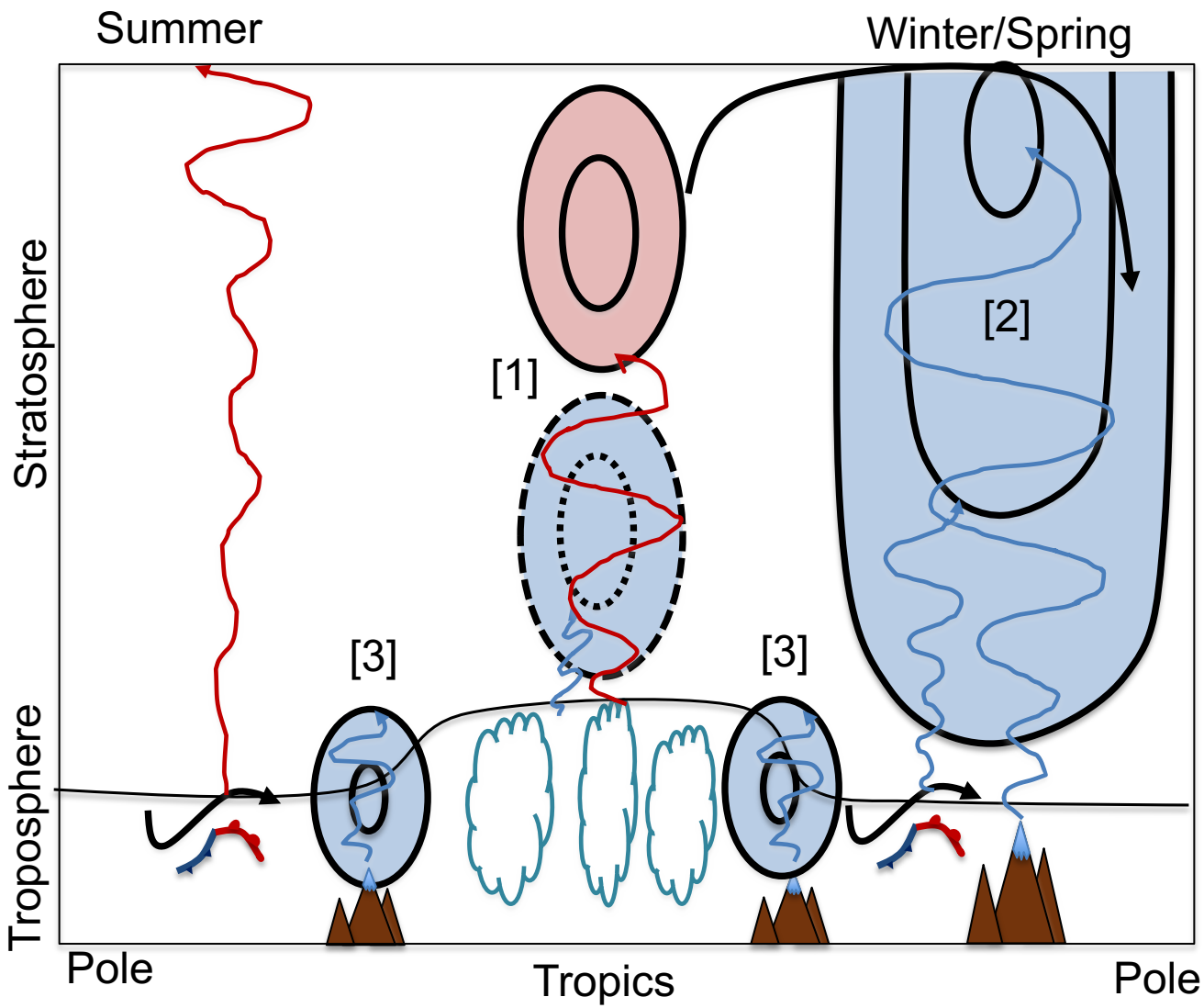




Kim et al. 2003

Background: Importance of GWs

$$\overline{u}_t = \overline{v}^*[f - (a\cos\phi)^{-1}(\overline{u}\cos\phi)_\phi] - \overline{w}^*\overline{u}_z + (\rho a\cos\phi)^{-1}\nabla\cdot\mathbf{F} + \frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho\overline{u'w'}\right) + \overline{X}$$



GWs:

[1] Are important drivers of the westerly and the easterly phases of the **QBO**.

[2] Contribute to the deceleration of the **polar night jet** (especially in the spring season) and to polar-cap downwelling.

[3] Contribute to the deceleration of the **sub-tropical jets**.

→ GWs affect stratospheric circulation & variability, which can impact surface weather.

→ Important to represent accurately in NWP models.

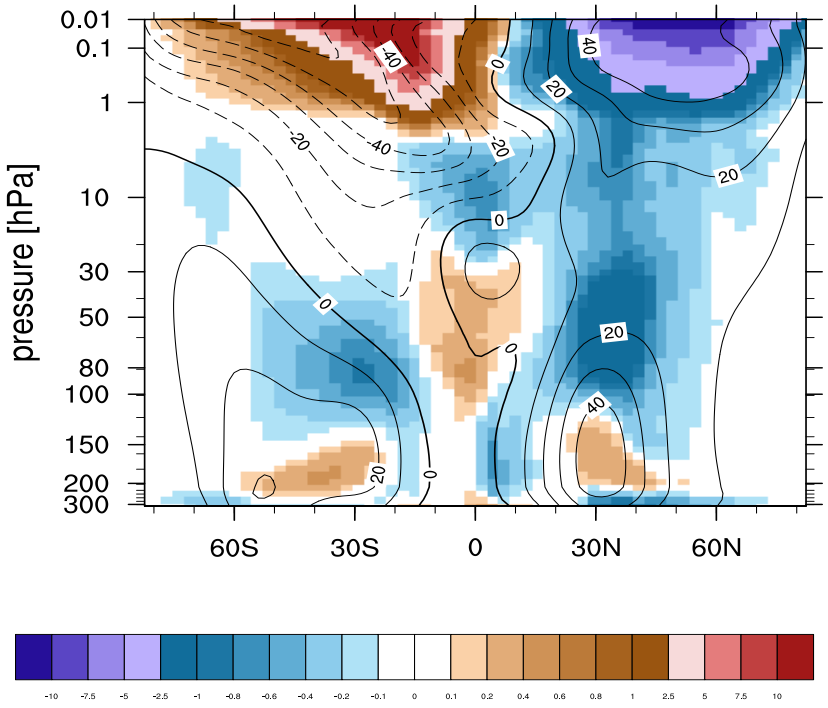
Gravity waves in models

Overarching questions:

- At what horizontal resolutions do we expect to resolve the whole of GW spectrum?
- Do we need to continue to parametrize GW forcing at 3-5 km grid-spacings?

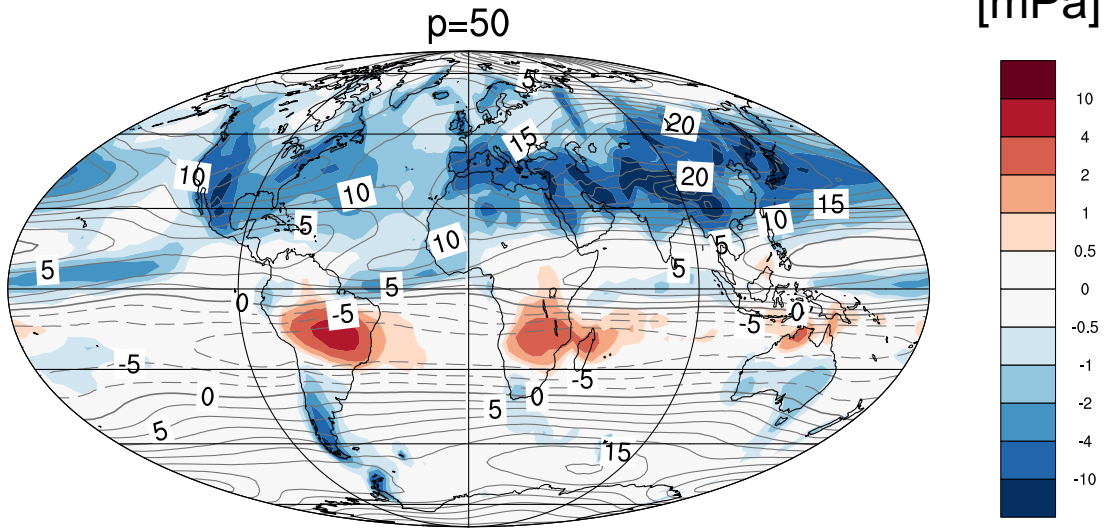
Tool: Nov-Feb 2018/2019 global (hydrostatic!?) simulations with ECMWF IFS at 1 km horizontal grid-spacing (TCo7999). Resolves most GW spectrum.

$$\frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho\overline{u'w'}\right)$$



[m/s/day]

$$\overline{\rho}\ (\overline{u'w'})$$



Method

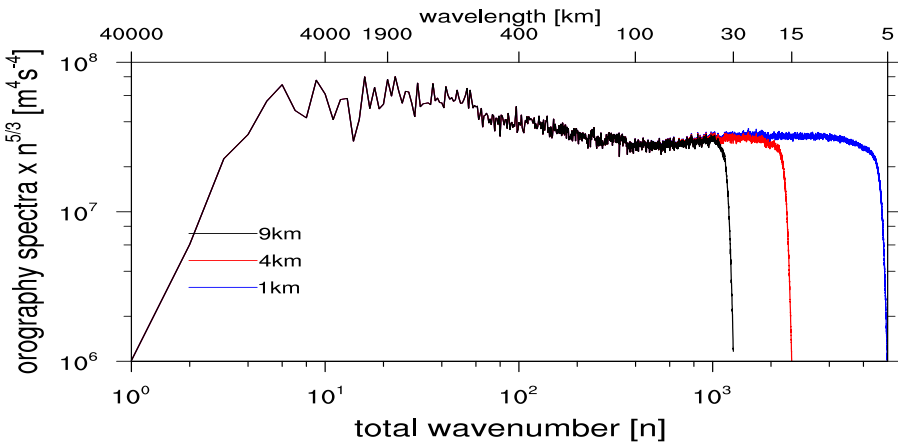
- Compare IFS simulations at 1km, 4km (TCo2559) and 9km (TCo1279) horizontal grid-spacing for **Nov 2018** to assess how GW forcing changes from O(10 km) to O(1 km) grid-spacing.

- Examine zonal GWF for the first 15 days, from 3-hrly fields. Primes T>21.

  GWF = $\mathrm{g}\frac{\partial}{\partial p}(\rho\overline{u'w'})$

  and assess contribution to GWF of large-scale waves with 100<λ_h<2000 km vs. smaller-scale waves with λ_h <100 km.

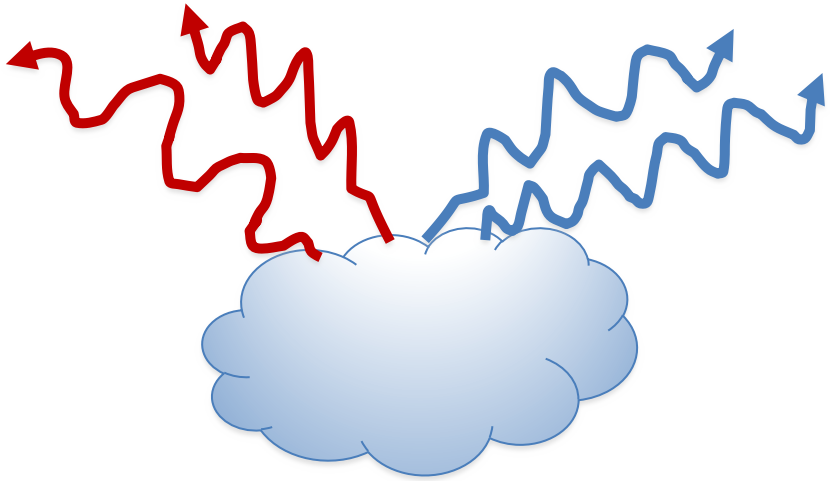
- What changes from O(10 km) to O(1 km)?
  1. Convection resolved explicitly.
  2. Smaller scales in the resolved orography.
  3. Less implicit and explicit model diffusion.



The model

- Semi-implicit, semi-Lagrangian spectral dynamical core
- Model top 80 km,137 vertical levels.
- Time steps: 60s (1km), 240s (4km), 750s (9km)
- Parametrized orographic (Lott & Miller, 1997) and non-orographic (Scinocca, 2003) GWF: @9km and 4km
- Parametrized deep convection(Tiedke-based): Only in one 9 km simulation.

Part I: Convectively generated GWs in the tropical stratosphere



Q1: How does parametrized DC impact resolved GWs?

Q2: How does horizontal resolution impact resolved GWs?

Polichtchouk, Wedi & Kim (QJRMS, 2021)

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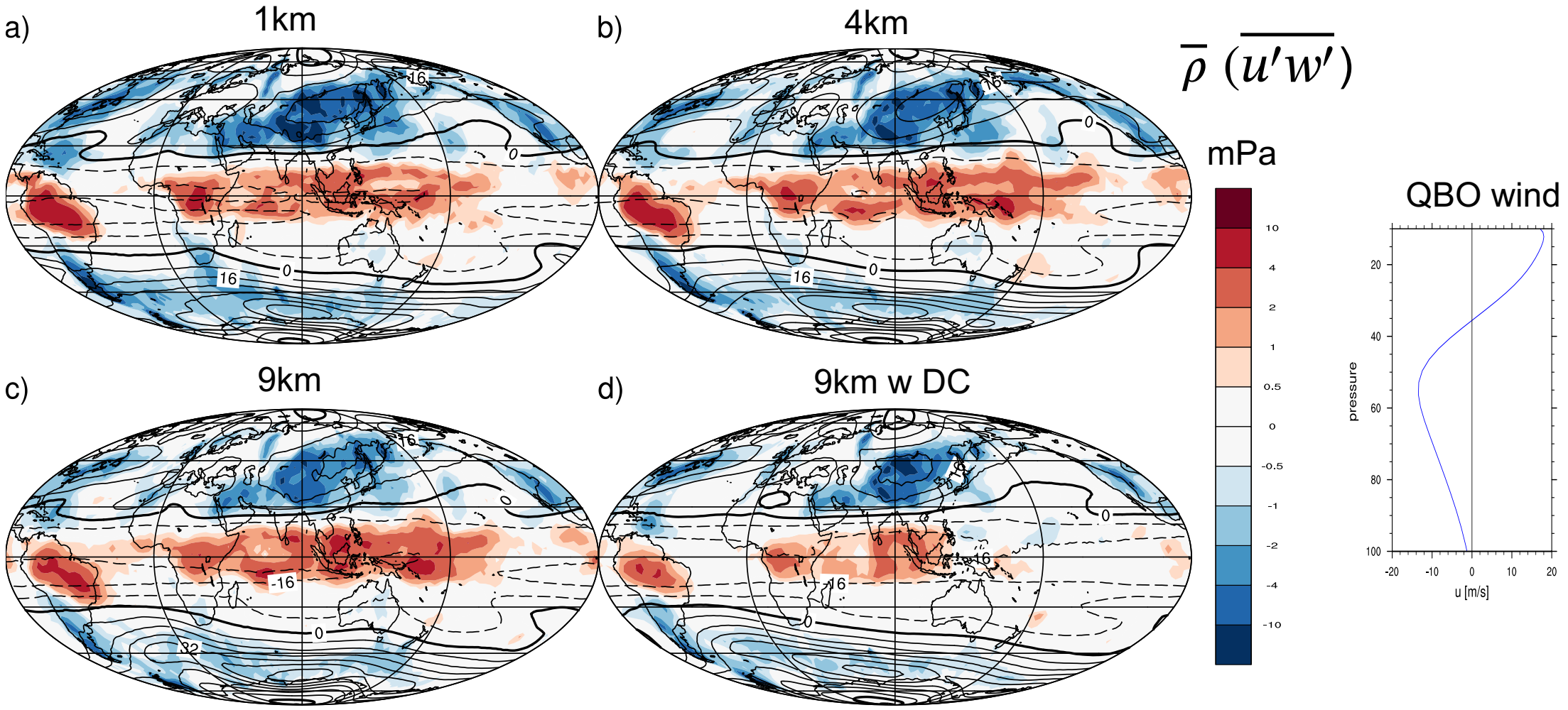
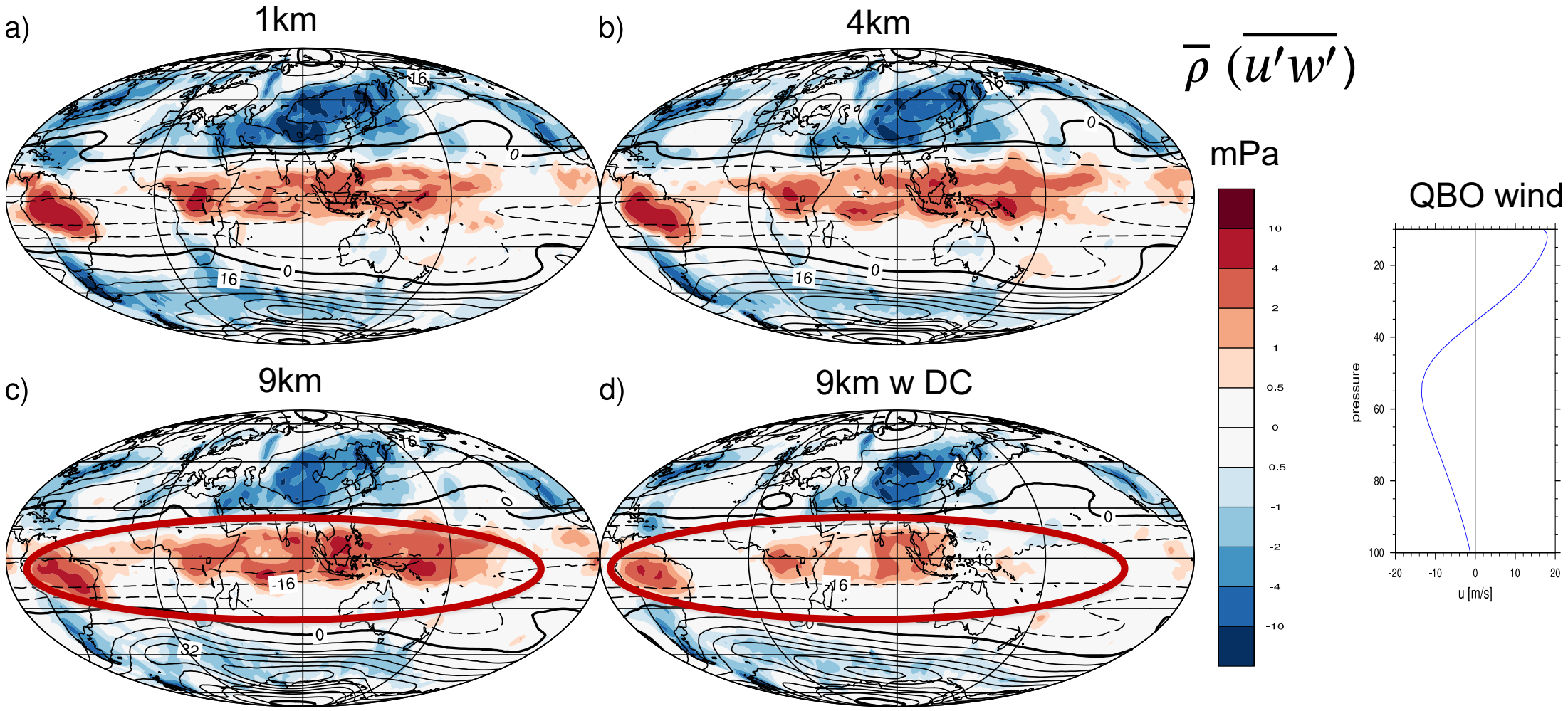
Vertical flux of zonal momentum at 50hPa, November 2018



Polichtchouk, Wedi & Kim (2021, QJRMS)

ECMWF

Vertical flux of zonal momentum at 50hPa, November 2018



Observation 1: Parametrization of DC inhibits resolved convective GW generation.

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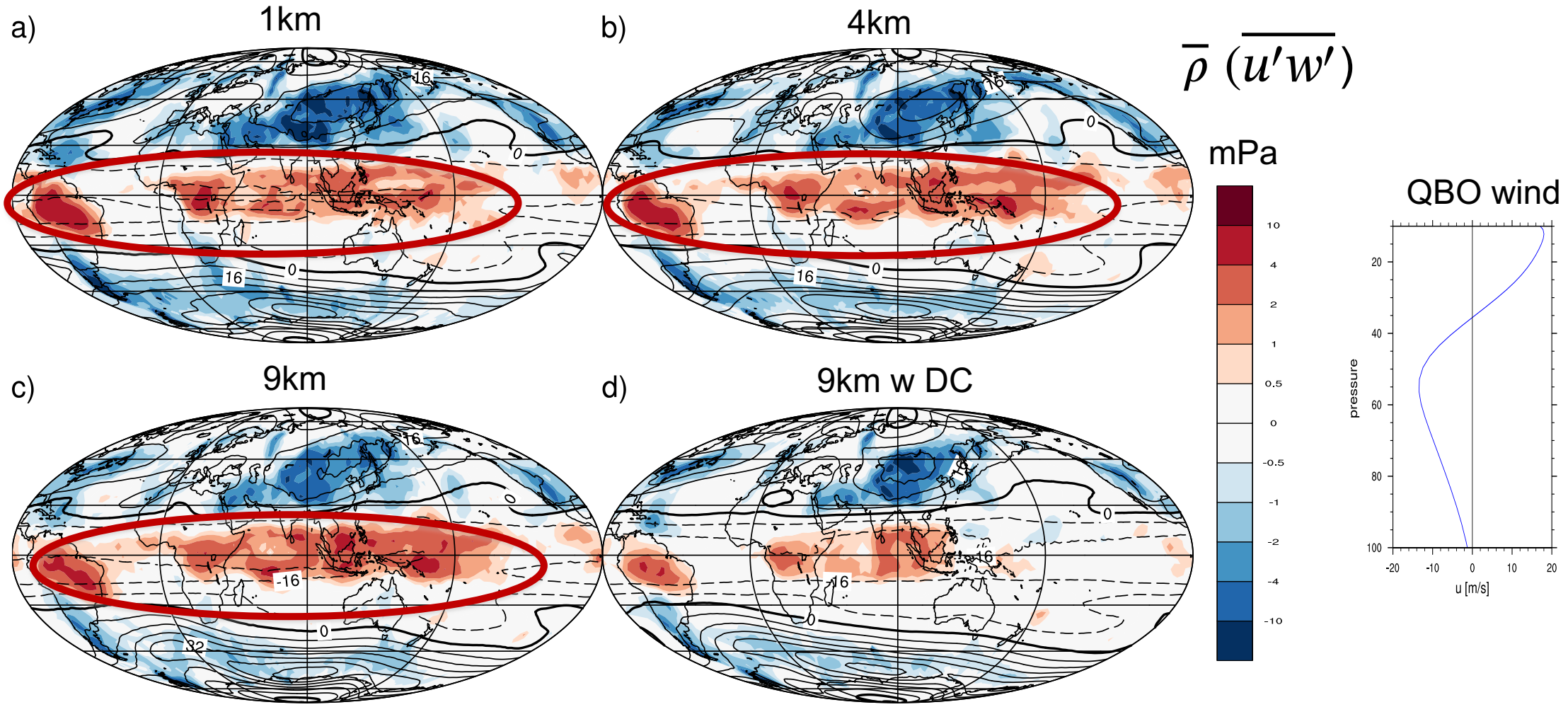
Vertical flux of zonal momentum at 50hPa, November 2018



Observation 2: With explicit representation of DC, convective GW activity is almost unchanged from O(10 km) to O(1 km) horizontal resolution.

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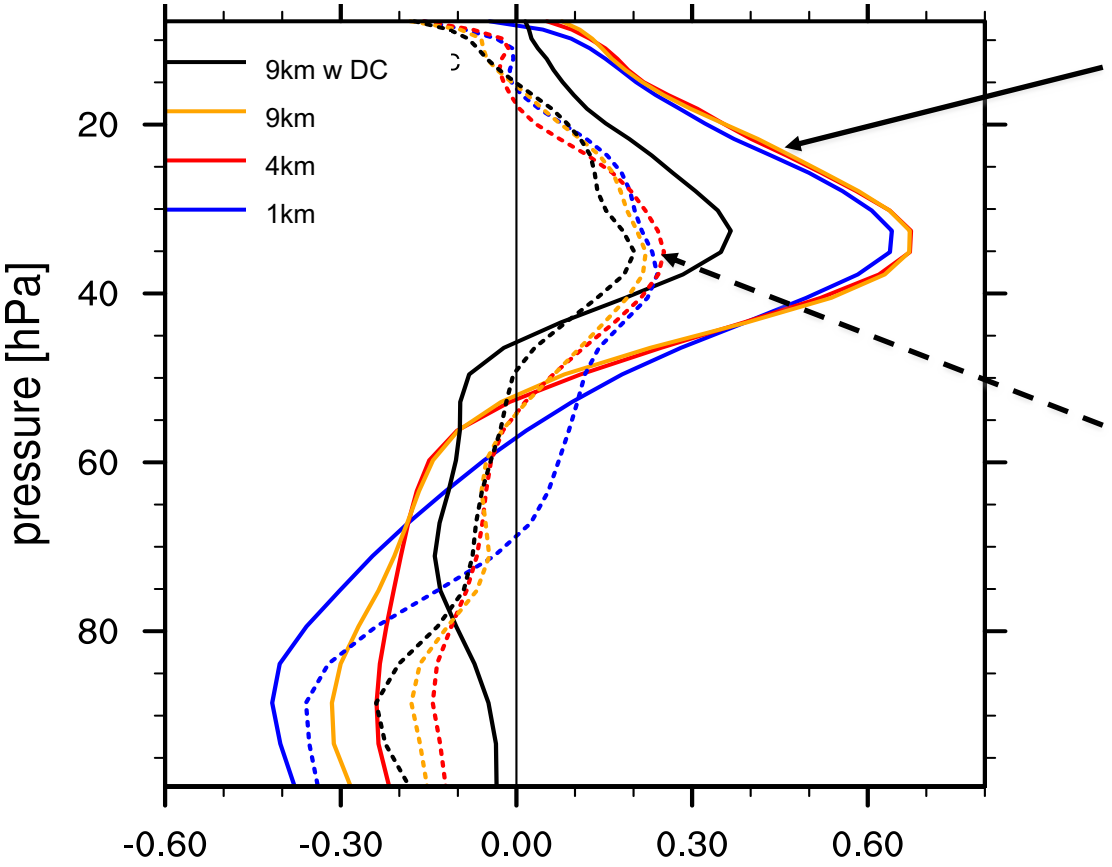
Comparison of resolved GWF with large-scale wave forcing

$$\overline{u}_t = \overline{v}^*\left[f - (a\cos\phi)^{-1}(\overline{u}\cos\phi)_\phi\right] - \overline{w}^*\overline{u}_z + (\rho a\cos\phi)^{-1}\nabla\cdot\mathbf{F} + \frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho\overline{u'w'}\right) + \overline{X}$$

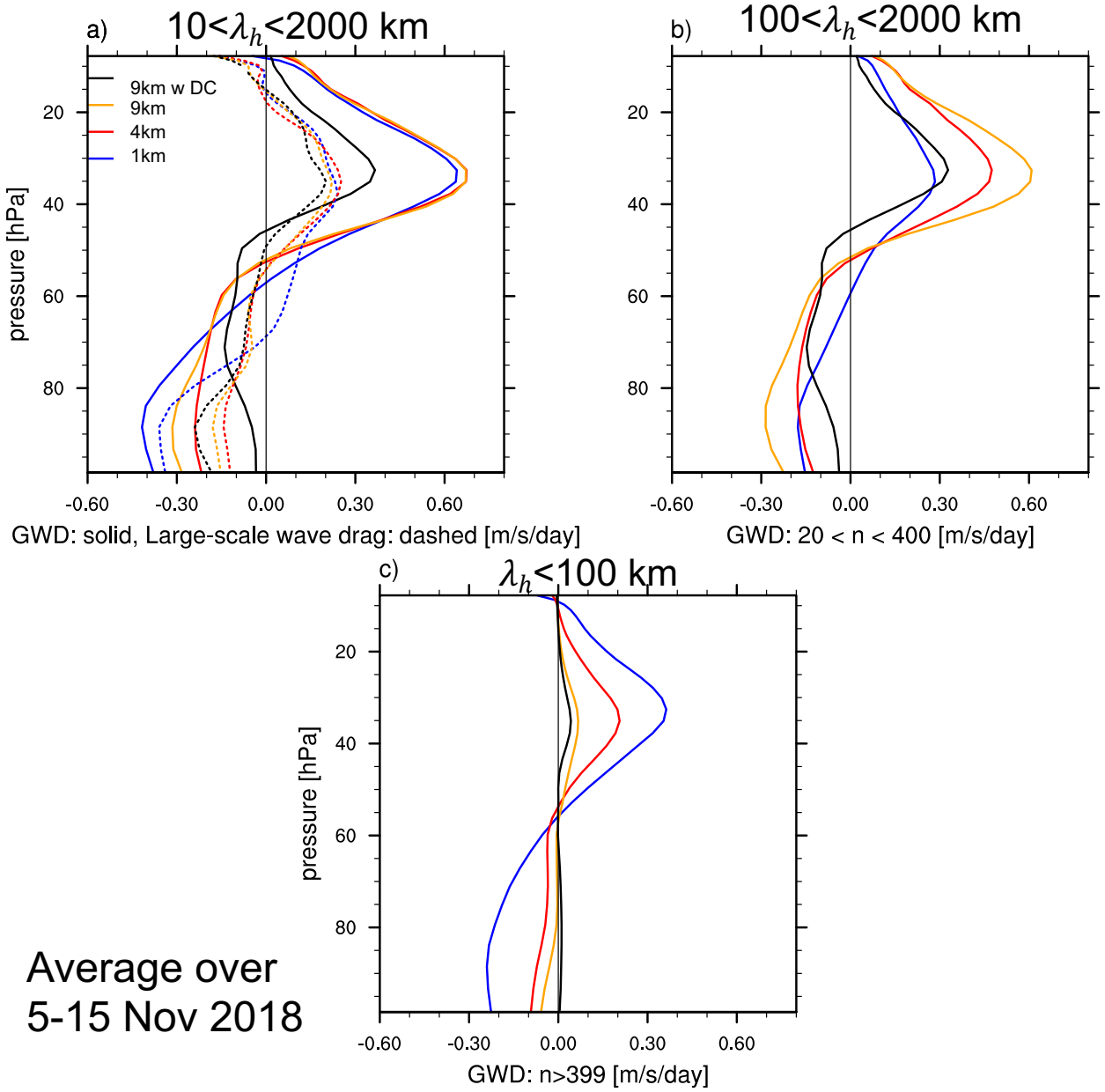


GWD: solid, Large-scale wave drag: dashed [m/s/day]

Average over 5-15 Nov 2018

- Resolved equatorial **GWF is stronger w/o parametrized DC** AND almost independent of the horizontal resolution → implications for the QBO.
- Resolved GWF is 2-3x> the larger-scale wave forcing from Rossby, Kelvin and Rossby-gravity waves.
- Also true for the easterly shear phase of the QBO in Aug 2019 (see paper).

Scale decomposition of resolved GWF

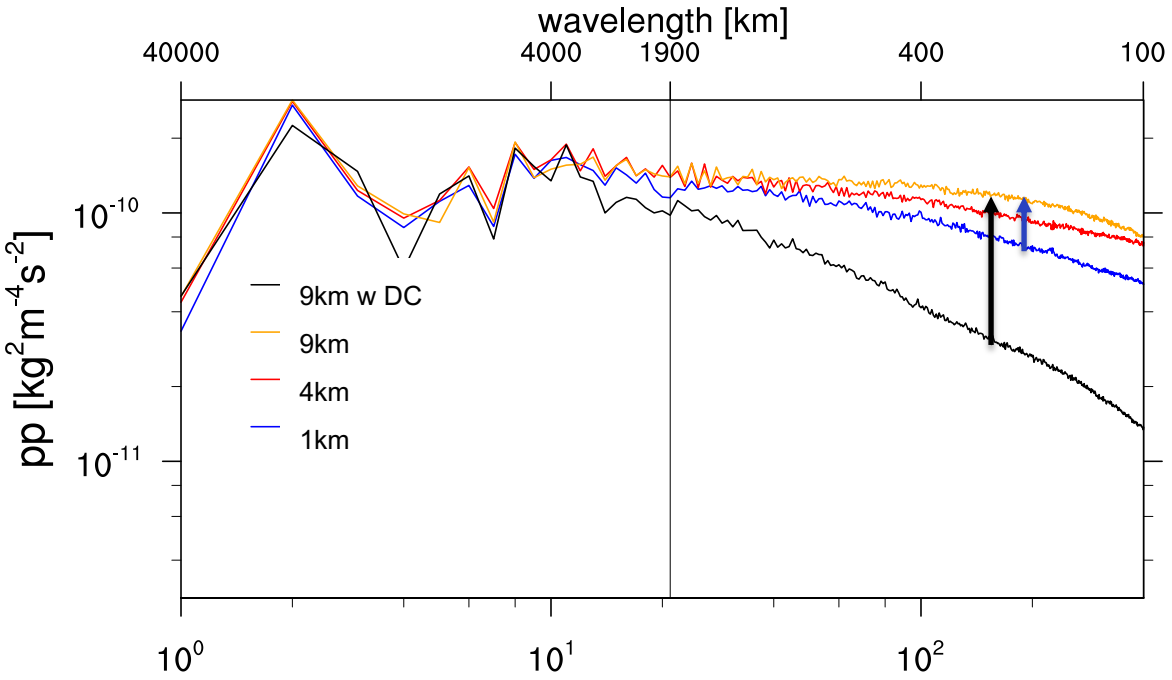


Average over
5-15 Nov 2018

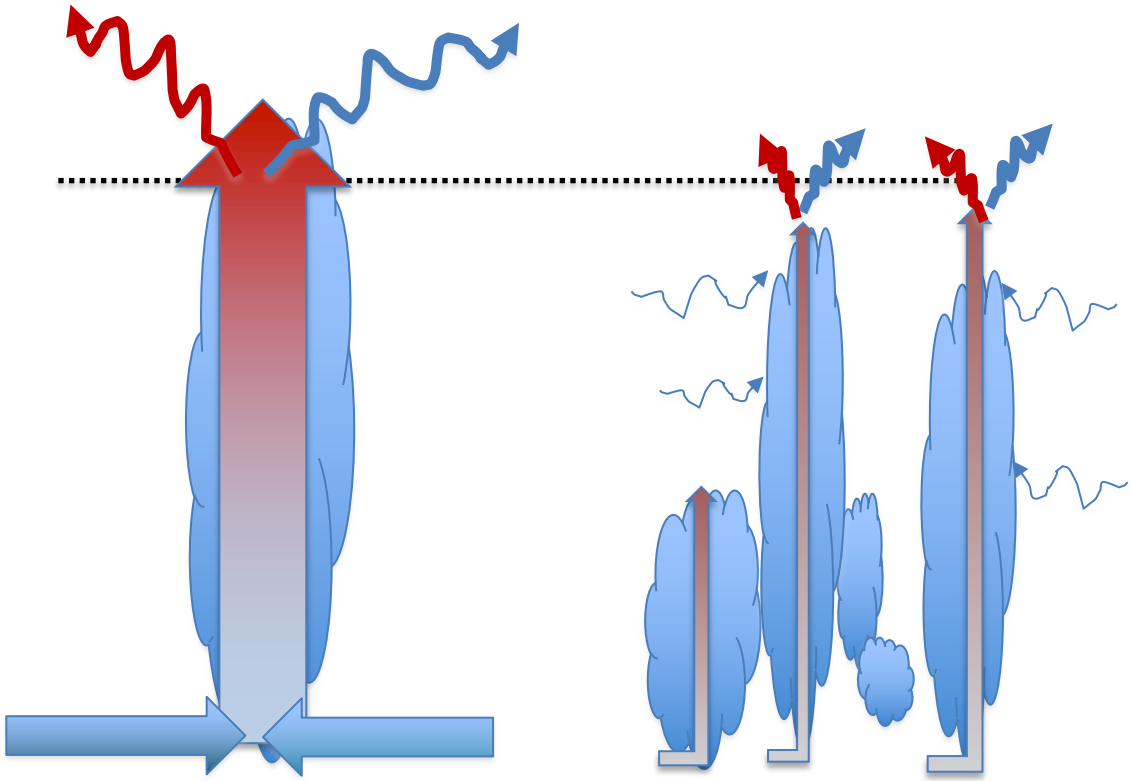
- As the horizontal resolution increases, forcing from λ_h<100 km GWs increases.
- When DC is explicitly resolved @9km and 4 km, resolved 100 <λ_h<2000 km GWF is too strong.
- Need to parametrized DC @9km and 4km together with the parametrization of non-orographic GWF to represent missing forcing from λ_h<100 km GWs.

Why explicit DC and lower resolution amplify GWs with λ_h>100 km?

Precipitation a proxy for latent heating, exciting GWs in convective updrafts.



Global total precipitation power spectrum



Unresolved explicit DC. Too strong, triggered only near large-scale low-level convergence, entrainment not resolved. Top-heavy.

Well-resolved OR parametrized DC.

- DC param. inhibits latent heating at all scales.
- Unresolved explicit DC excites GWs that are too large.

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Conclusions: Convectively generated GWs in the tropics

- While parametrization of DC inhibits resolved convective GW generation, it can not be switched off @9km & 4km grid-spacings as GWF from $100<\lambda_h<2000$ km waves is too strong.

- While total convective GWF is the same at O(10 km) and O(1 km) when DC is explicitly resolved, there is no convergence to resolution of GWs with $100<\lambda_h<2000$ km.

- Need to continue using non-orographic GWF parametrization to account for missing forcing from small-scale GWs @9km and 4km.

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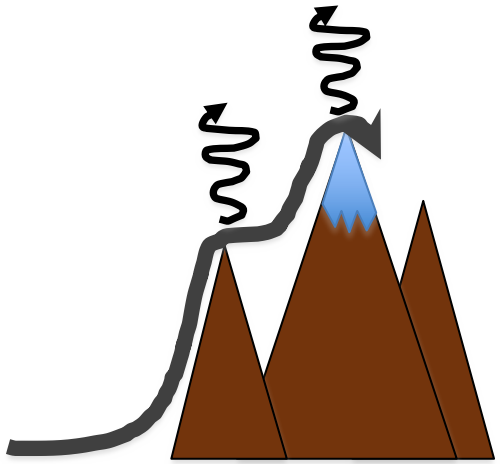
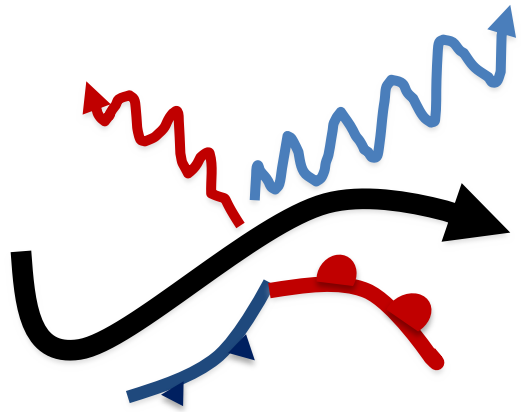
Part II: Resolved GWs in the extra-tropical stratosphere





Q1: How does horizontal resolution impact resolved GWs?

Q2: Is the total (resolved + param.) GWF at O(10 km) resolution equal to resolved GWF at O(1 km) resolution?

Polichtchouk, van Niekerk & Wedi (JAS, in revision)

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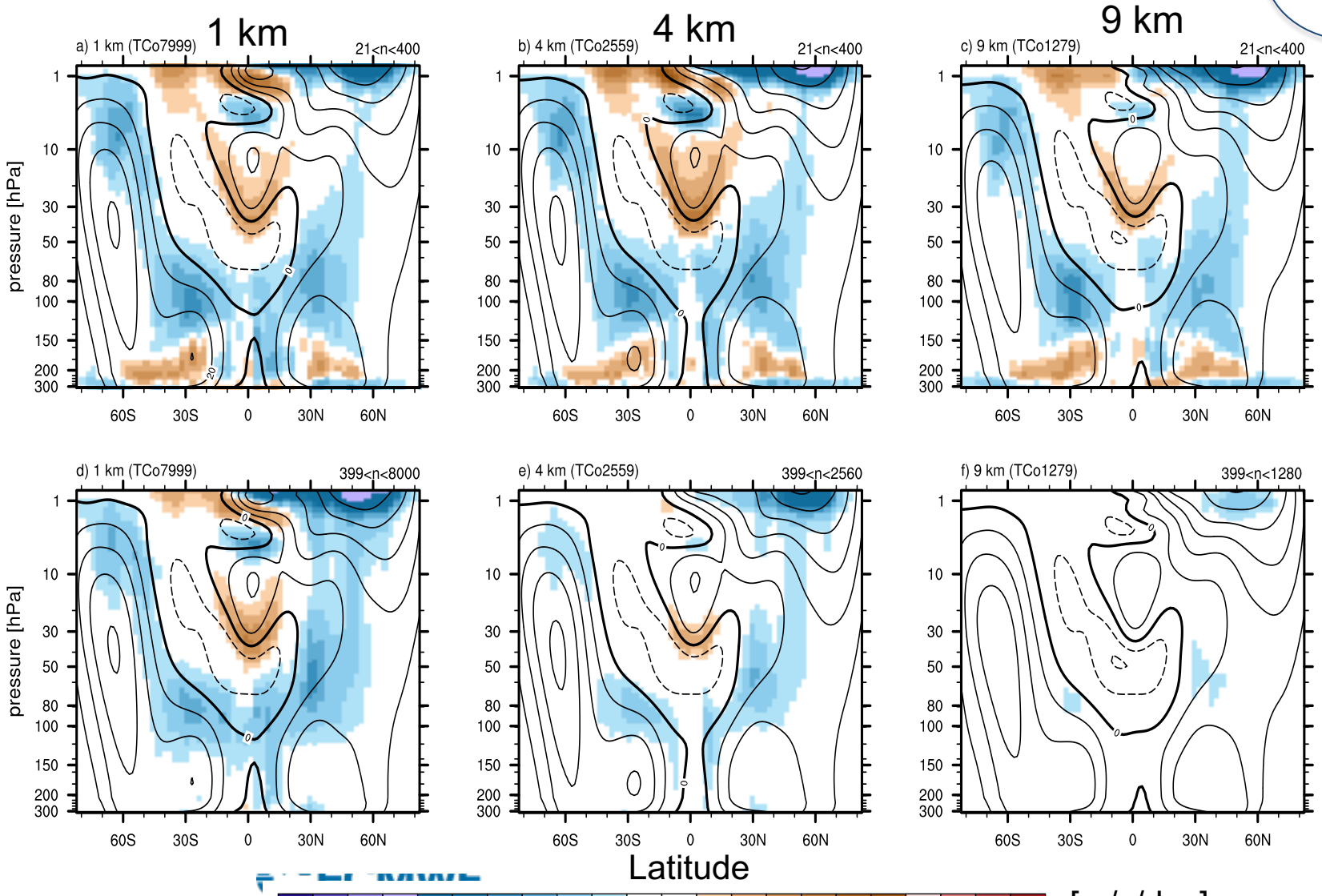
Does resolved GWF increase as the horizontal resolution increases?

$$\overline{u}_t = \overline{v}^*\left[f - (a\cos\phi)^{-1}(\overline{u}\cos\phi)_\phi\right] - \overline{w}^*\overline{u}_z + (\rho a\cos\phi)^{-1}\nabla\cdot\mathbf{F} + \frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho\overline{u'w'}\right) + \overline{X}$$

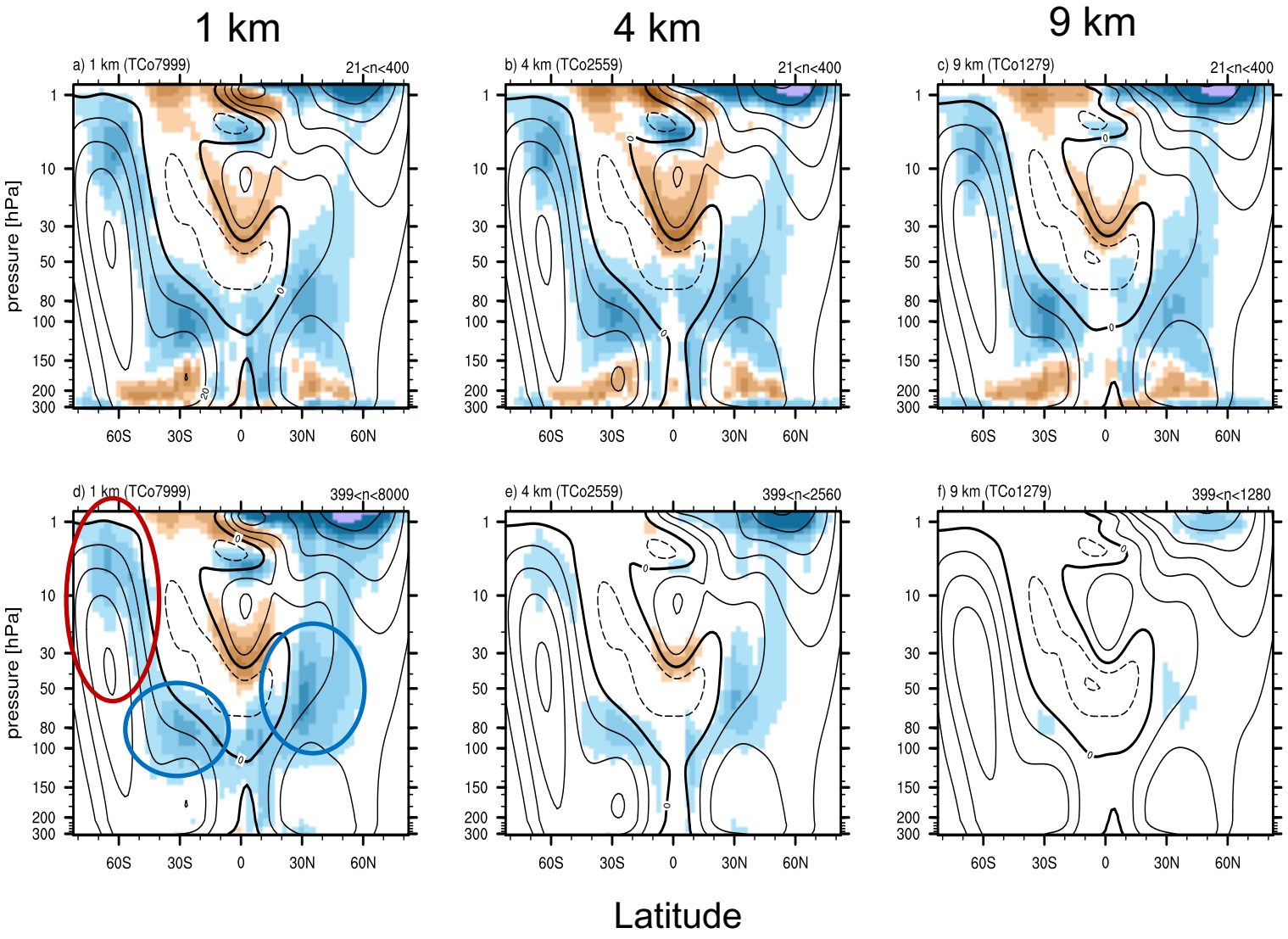


Long and meso-scale GWs
100 <λ_h<2000 km

Smaller scale GWs
λ_h<100 km

Resolved GWF, 1-15 Nov 2018

Does resolved GWF increase as the horizontal resolution increases?



Extratropical GWF from long- and meso-scale waves **converged** with horizontal resolution.

Increasing the horizontal resolution increases resolved GWF from **smaller scale waves** over:

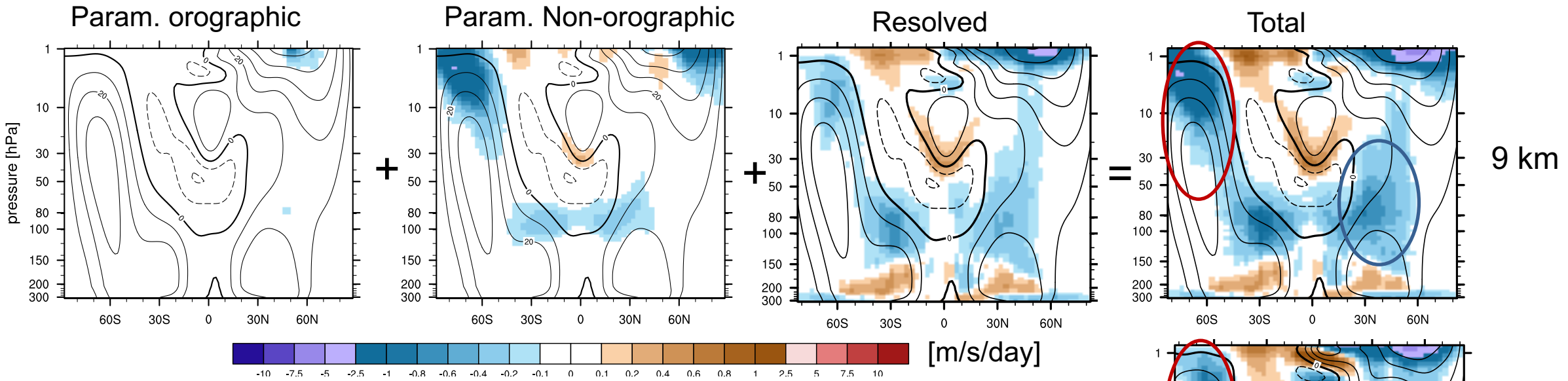
- The Southern Hemisphere, during the spring-time polar vortex breakdown.
- Above the subtropical jets, in both hemisphere.

No clear impact of DC on extratropical GWs.

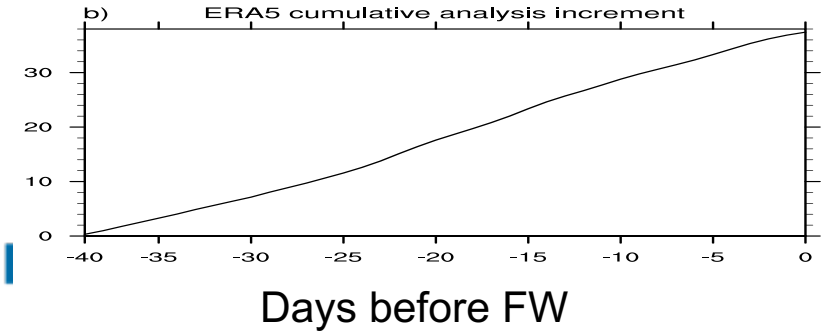
Is total GWF at O(10 km) equal to resolved GWF at O(1km)?

- During the Antarctic final warming total GWF@9km 1.5x>> resolved GWF@1km, due to large parametrized non-orographic GWF.

- Above subtropical jets total GWF@9 km 10%<resolved GWF@1km.

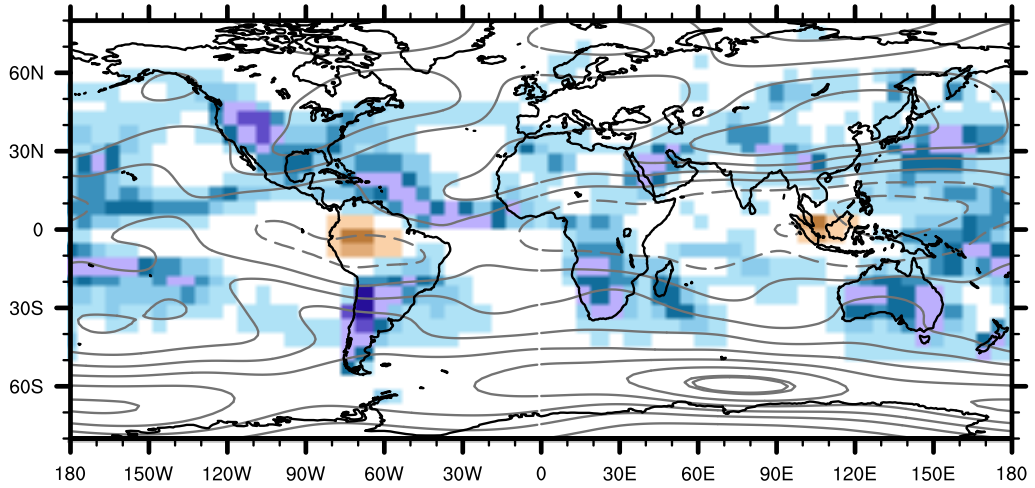


ERA5, U an incr, 60-90S@10hPa

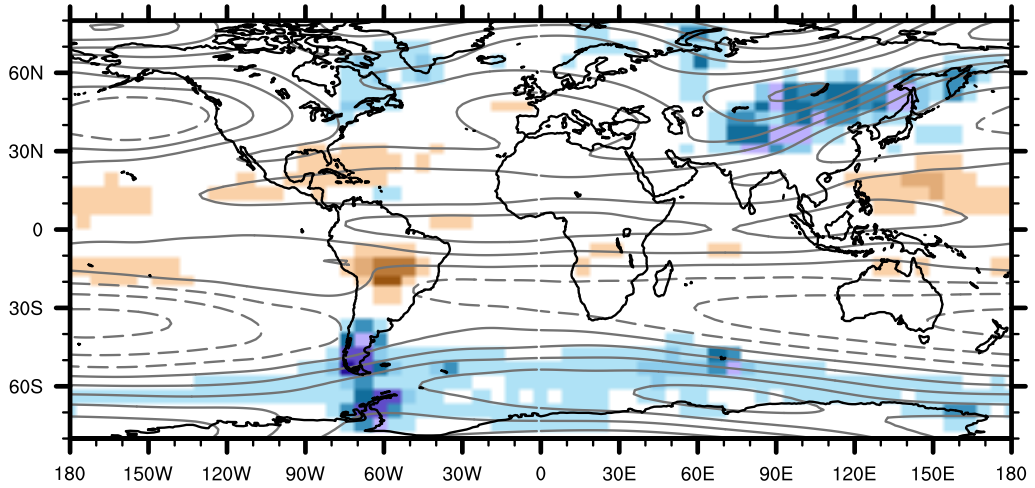


Where does the increase in resolved small-scale GWF occurs?

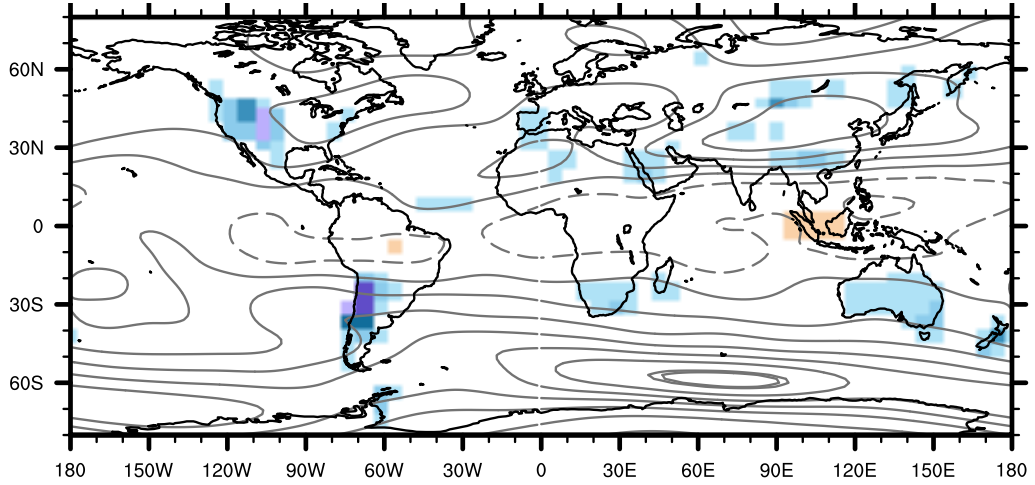
1km @80hPa: GWs with λ_h<100 km



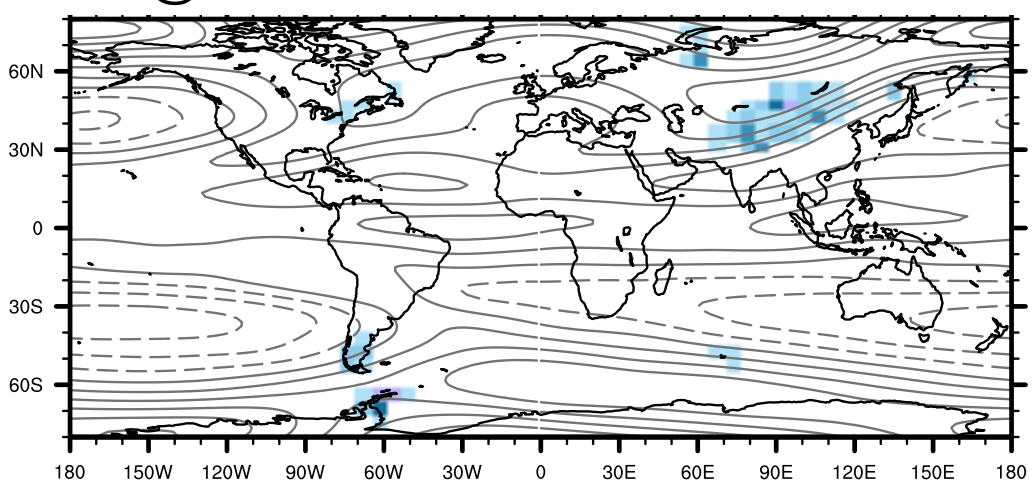
1km @10hPa: GWs with λ_h<100 km

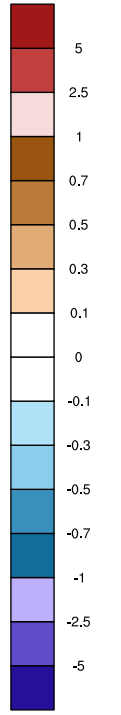


9km @80hPa

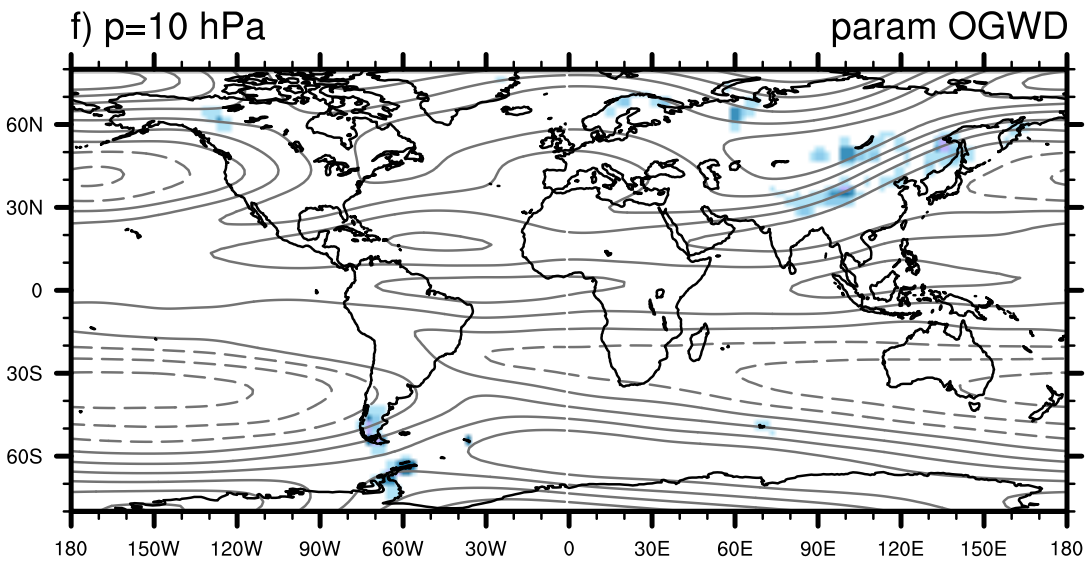


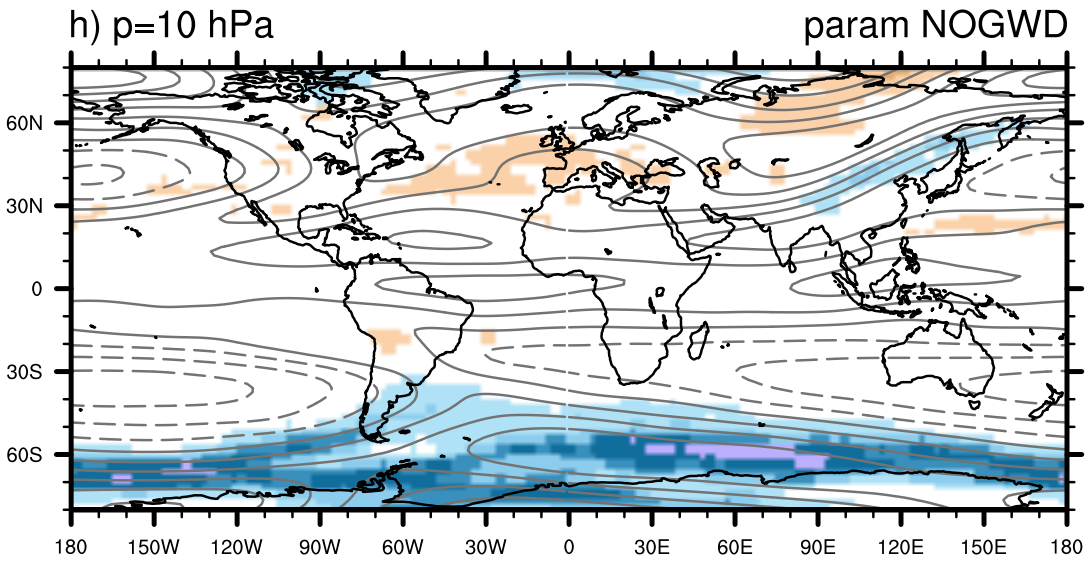
9km @10hPa

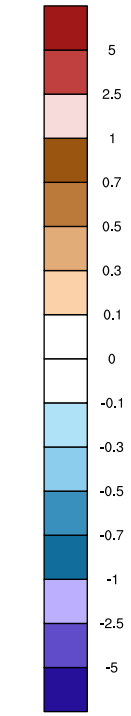




Are the parameterizations putting the GWF in the right place?





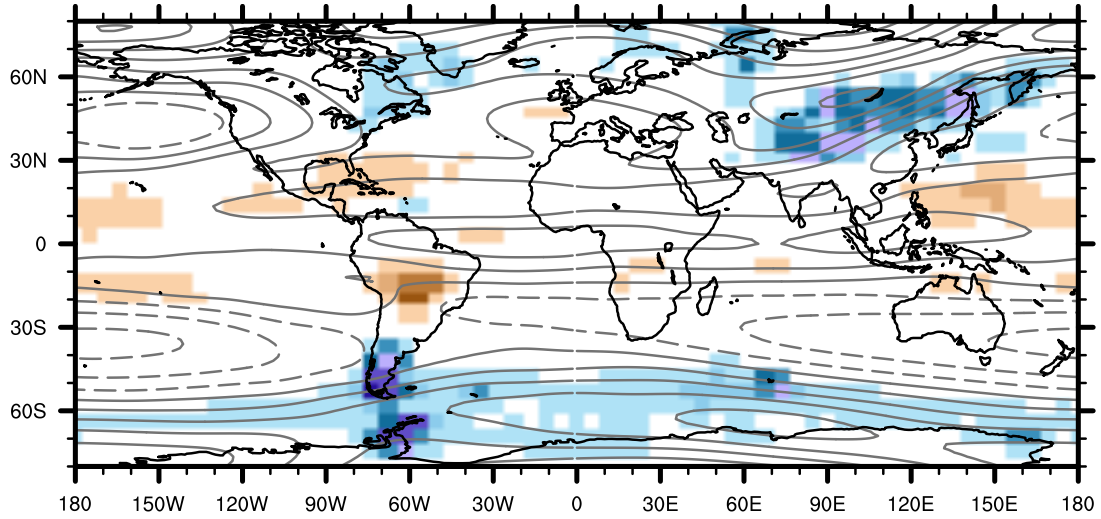


Not enough parametrized orographic GWF. Too much non-orographic GWF.

→

partitioning of orographic vs. non-orographic parametrizations needs revising?

1km @10hPa: GWs with λ_h<100 km



Conclusions: Extra-tropical GWs

- Resolved GWF increases from O(10 km) to O(1 km) horizontal resolution due to GWs with λ_h<100 km → Continue to use orographic and non-orographic GWF parametrizations even at 4km.

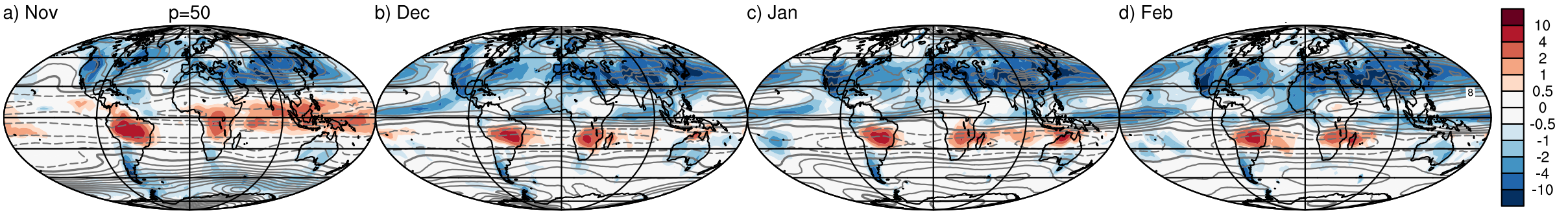
- Parameterizations in IFS need re-partitioning? More orographic GWF is needed above sub-tropical jets and less non-orographic forcing is needed in the polar night jets.

- In contrast to the tropics, long- and meso-scale GWF is converged to horizontal resolution.

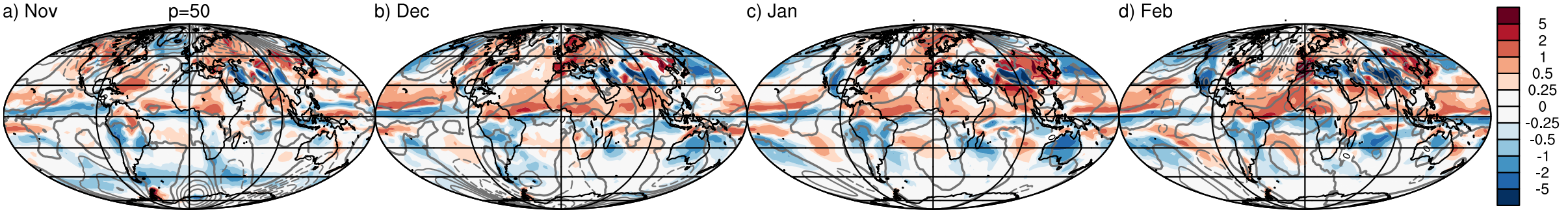
Overall conclusion: Still need for parametrization development even in the grey-zone of 3-5km grid-spacing.

Vertical fluxes of zonal and meridional momentum at 1km

$\overline{\rho}\ (\overline{u'w'})$



$\overline{\rho}\ (\overline{v'w'})$



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Zonal and meridional GWF at 1km