Gravity Wave Momentum Fluxes (GWMF) in the Southern Winter Stratosphere Across Observations, Reanalyses and O(1 km) Resolution Climate Models

Aman Gupta[1,2], Robert Reichert[1,3], Thomas Birner[1,3], Andreas Dörnbrack[3], Hella Garny[1,3], Roland Eichinger[3,4], Inna Polichtchouk[5], Aditi Sheshadri[2]

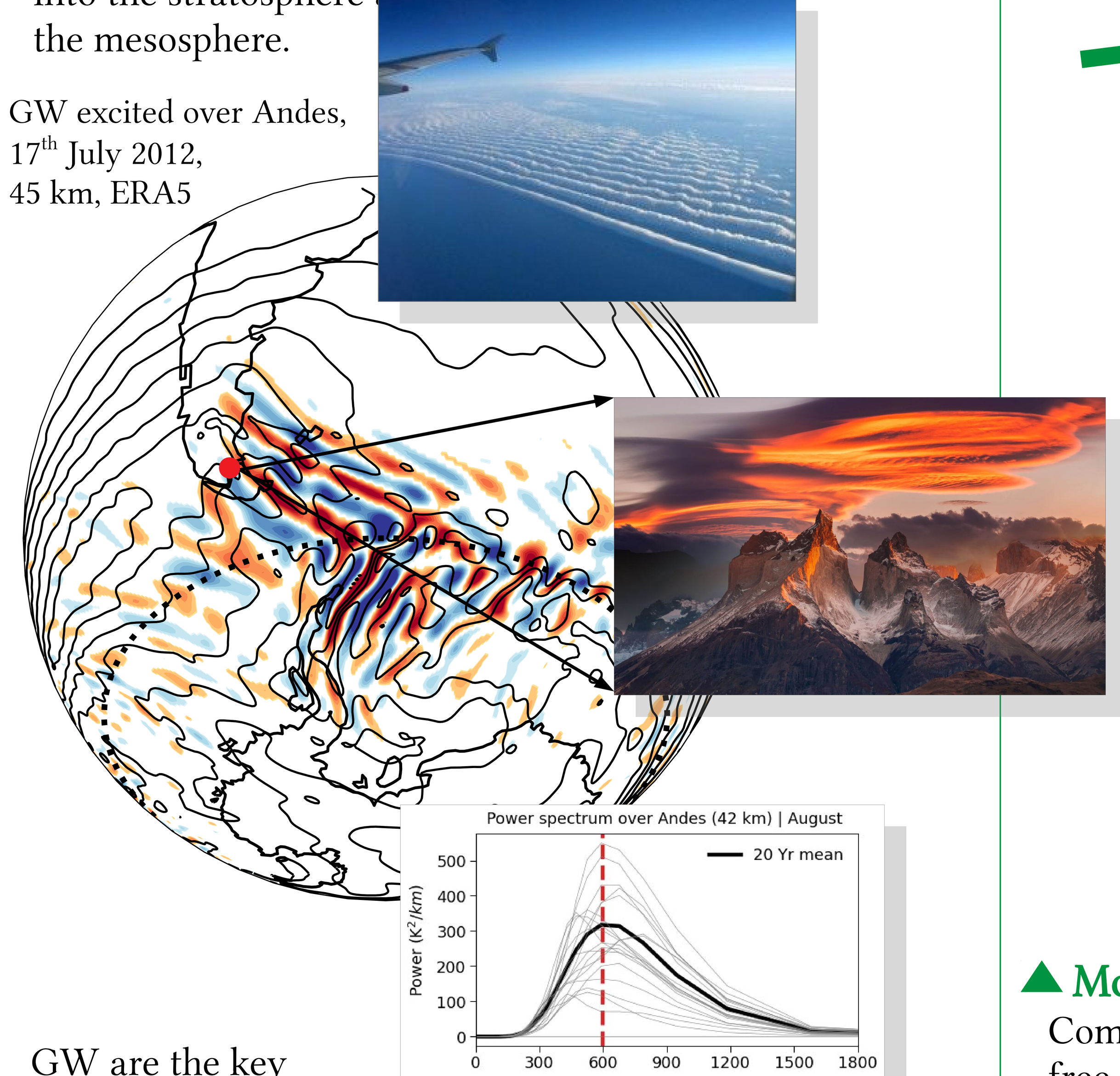
1: Ludwig Maximilian University Munich | 2: Stanford University | 3: German Aerospace Center (DLR) | 4: Charles University | 5: ECMWF

Aman.Gupta@lmu.de | ag4680@stanford.edu

Can you remind me what gravity waves are?

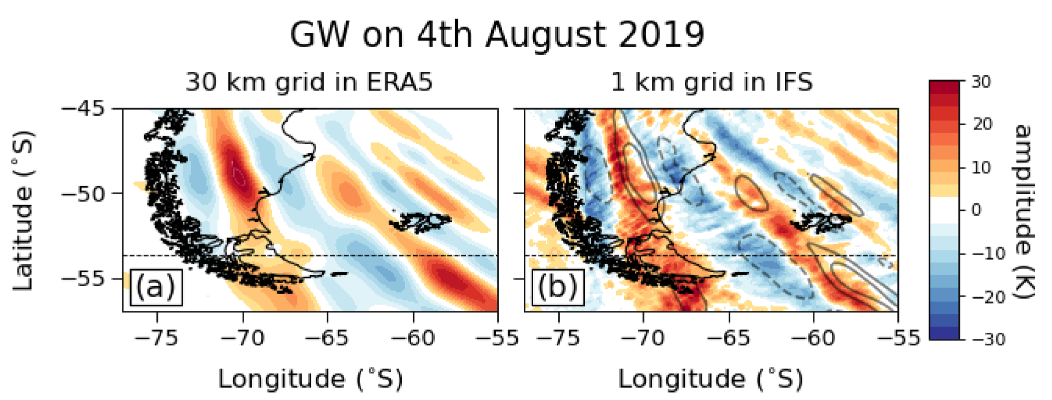
Yes, gravity waves (GW) are buoyancy perturbations generated by flow over mountains, geostrophic adjustment, convection, jet instability etc. Mountain waves generated over the Andes are one of the strongest of such waves. They carry momentum from the surface into the stratosphere and the mesosphere.

GW excited over Andes, 17th July 2012, 45 km, ERA5



GW are the key drivers of the mesospheric circulation and the tropical QBO, and play a crucial role in the Antarctic polar vortex breakdown[2].

GW elude low-resolution climate models



GW manifest over a wide range of spatial scales. Even at 50-100 km resolution, climate models barely resolve GW and use parameterizations to represent them. More than four decades since first such parameterization was introduced, the parameterized fluxes are still poorly constrained on account of limited observations and computational limitations.

Observationalists and modelers tend to estimate gravity wave momentum fluxes differently since most observations measure only the temperature[1], while models produce both global winds and global temperature[2].

We employ observations and a spectrum of GW resolving models and compare momentum fluxes during a mountain wave event over the Andes during August 2019, using two different methods

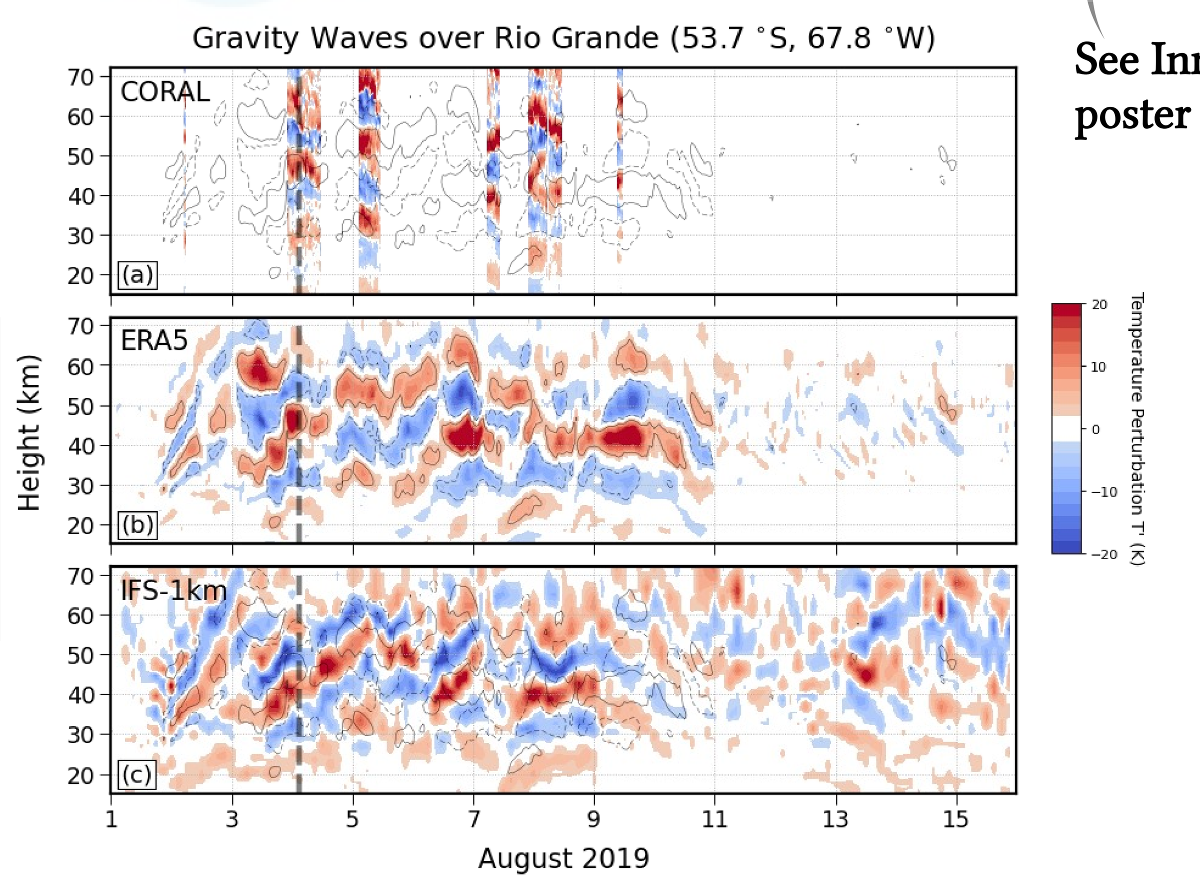
EMAC Climate Model
300 km grid
Nudged to ERA5
All GW are parameterized

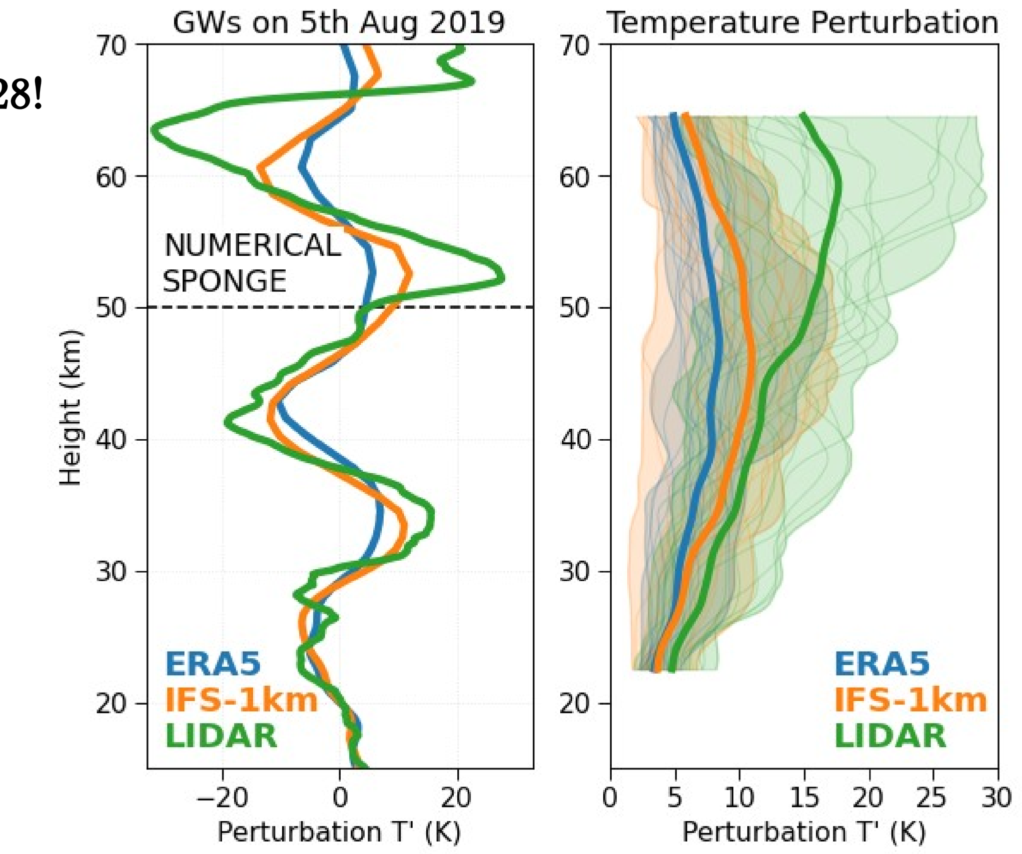
ERA5 Reanalysis
30 km grid
Partially resolves the mesoscale GW spectrum

Free Running ECMWF IFS
1 km grid[3]
Completely resolves the mesoscale GW spectrum

Ground based CORAL LIDAR observational "truth"
0.1 km vertical resolution
Rio Grande, Argentina

See Inna's poster RS1-28!





▲ Models and Observations agree on the vertical wave structure

Commendably similar vertical profiles obtained over Rio Grande among free running IFS, ERA5, and observations.

▲ Is ~1 km grid resolution sufficient to resolve the wave packet?

GW resolved in IFS and ERA5 have weaker amplitudes than those observed by CORAL throughout the stratosphere. Model sponge further dampens amplitudes in the mesosphere in IFS and ERA5.

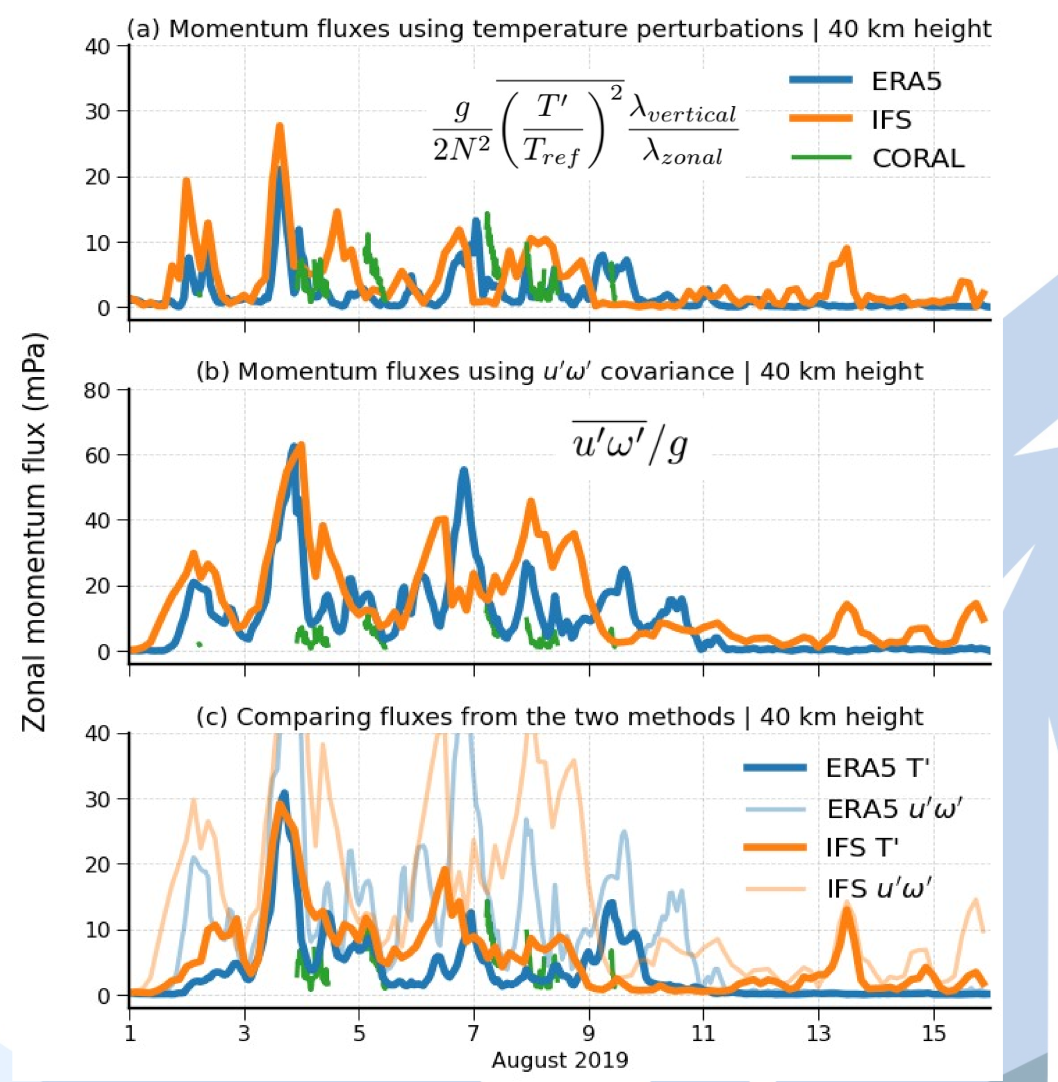


Fig: GWMF over Rio Grande, Argentina for August 2019: (a) using linearly interpolated temperature, (b) using coarse-grained covariances, (c) using coarse-grained potential energy.

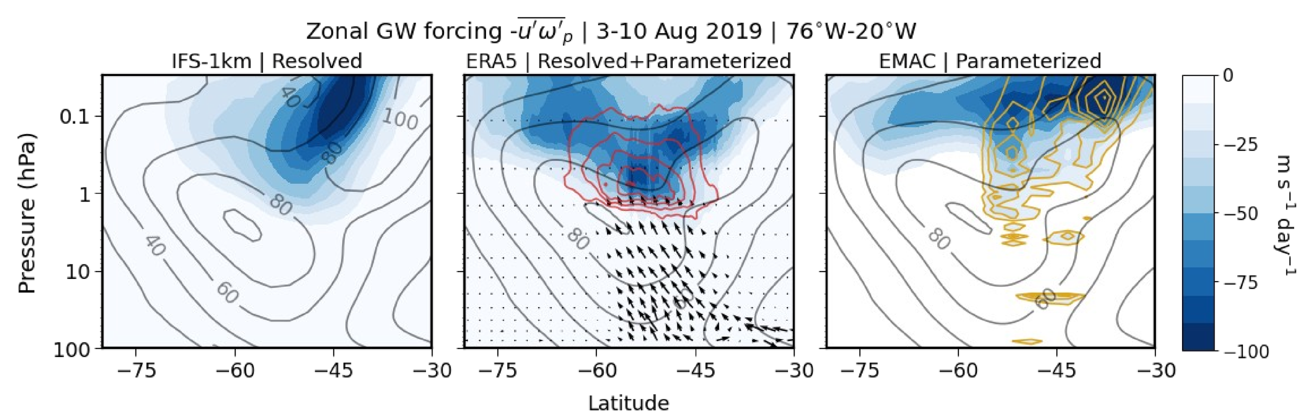


Fig: GW forcing around the Andes. Black curves show the zonal winds. Red curves show the resolved forcing in ERA5. Yellow curves show only the orographic drag in EMAC. Black arrows show the energy flux of the wave packet.

▲ Key differences in resolved vs. parameterized forcing

Forcing structures significantly differ in the three models. The parameterized forcing overestimates the non-orographic forcing poleward of 60°S.

◀ Reconciling local and global measures of GWMF

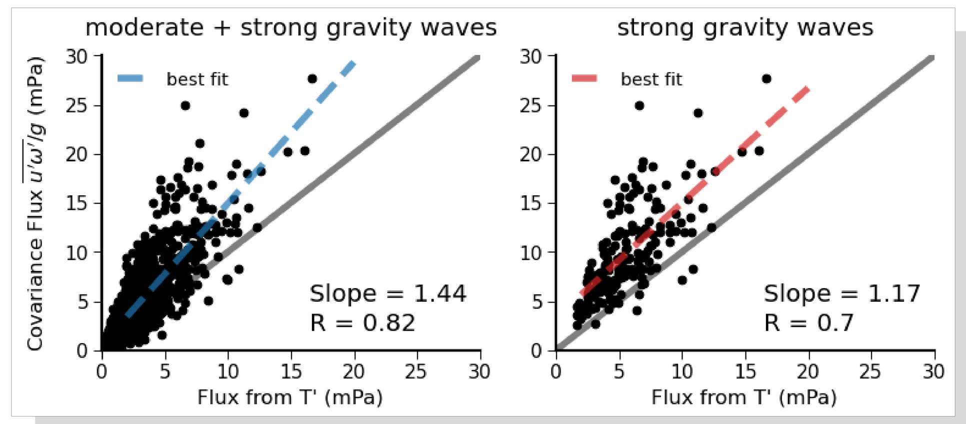
Both methods of GWMF estimation capture the variability associated with mountain waves. For both, fluxes in IFS are stronger than in ERA5. The temperature based "Ern-style" fluxes[1] (in (a)) are consistently weaker than the covariance-based fluxes (in (b)). For second week of August, the background variability in IFS is clearly stronger than that in ERA5.

Two approaches to computing GWMF: temperature-based and winds-based, yield different magnitudes

$$\text{Zonal GWMF (from } T'\text{)}: \frac{g}{2N^2}\overline{\left(\frac{T'}{T_{ref}}\right)^2}\frac{\lambda_{vertical}}{\lambda_{zonal}}$$

$$\text{Zonal GWMF (from wind covariances)}: \overline{u'\omega'}/g$$

$\overline{(\ldots)}$: averaging over single/multiple wave cycles



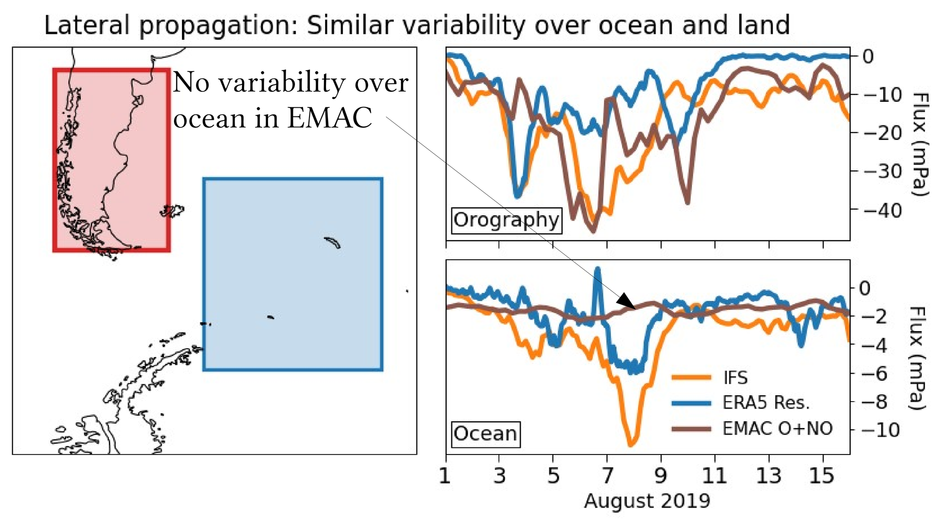
▲ Even in a climatological context, Ern-style fluxes over a 20 year period are consistently weaker than the wind-based covariance fluxes.

Conclusions

- Key differences between resolved vs parameterized GW forcing due to mountain waves excited over the Andes.
- Even at 1 km resolution, climate models do not capture the whole GW packet excited over complex topography.
- Temperature-based momentum flux estimates are significantly weaker than wind covariance-based momentum flux estimates.

Ongoing and Future Work

A data-driven approach to GW parameterizations:
Training neural networks to learn GWMF from O(1 km) resolution global models, and representing them in coarser climate models.



▲ Challenging the columnar parameterization choice:
Ignoring lateral propagation of GW impacts large-scale momentum distribution. How can we develop machine learning based GW schemes that learn the wave dynamics from high resolution climate runs?

References:
[1] Ern et al., 2004: J Geophys Res.: Atm.
[2] Gupta et al., 2021: Geophys. Res. Letters
[3] Polichtchouk et al. 2022: J. Atmos. Sci.

tinyurl.com/sparcga22