Gravity Waves in 14-km CESM

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Outline

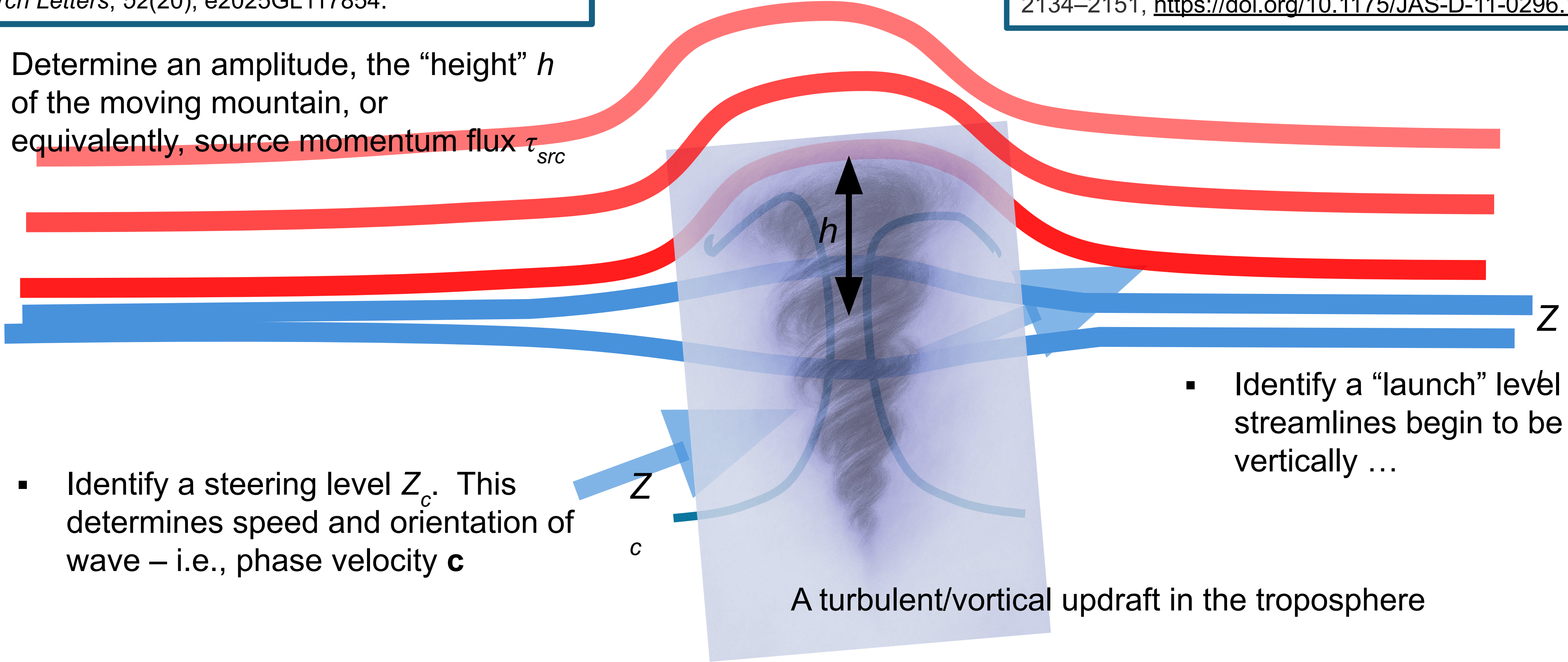
- Brief review of “moving mountain” GW scheme
- High horizontal resolution simulations
  - 14km / ne240
  - Analysis of small-scales
- Gravity Wave Unit Test compared with 14km run
- Summary, future work

“Moving mountain”

Paper on moving mountain GW just appeared:
Bramberger, M., & Bacmeister, J. (2025). Improving representation of stratospheric Polar Vortex in Southern Hemisphere with low-frequency frontal waves. *Geophysical Research Letters*, *52*(20), e2025GL117854.

Possible theoretical justification
Lott, F., R. Plougonven, and J. Vanneste, 2012: Gravity Waves Generated by Sheared Three-Dimensional Potential Vorticity Anomalies. *J. Atmos. Sci.*, **69**, 2134–2151, https://doi.org/10.1175/JAS-D-11-0296.1.

- Determine an amplitude, the “height” h of the moving mountain, or equivalently, source momentum flux τ_{src}



- Identify a “launch” level Z_L , i.e., where streamlines begin to be displaced vertically …

- Identify a steering level Z_c. This determines speed and orientation of wave – i.e., phase velocity **c**

A turbulent/vortical updraft in the troposphere

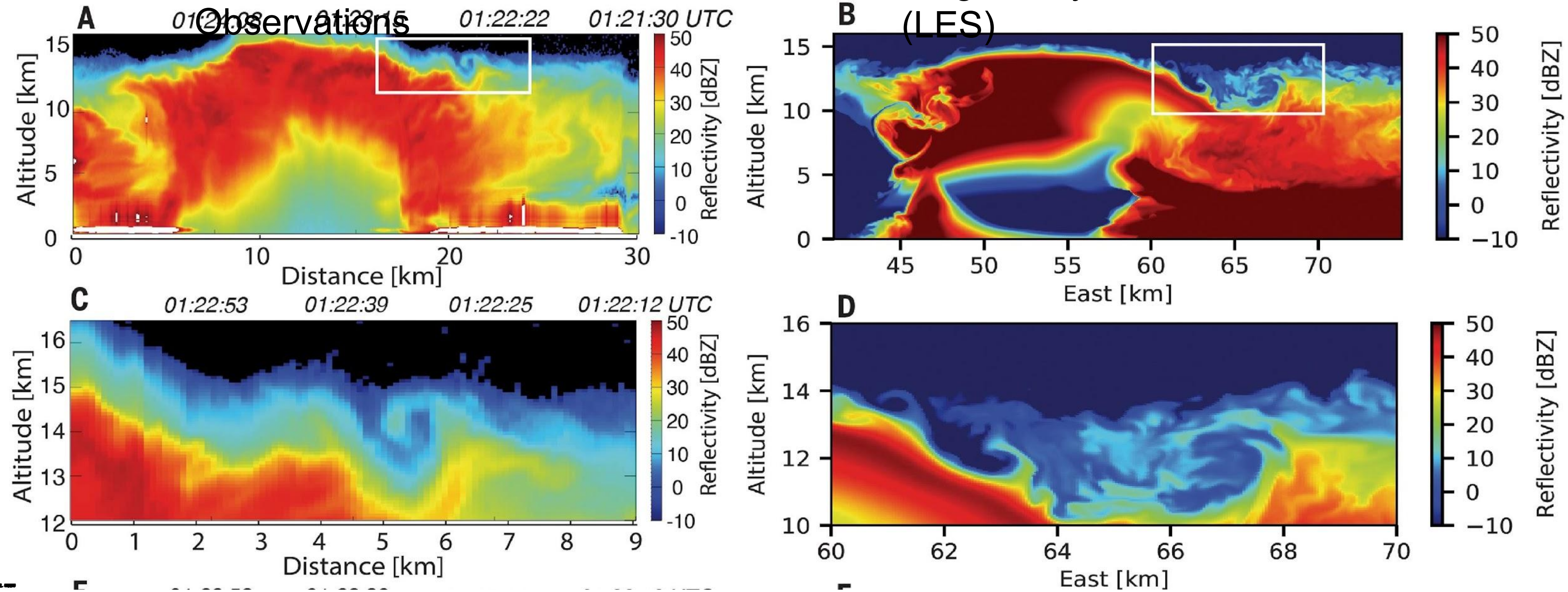
Current implementation:

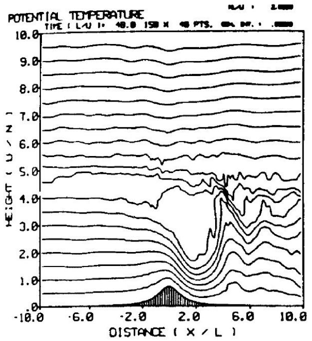
Z_c=650 hPa, Z_L=325 hPa, $\tau_{src}=\alpha\ [|\zeta|]_{0\text{-}1km}$; α – tunable parameter

“Moving mountains” really do exist in the atmosphere!

Aircraft Observations

Large Eddy Simulation (LES)





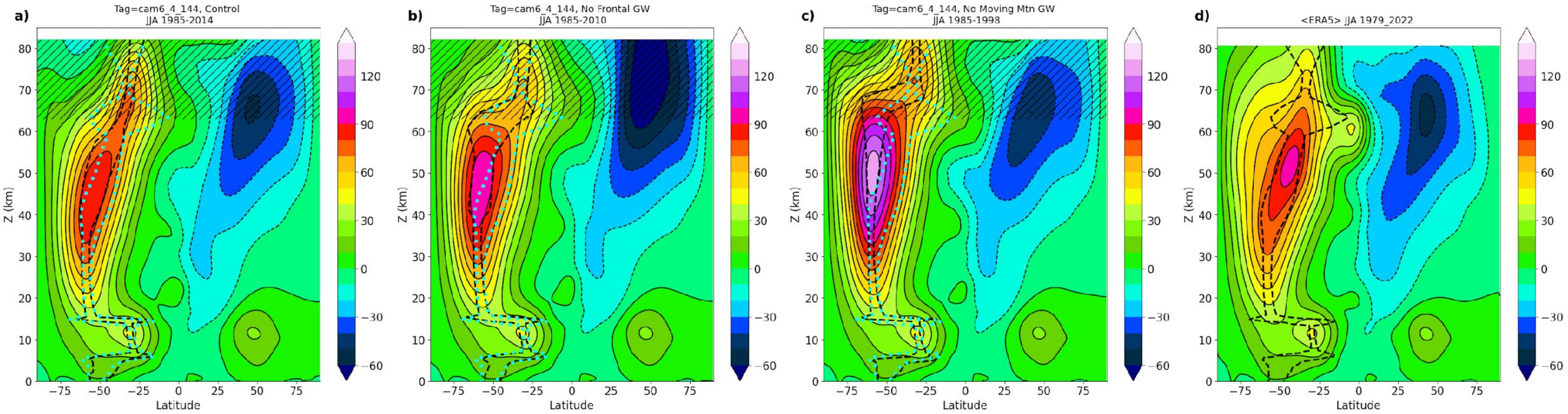
Smith, R. B. (1985). On severe downslope winds. *Journal of Atmospheric Sciences*, *42*(23), 2597-2603.

Bacmeister, J. T., & Pierrehumbert, R. T. (1988). On high-drag states of nonlinear stratified flow over an obstacle. *Journal of Atmospheric Sciences*, *45*(1), 63-80.

Morgan E O’Neill *et al.* Hydraulic jump dynamics above supercell thunderstorms. *Science* **373**,1248-1251(2021).DOI:10.1126/science.abh3857

Observation of Gravity Waves Generated by Convection and the “Moving Mountain” Mechanism During Stratéole-2 Campaigns and Their Impact on the QBO (2025) Corcos, M., M. Bramberger, M.J. Alexander, A. Hertzog, C-T Liu, C. Wright. *J. Geophys. Res.*, **https://doi.org/10.1029/2024JD041804**

Zonal Mean winds JJA



Biases (*similar to WACCM6*):

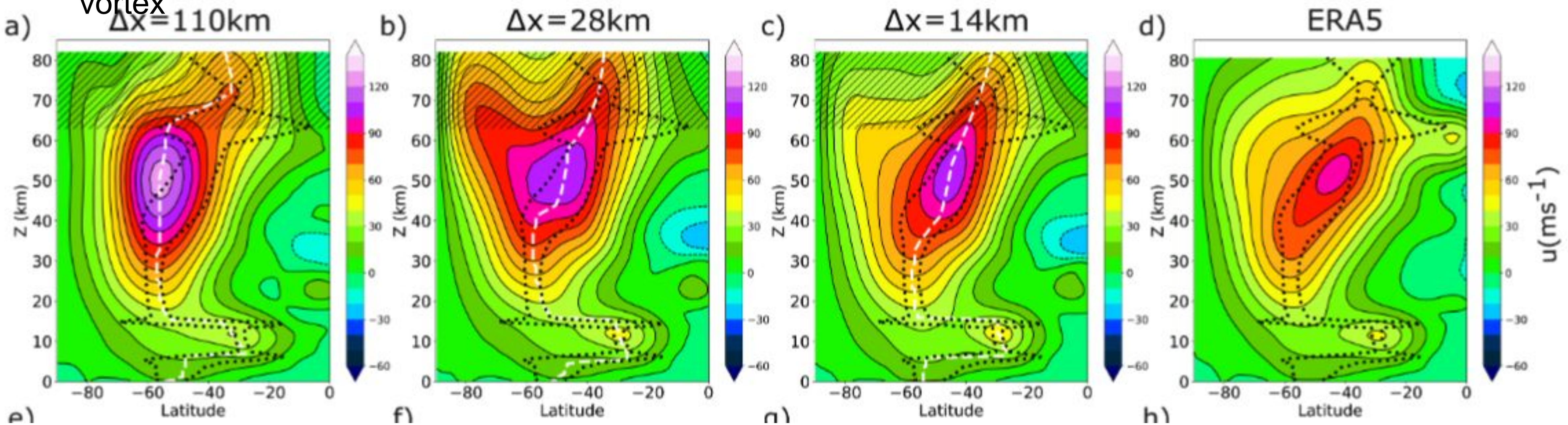
- Excessive strength of jet (cold stratosphere)
- Lack of “tilt”
- Lack of variability
- Late breakdown/warming in spring (*not shown)*

Why not tune previous suite of GW sources?

- Pre-Moving Mountain sources
  - Deep Convection: broad phase speed spectrum -100 to 100 m/s. Not very active at high latitude.
  - Orography: zero phase speed. Limited leverage in SH
  - Fronts: Also broad phase speed spectrum -100 to 100 m/s. This turns out to limit its usefulness
- Tuning for SH JJA jet with orographic and frontal waves was not successful
- Even mimicking horizontal propagation by diffusing orographic GW tendencies did not help
- Previous versions of model have arbitrarily doubled orographic GW drag in the SH. Don’t want to. Doesn’t really improve vortex in JJA.

But resolution seemed to help

Higher resolution (□) improves southern hemisphere vortex

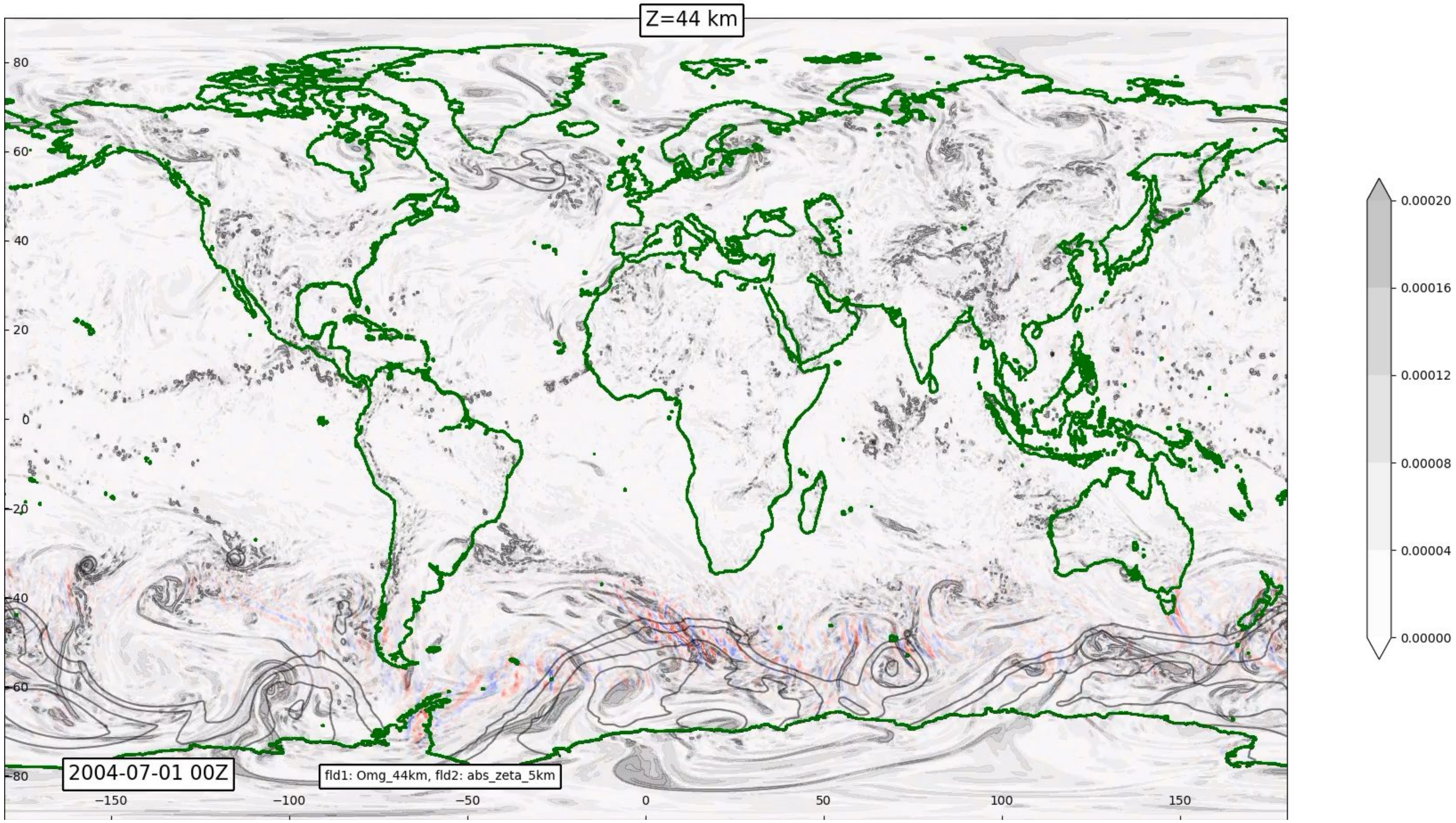


High-resolution CAM

- ne120-L93 AMIP runs (Δx~28km) *decades*
- ne240-L93 AMIP runs (Δx~14km) *months to one year*
- 3km MPAS (L58) *days to weeks*

Use ne240 simulation for GW parameterization development ?

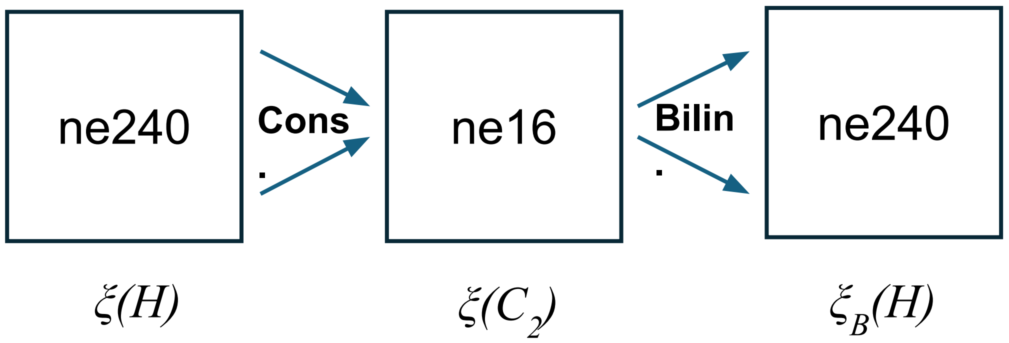
Model Cost (L93):
ne30/dx=100km ~7,000 pe-hrs/simulated_year
ne120/dx=27km ~448,000 pe-hrs/simulated_year
ne240/dx=14km ~5,000,000 pe-hrs/simulated_year (extra slow-down in dycore needed for stability)
Mpas-L58 dx=3km ~100,000,000 – 200,000,000 pe-hrs/simulated_year (still not clear)



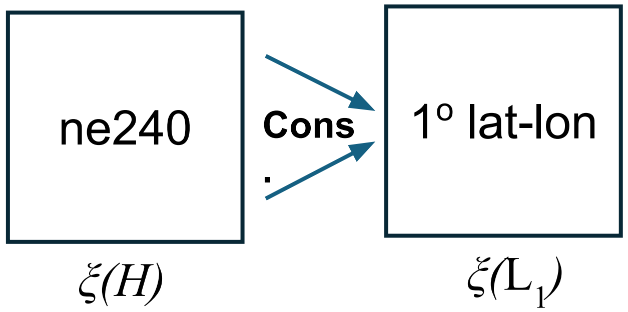
Z=44 km
80
60
40
20
0
-20
-40
-60
-80
2004-07-01 00Z
fld1: Omg_44km, fld2: abs_zeta_5km
−150
−100
−50
0
50
100
150
0.00020
0.00016
0.00012
0.00008
0.00004
0.00000

Diagnosing ne240 small scales

"Background" flow for waves calculated by conservative remapping from ne240 to ne16, then bilinear mapping back to ne240. Consistent scales at all latitudes.



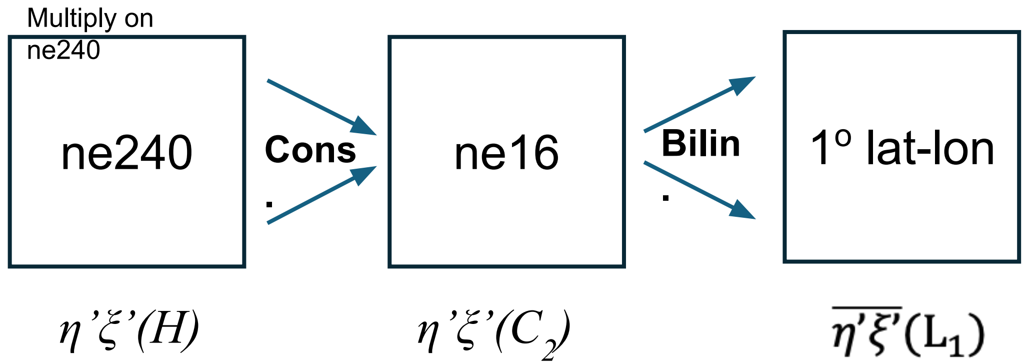
All other fields conservatively remapped from ne240 to 1° lat-lon



Wave perturbations are calculated on ne240

$$\xi'(H) = \xi(H) - \xi_B(H) \quad : \xi = T, U, V, w$$

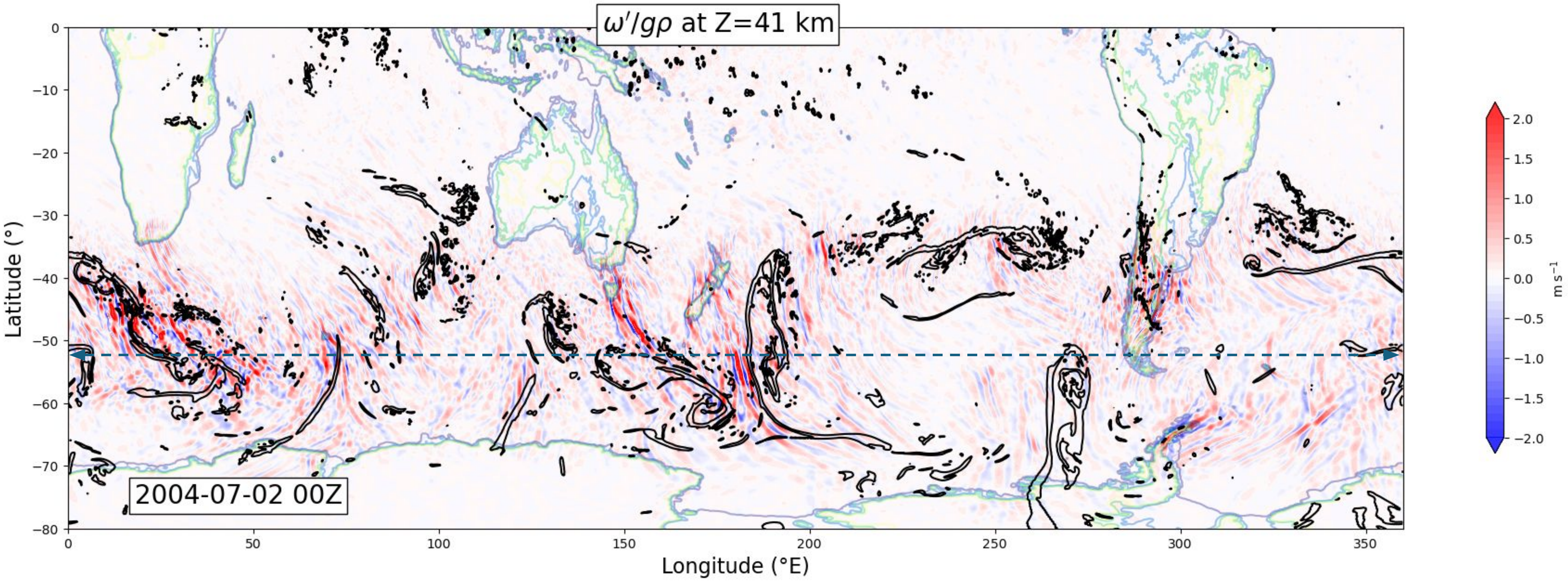
Fluxes calculated by conservative remapping of quadratics to ne16 then bilinear mapping to 1° lat-lon



$: \{\eta, \xi\} = T, U, V, w$

ne240 ~ 14 km Δx
ne16 ~ 224 km Δx

Snapshot from ne240 simulation

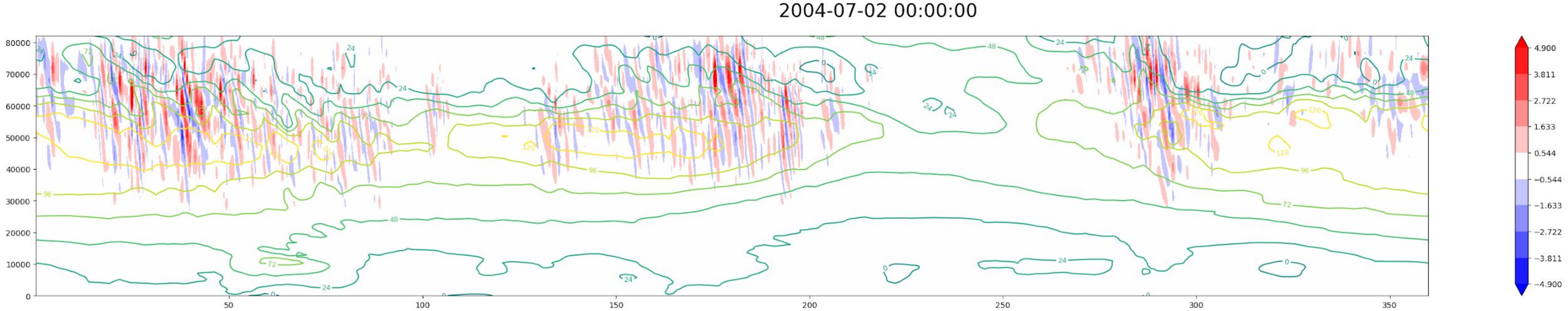


Black contours: vorticity at around z=5km. Color shading: vertical motion at around z=41km

Snapshot from ne240 simulation

simulation

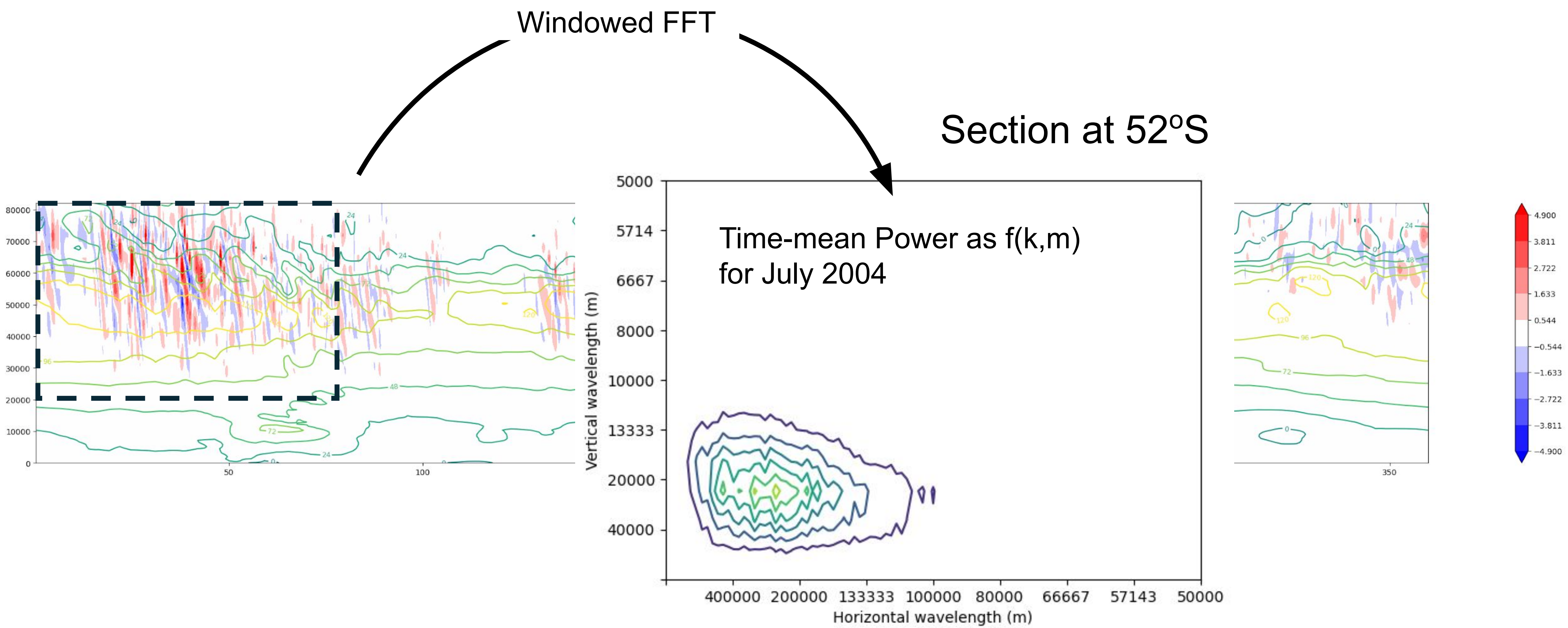
Section at 52ºS



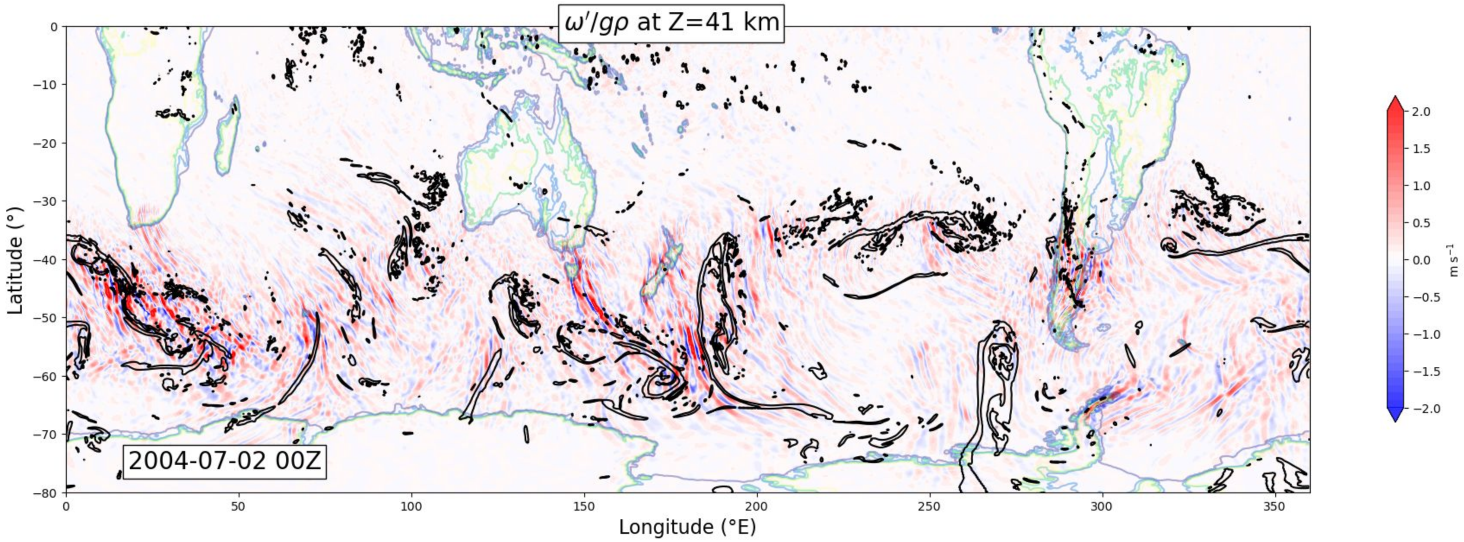
*Fields mapped from ne240 to 1/8ºx1/8º grid

Scale analysis for ne240 simulation

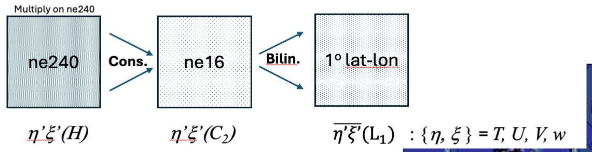
simulation

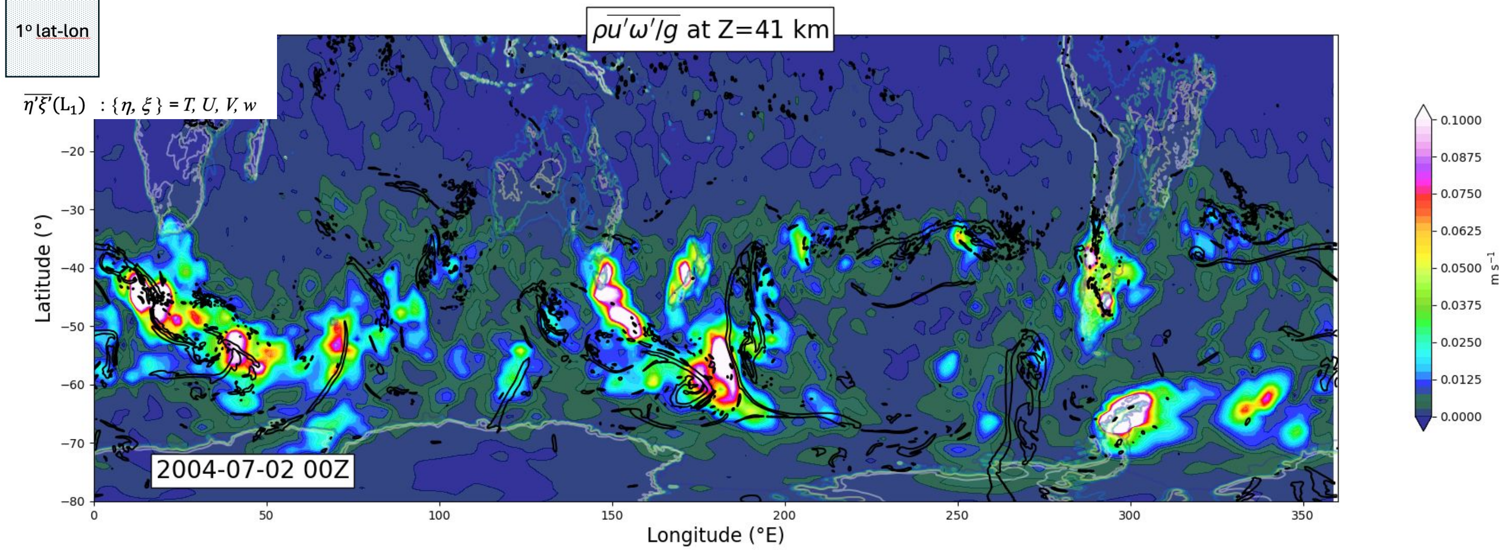


Snapshot from 14km simulation



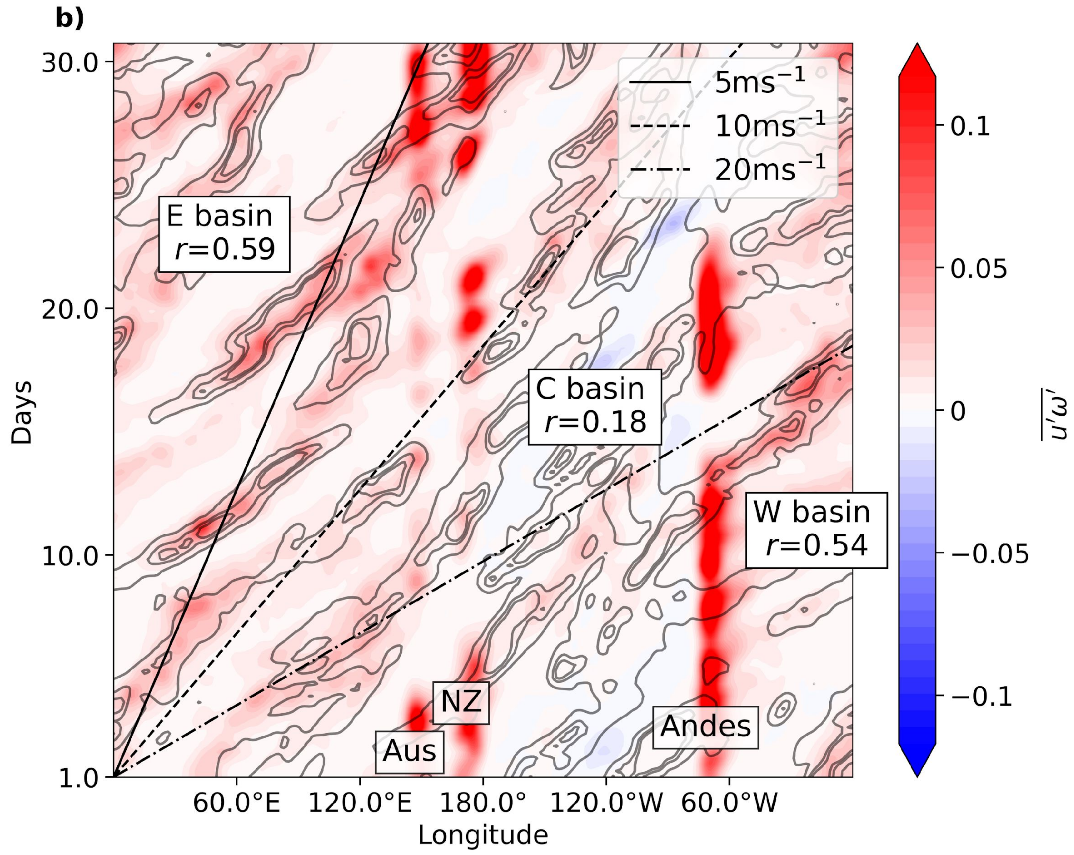
Black contours: vorticity at around z=5km. Color shading: vertical motion at around z=41km





Color shading: Diagnosed momentum fluxes from 14km-resolution run at around z=41km

Stratospheric GW fluxes seem to be "attached" to lower tropospheric flow features ...

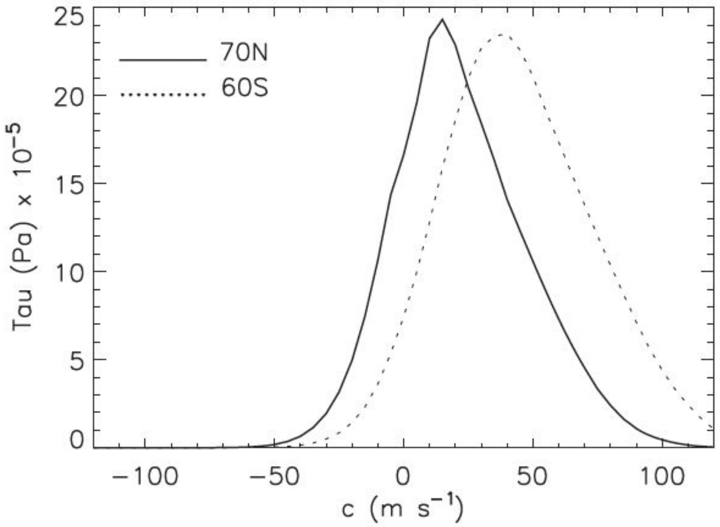


Shading: momentum flux at 20km

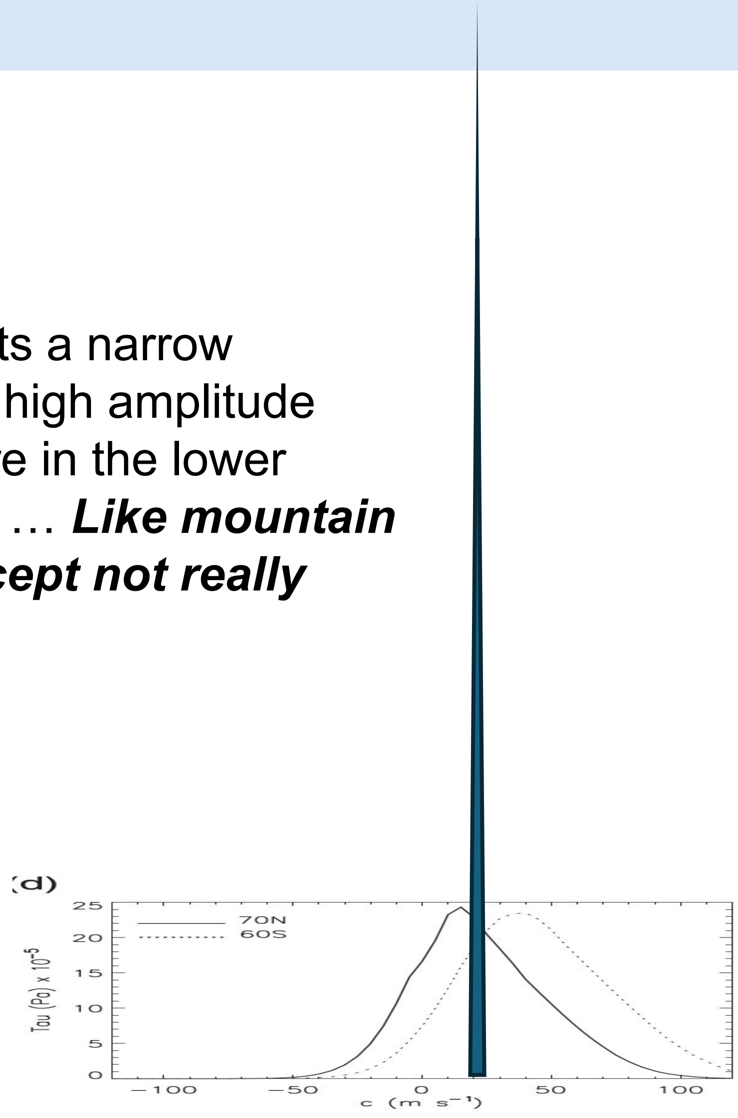
Contours: high vorticity at 5km

What we get from frontal GW vs. what the ne240 analysis seems to be telling us we need

Current frontal scheme (Charron&Manzini) produces a broad spectrum of waves.



ne240 suggests a narrow spectrum with high amplitude tied to a feature in the lower atmosphere… … ***Like mountain waves … except not really stationary***



Charron, M., & Manzini, E. (2002). Gravity waves from fronts: Parameterization and middle atmosphere response in a general circulation model. *Journal of the Atmospheric Sciences*, *59*(5), 923-941.

Synopsis

- High-resolution simulations suggest a GW source tied to effective obstacles produced by tropospheric flow
- Simple ”moving mountain” GW source contributes to improved simulations of SH wintertime jet and temperatures
  - Better theoretical justification needs to be developed
  - Relationship to fronts/frontogenesis should be explored
  - Tuning still needed …

Paper on moving mountain GW:

Bramberger, M., & Bacmeister, J. (2025). Improving representation of stratospheric Polar Vortex in Southern Hemisphere with low-frequency frontal waves. *Geophysical Research Letters*, *52*(20), e2025GL117854.

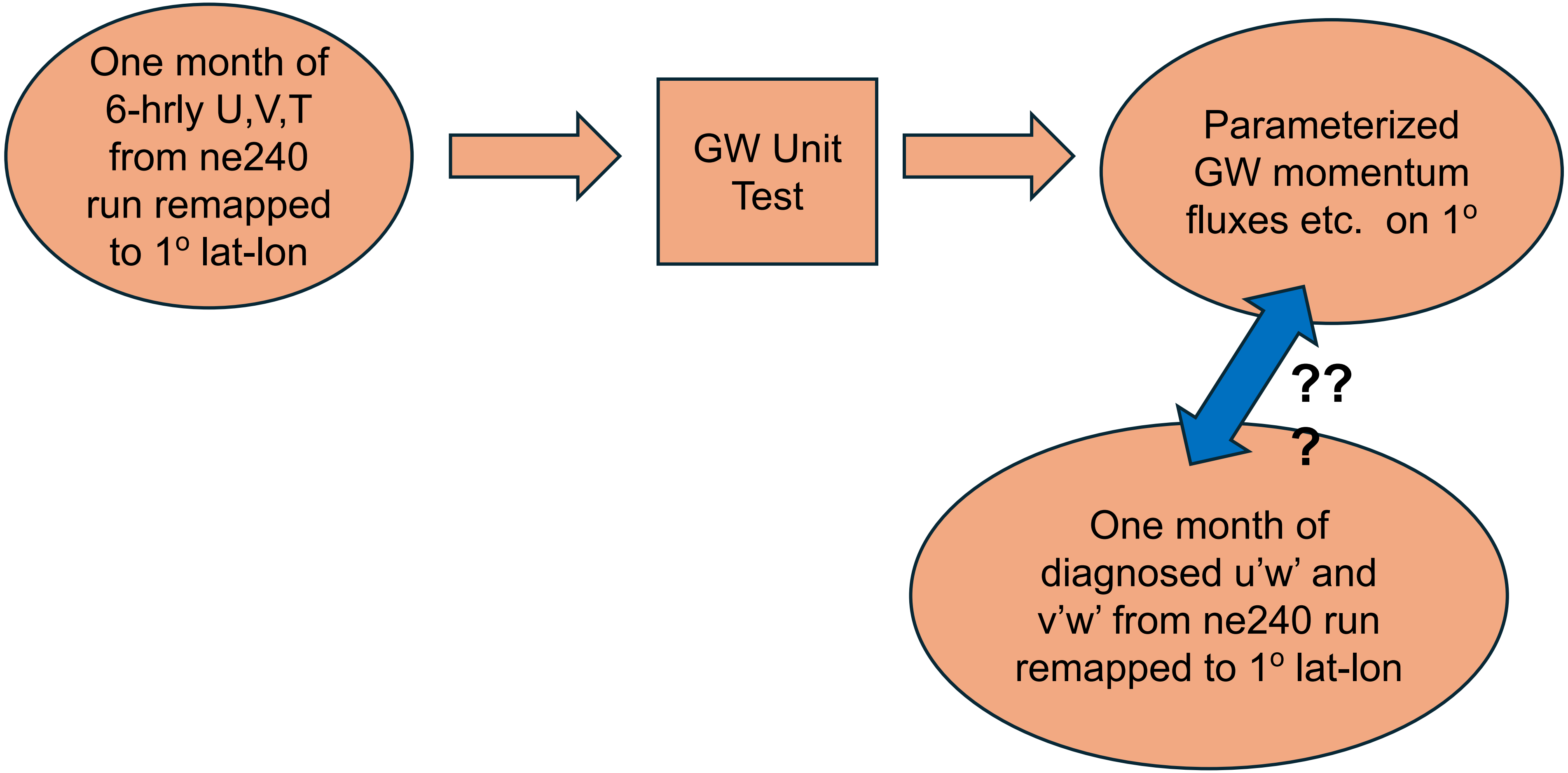
Off-line Unit Test for gravity wave parameterizations

(https://github.com/JulioTBacmeister/GW_UnitTest)

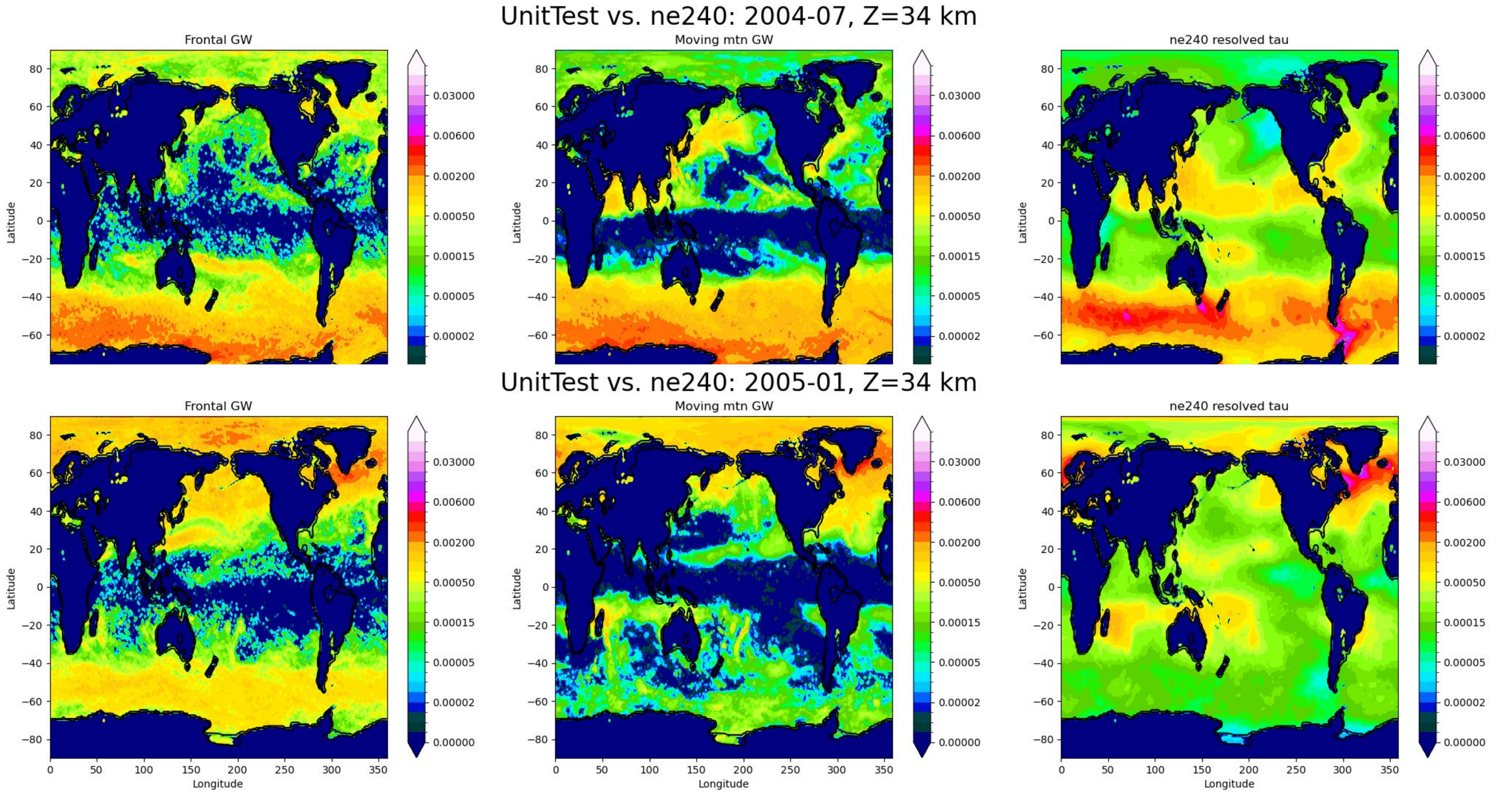
Unit Tests have not been easy to make for CAM parameterizations. Hope CCPP (a new software infrastructure) will make this easier … or unnecessary .

Unit Test Code doesn't yet include convective GW. Shouldn't be too hard but …

Unit test driven with remapped ne240 fields compared to diagnosed momentum fluxes



Unit test driven with remapped ne240 fields compared to resolved momentum fluxes



Summary, Questions, and Future Plans

- Offline GW Unit Test shows some agreement with ne240 results.
- Source for ”moving mountains” needs a theory.
  - What is relationship to frontogenesis, convection, shallow convection, PBL turbulence?
- Is ne240 sufficient to test GW parameterizations for 1^{o} models?
  - Analysis of CESM-MPAS 3.75km DYAMOND runs has begun
- Can we detect secondary generation of GW? In ne240? In 3.75km MPAS?
- Do moving mountain GW have any impacts on seasonal forecasts …? Sudden Warmings?
- Can Unit Test analysis assist in ML parameterization development?
- Should we remove CM frontal GW? Mesopause simulation would need to be addressed.

Infrastructure note …

- “CCPP” - Common Community Physics Package (Software infrastructure intended to facilitate physics sharing between models. Joint with NOAA) will be used after CAM7.0
- Gravity wave codes have already been CCPP-ized (thanks Haipeng Lin!)
- GW “Unit Test” will be moved to this infrastructure … ASAP

Thank
you