

The path toward the vertical resolution of CAM7 and some new insights into its impacts

Vertical resolution task team and others: **Isla Simpson, Julio Bacmeister, Julie Caron, Nick Davis, Rolando Garcia, Cecile Hannay, Cristiane Jablonowski, Peter Lauritzen, Brian Medeiros, Rich Neale, Lorenzo Polvani, Yaga Richter, Simone Tilmes, Adam Herrington**

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SCRIPPS CW3E/NSF NCAR SMYLE team: **Michael DeFlorio, Luca Delle Monache, Jiabao Wang, Isla Simpson, Nora Mascioli, Jim Edwards, Nan Rosenbloom, Matthew Simpson, Gokhan Danabasoglu, Peter Gibson, Patrick Mulrooney, Yaga Richter, Steve Yeager, Aneesh Subramanian**



The change in CAM's vertical resolution is old news...

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The purpose of this talk:

- (1) Summarize what we learned from the vertical resolution task team simulations with a more complete analysis than was performed at the time.
- (2) Introduce some new simulations that will be available soon and can be used to explore the impacts of free tropospheric/stratospheric resolution on climate variability and change.

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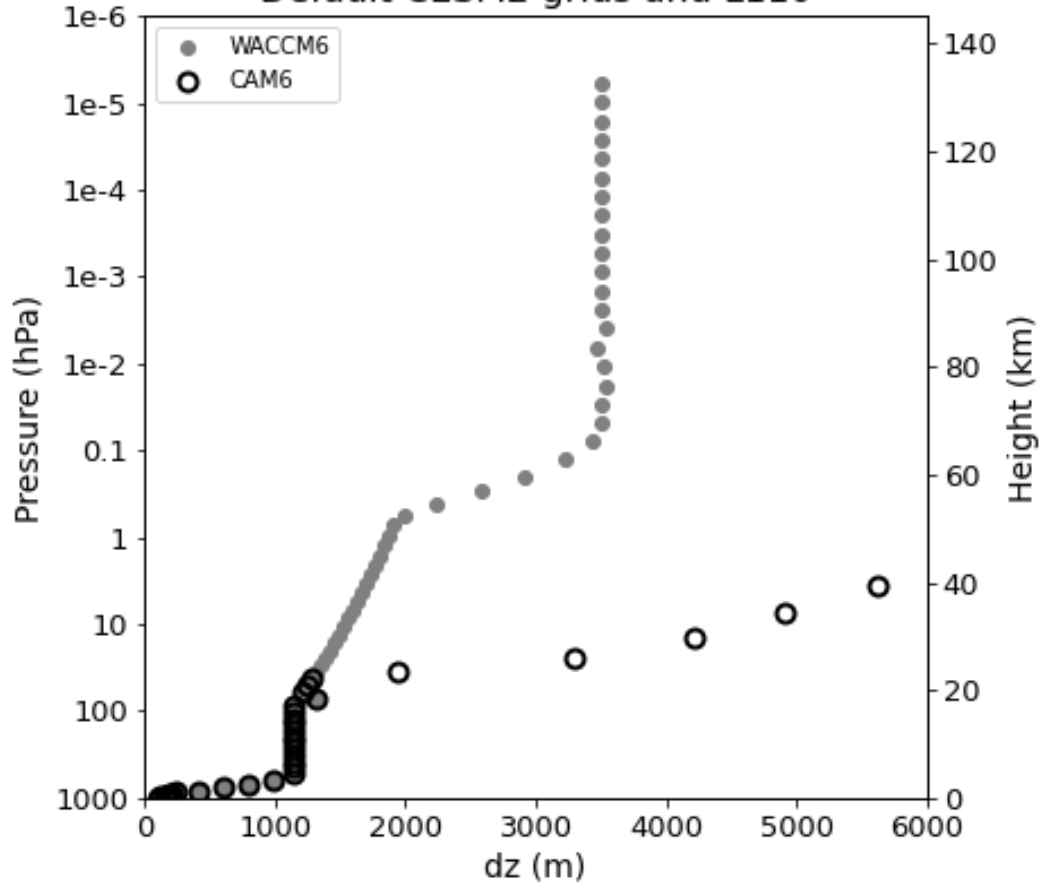
- (1) Summarize what we learned from the vertical resolution task team simulations with a more complete analysis than was performed at the time.
- (2) Introduce some new simulations that will be available soon and can be used to explore the impacts of free tropospheric/stratospheric resolution on climate variability and change.

Note: I won't be focusing on the changes in the boundary layer resolution as changes in physics and tuning have to accompany that.

Everything I'm showing here is using CESM2 with CAM6 physics and the FV dycore. The only thing that is changing is the vertical resolution. So these are clean tests of the impact of vertical resolution, but things could look very different in CAM7 with all the other changes that are implemented.

Why are we changing CAM's vertical resolution?

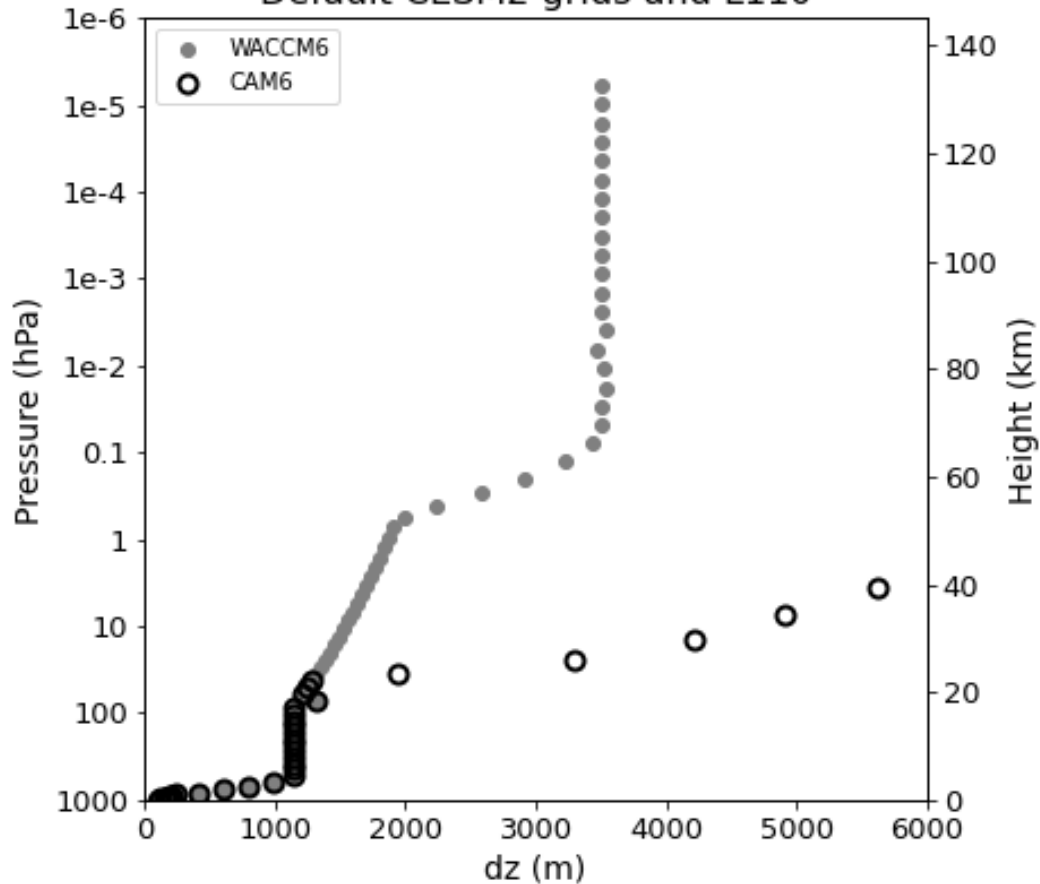
Default CESM2 grids and L110



Why are we changing CAM's vertical resolution?

(1) It has become well established that the stratosphere has an influence on the troposphere. WACCM6 had a good representation of the stratosphere, but CAM6 is lacking compared to most models nowadays

Default CESM2 grids and L110



NEWS & VIEWS

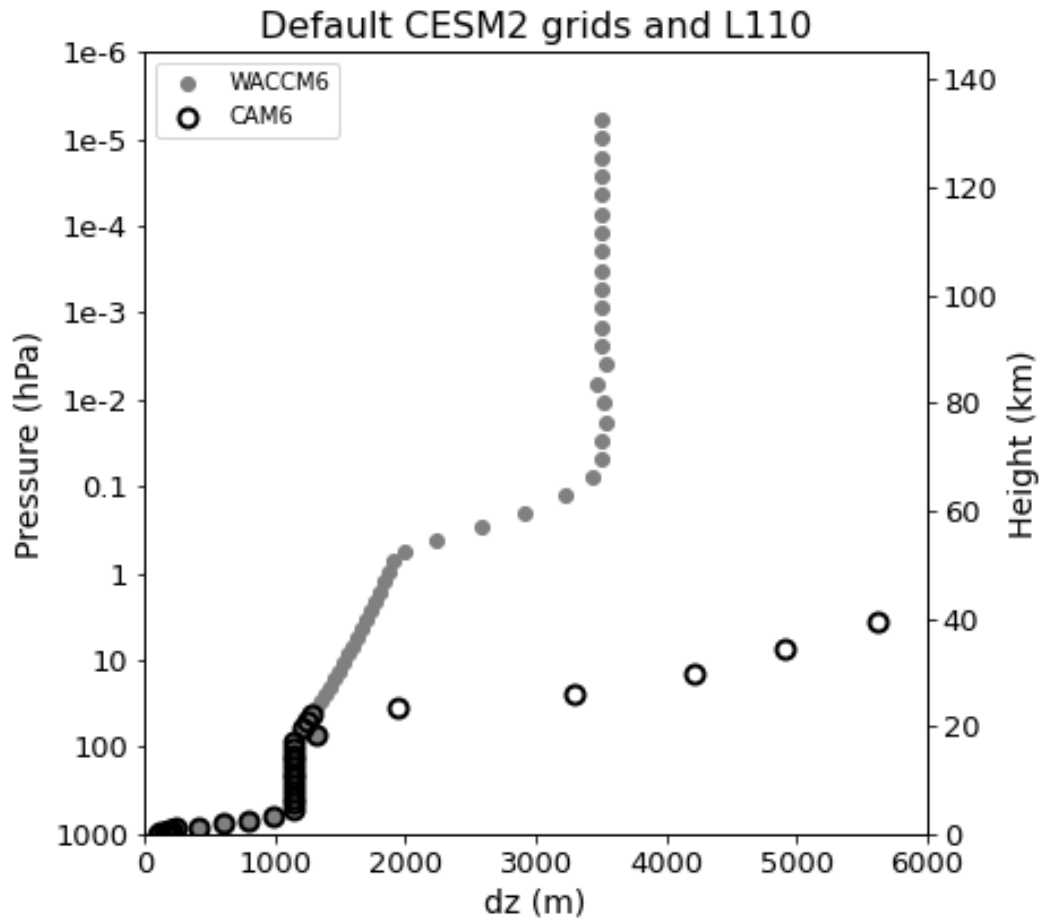
ATMOSPHERIC SCIENCE

Raising the roof

Shaw and Shepherd (2008) *Nature Geoscience*

The atmosphere's lowermost 10 km have long been assumed to be almost solely responsible for weather and climate on Earth. Emerging evidence points to the layer above as an important influence on surface winds and temperatures on seasonal to decadal timescales.

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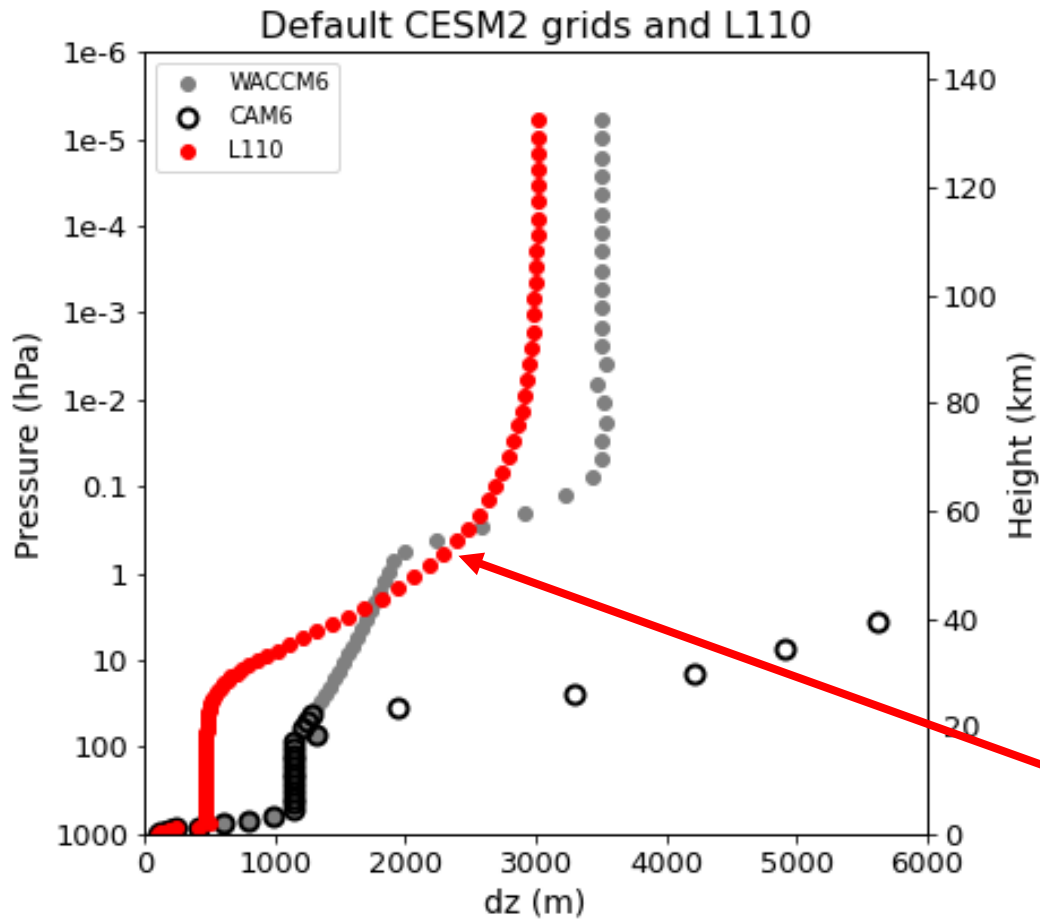
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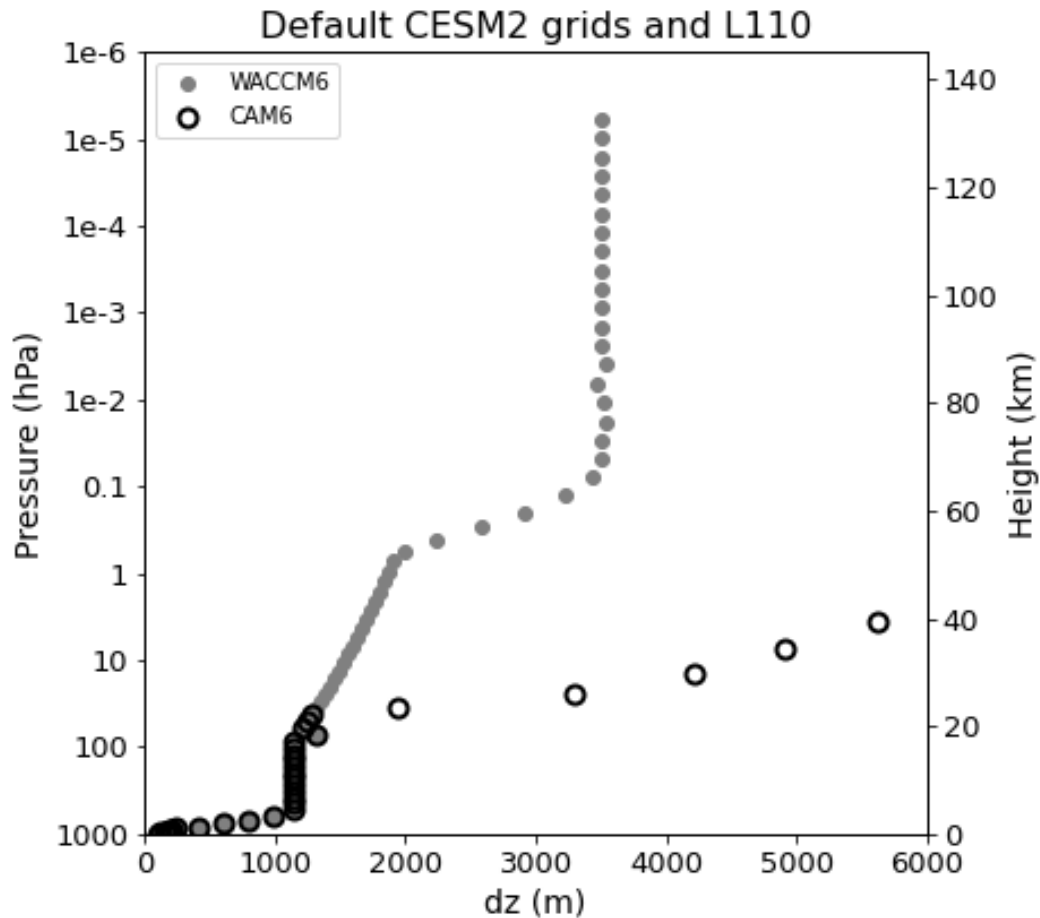
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The 110 level configuration of Garcia and Richter (2019) resulted in an improved QBO.

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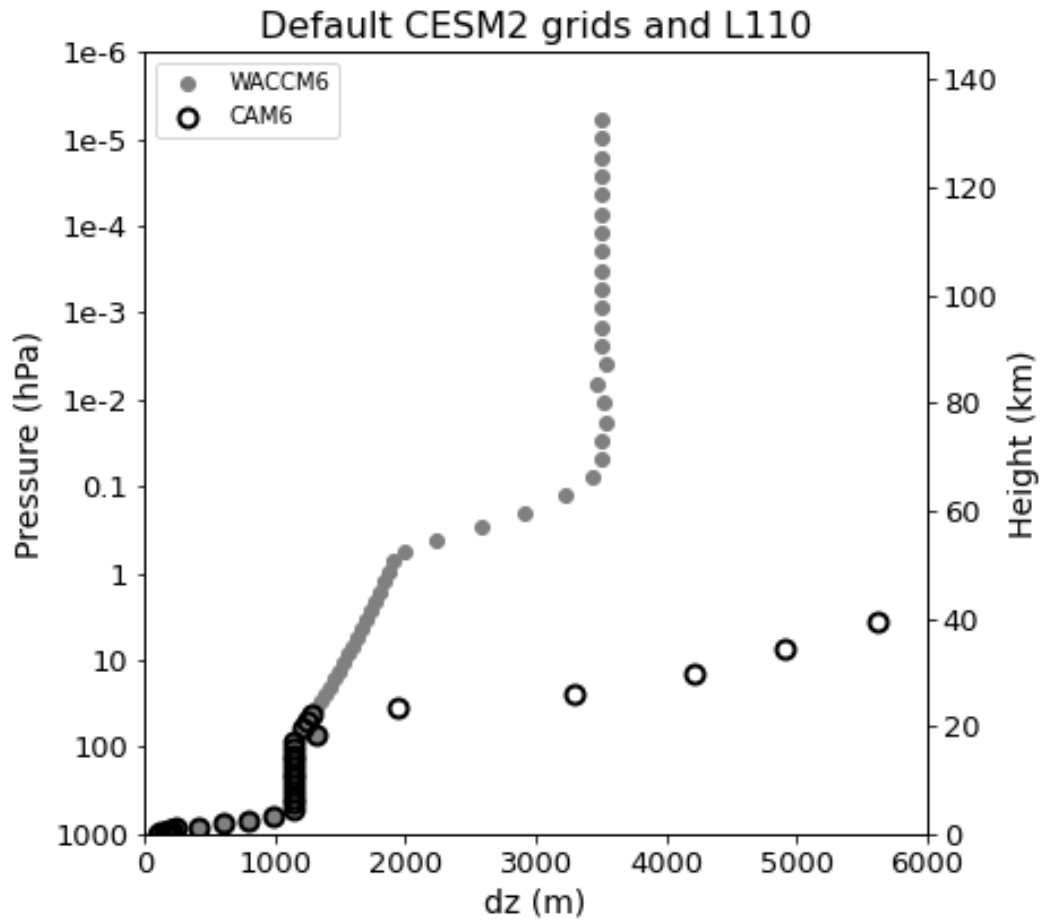
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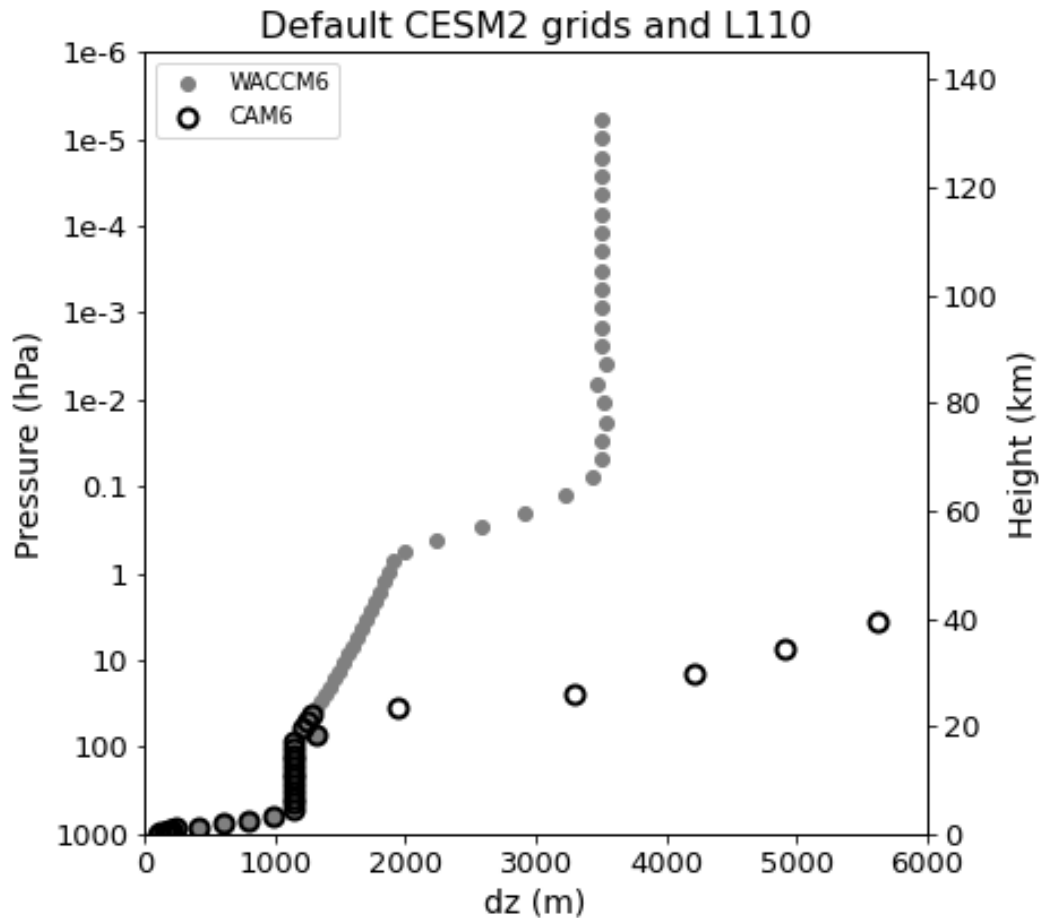
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(3) WACCM is difficult to initialize from other reanalyses because its model top is too high.

(4) As we move toward higher horizontal resolution, with regional refinement, or globally, higher vertical resolution is likely beneficial.

(5) We wanted to lower the lowest model level and increase resolution in the boundary layer.

Why should we care about the QBO?

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You

Why should we care about the QBO?



ChatGPT

The Quasi-Biennial Oscillation (QBO) is an atmospheric phenomenon that occurs in the equatorial stratosphere, characterized by alternating winds that change direction roughly every 14 months on average. While it may seem distant and irrelevant to everyday life, the QBO actually has significant impacts on weather patterns and climate around the globe.

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CECILE

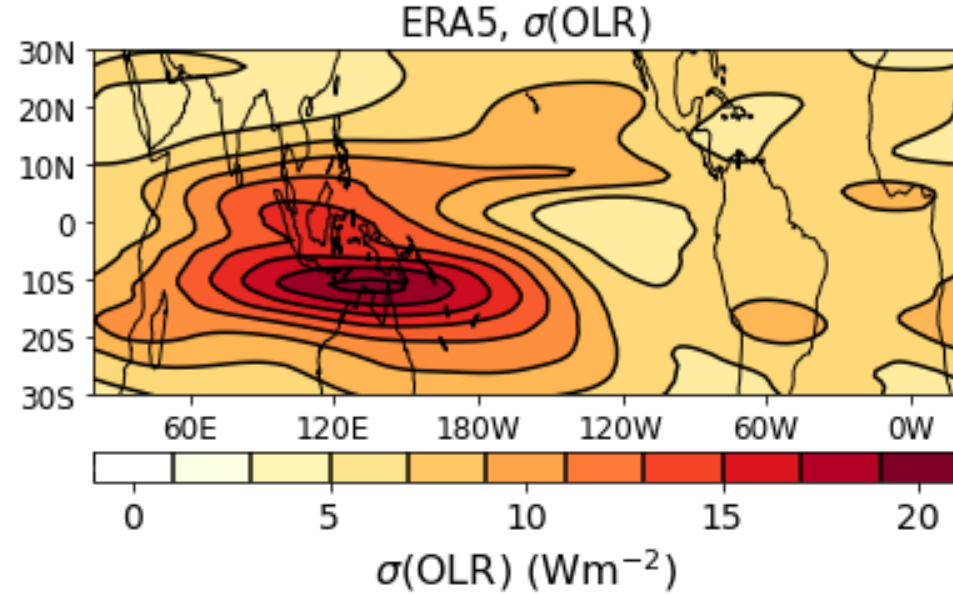
Why should I not care about the qbo?



CHATGPT

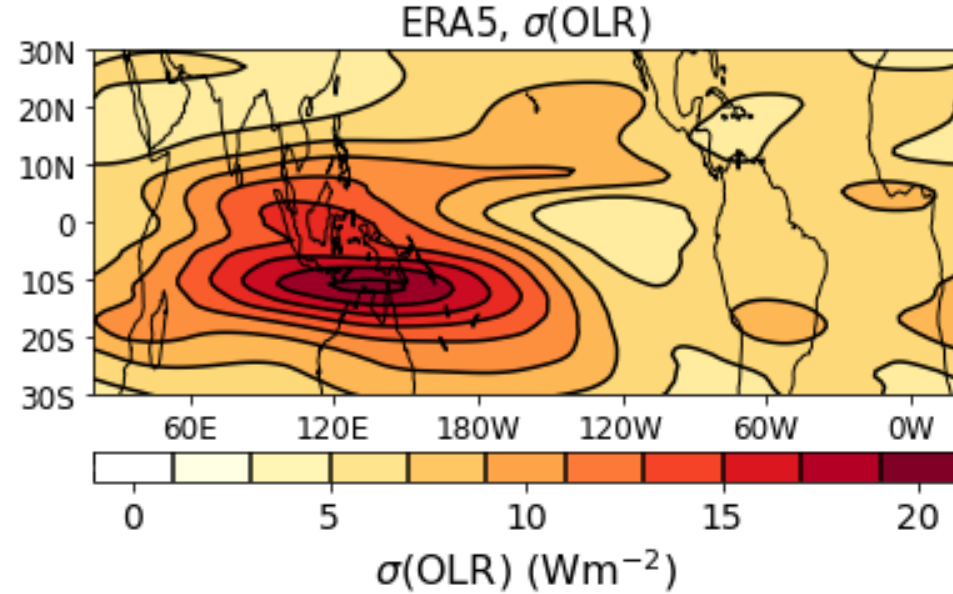
The Quasi-Biennial Oscillation (QBO) is a phenomenon related to stratospheric winds, which doesn't have a direct impact on everyday life for most people. Unless you're a meteorologist, atmospheric scientist, or someone studying climate patterns, it's not something you need to worry about in your daily life.

The most compelling reason (to me) why we care about the QBO?

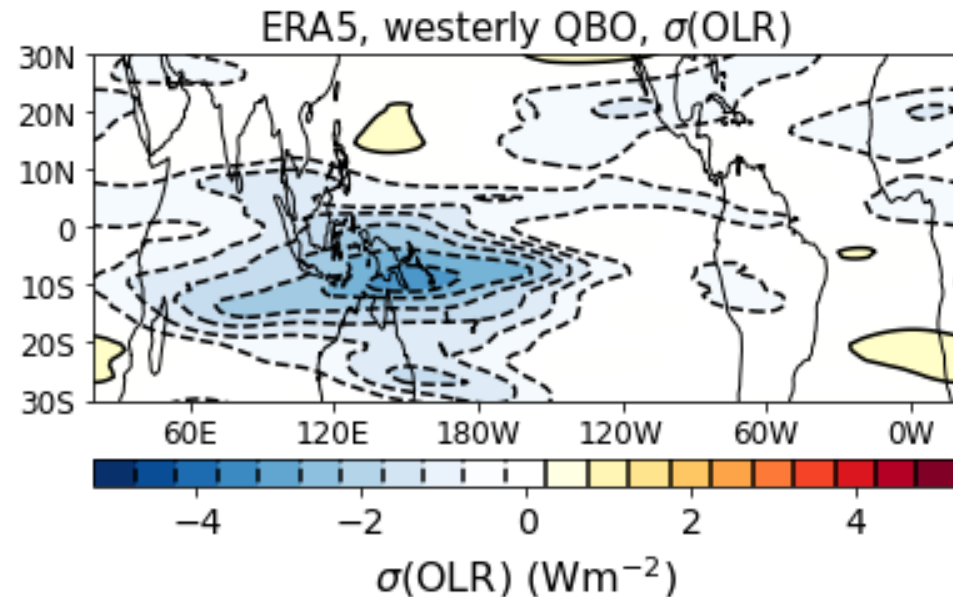


DJF, MJO filtered daily OLR variance
i.e., filtering daily OLR to retain only zonal
wavenumbers 1 to 5 and periods 20 to 100 days

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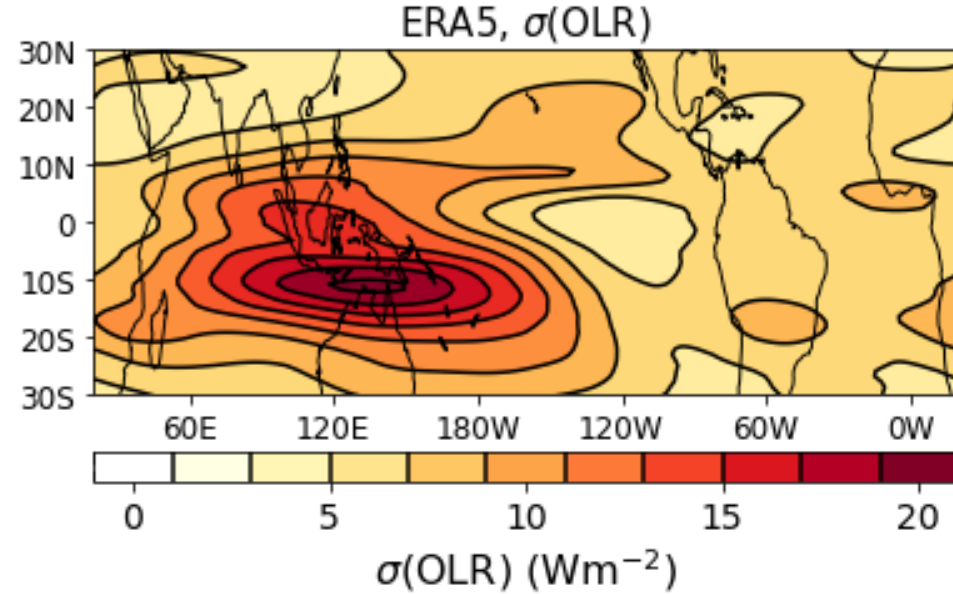


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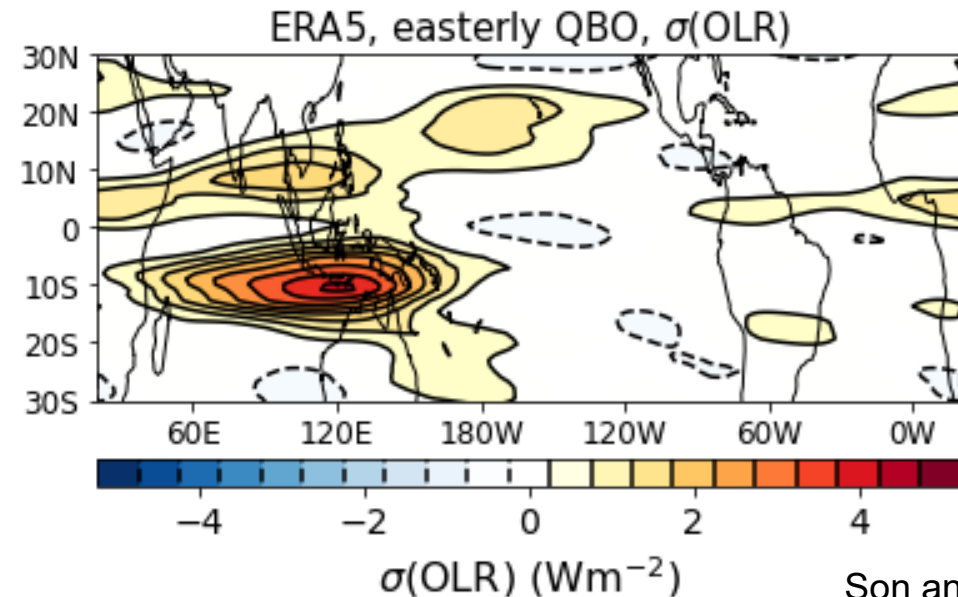
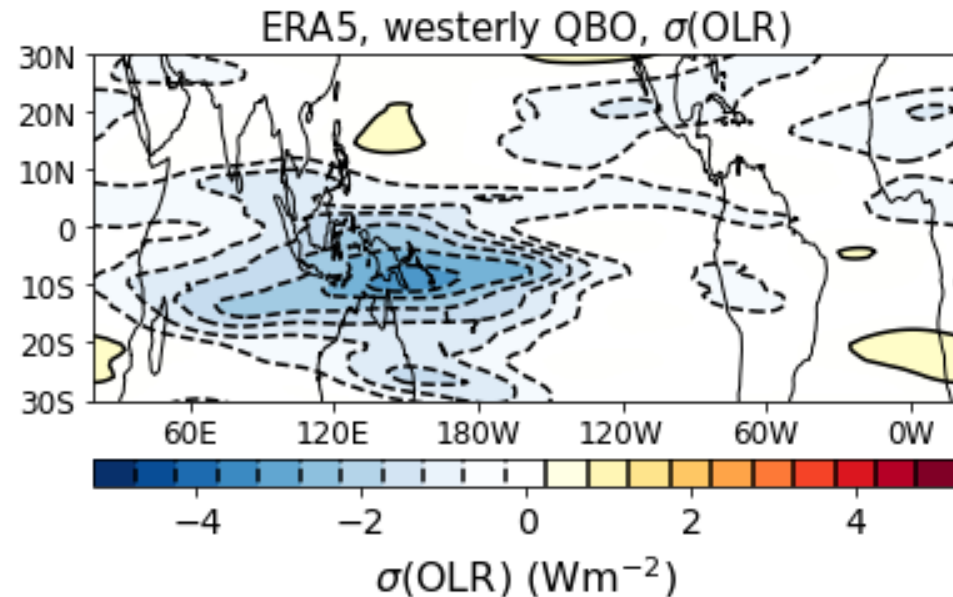
← Anomalies relative to climatology during winters
when the QBO at 50 hPa is westerly

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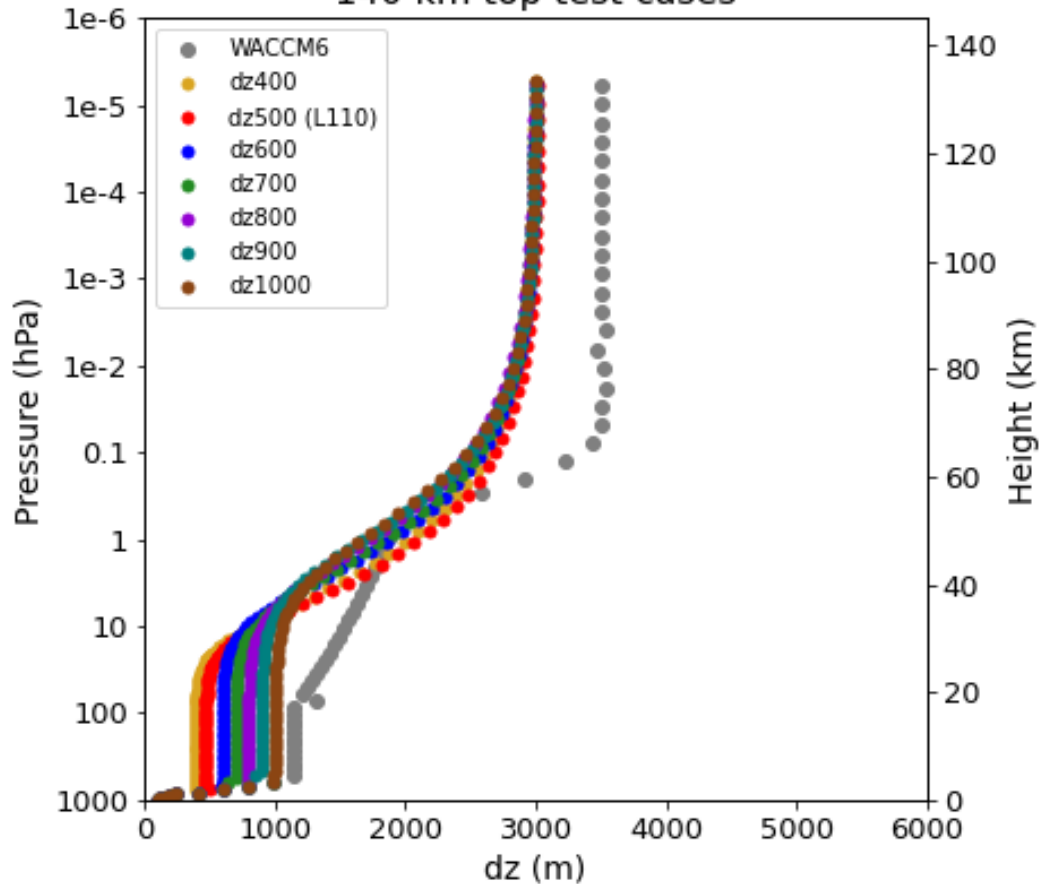
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Anomalies relative to climatology during winters
when the QBO at 50 hPa is easterly



The vertical resolution task team work

140 km top test cases



How much does the vertical grid spacing in the free troposphere and lower stratosphere impact on the QBO and other things?

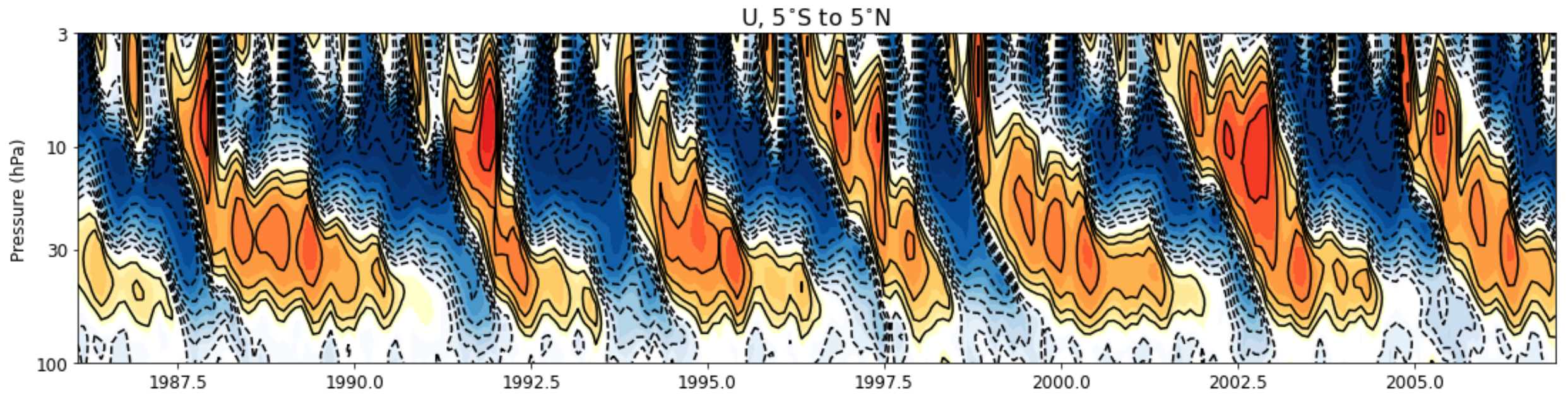
← A series of grids with the spacing (dz) in the free troposphere/lower stratosphere ranging from 1000 m to 400 m

Tapering off following a hyperbolic tangent to 3km grid spacing at the model lid at around 140 km

The dz=500 case is the same as the 110 level model of Garcia and Richter (2019)

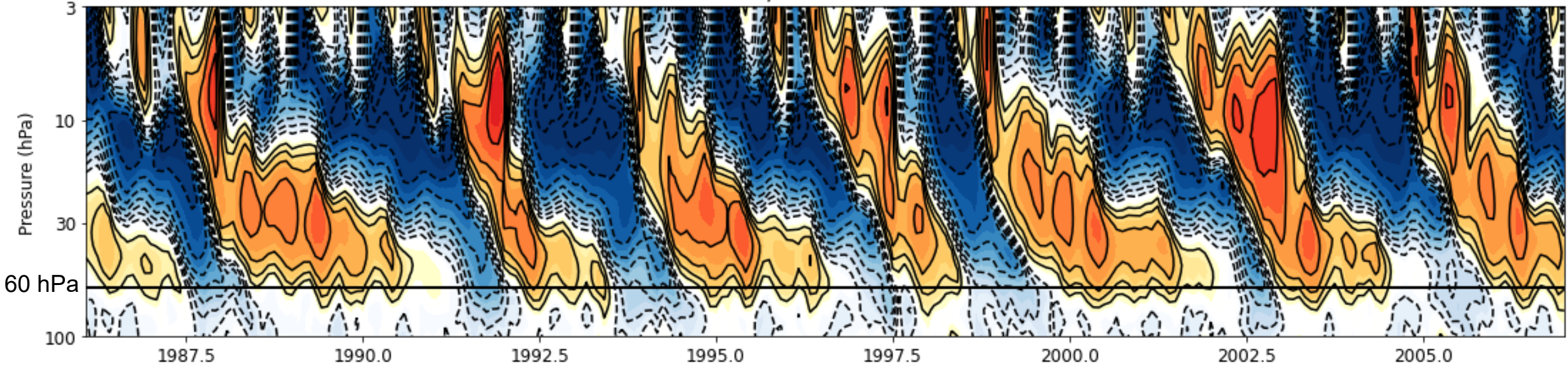
F-cases (prescribed SST), ~20 years

QBO composite method



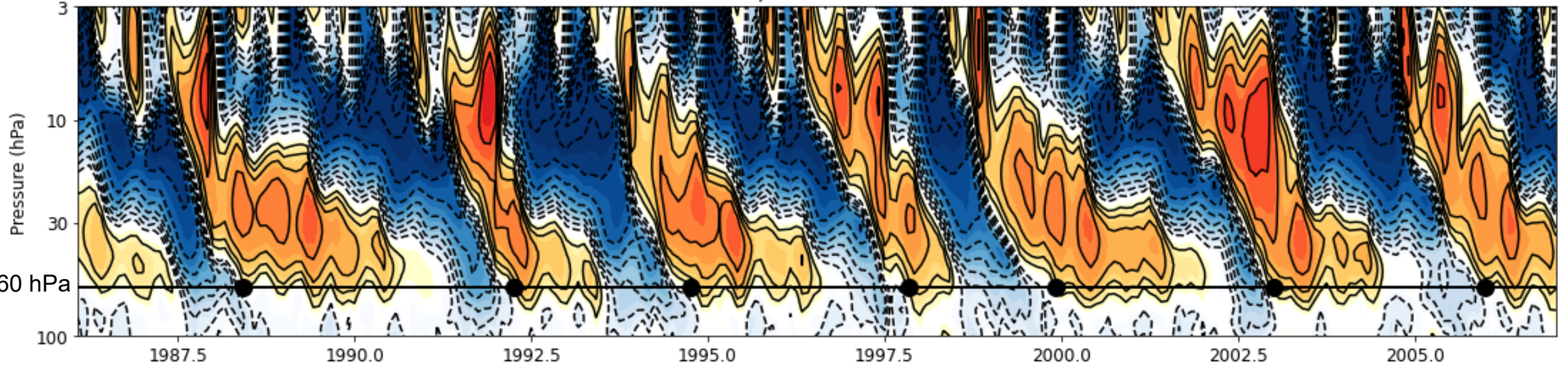
QBO composite method

U, 5°S to 5°N

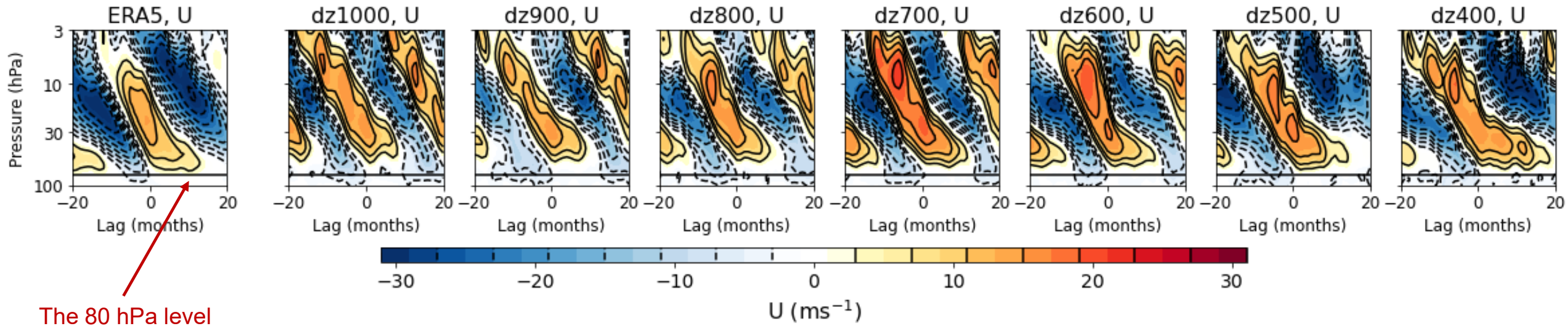


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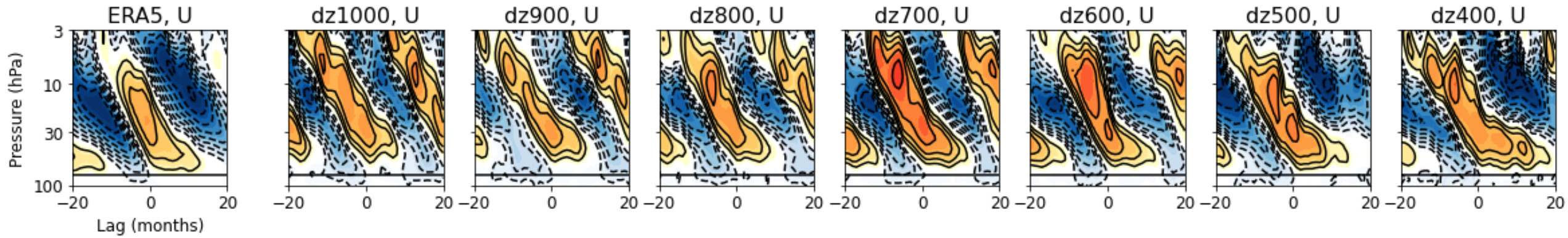
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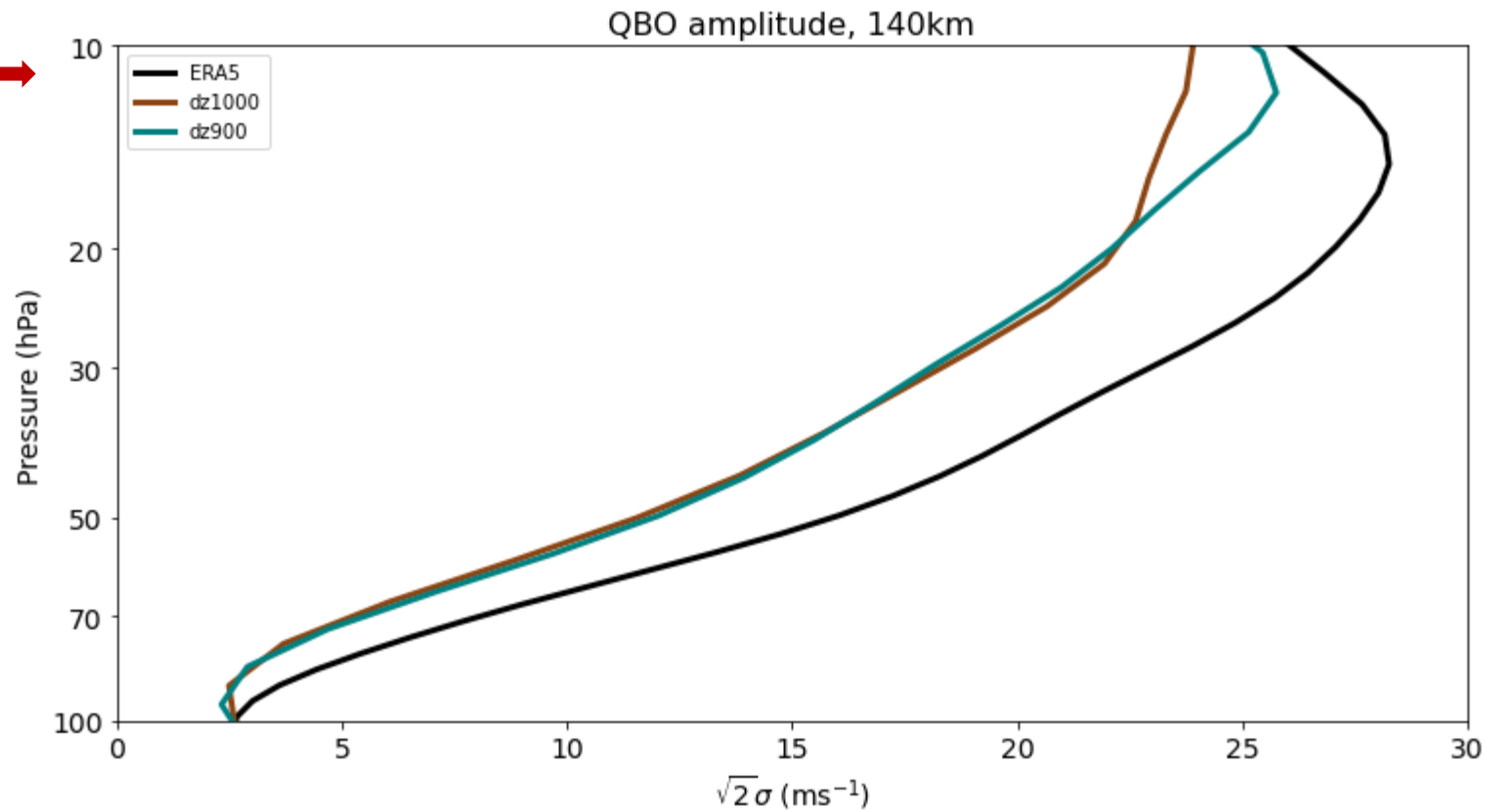
The influence of grid spacing on the QBO



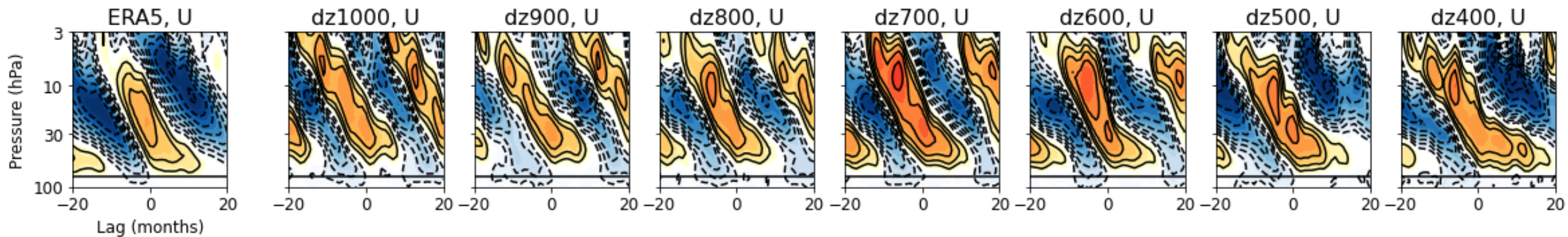
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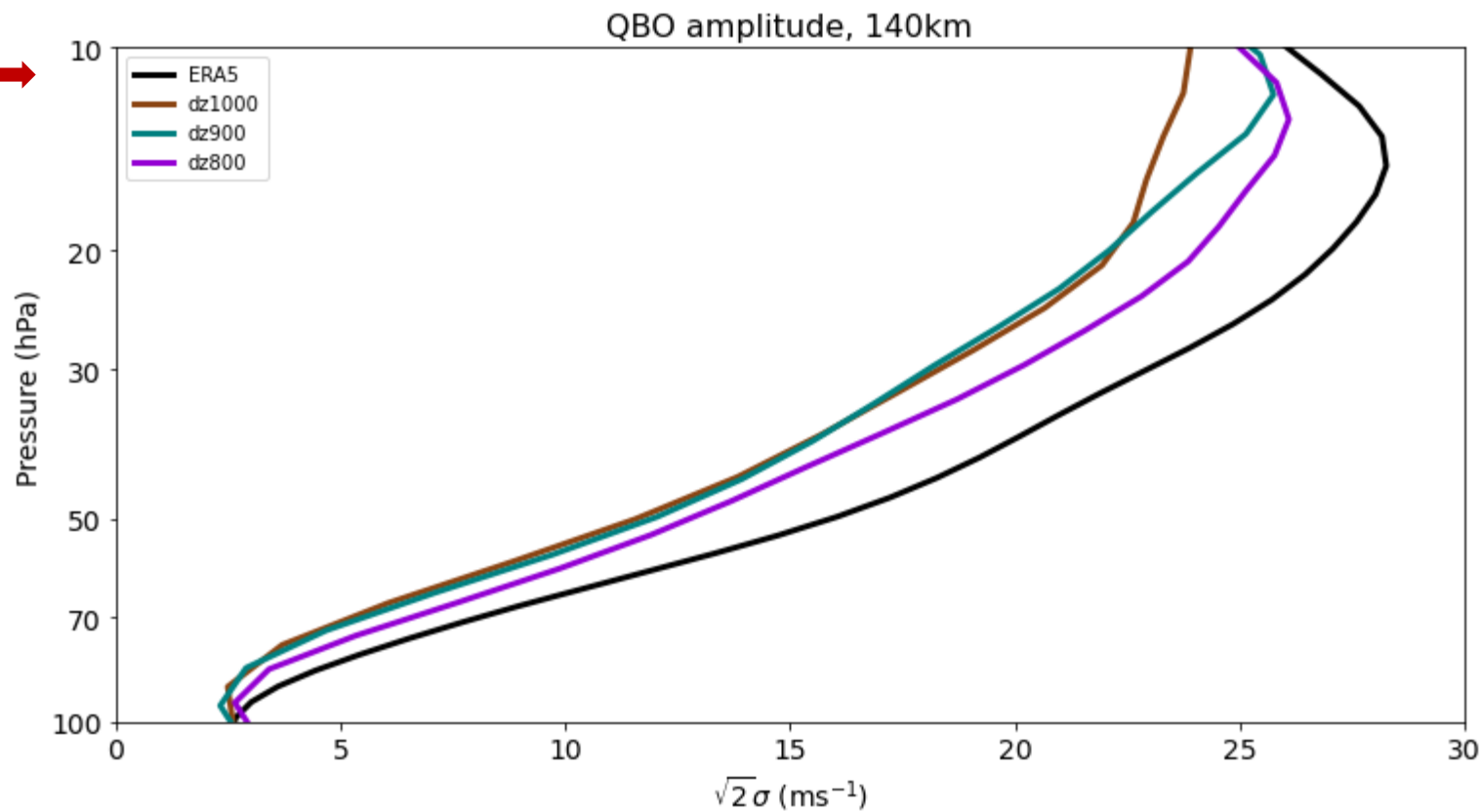
Dunkerton and Delisi QBO amplitude →



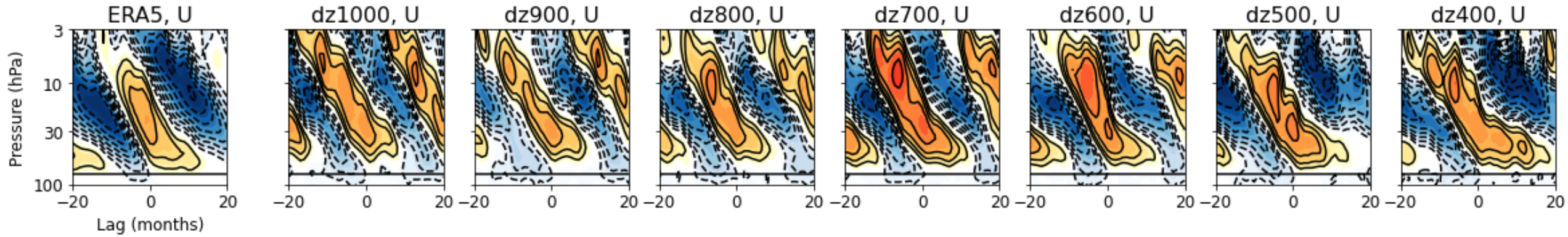
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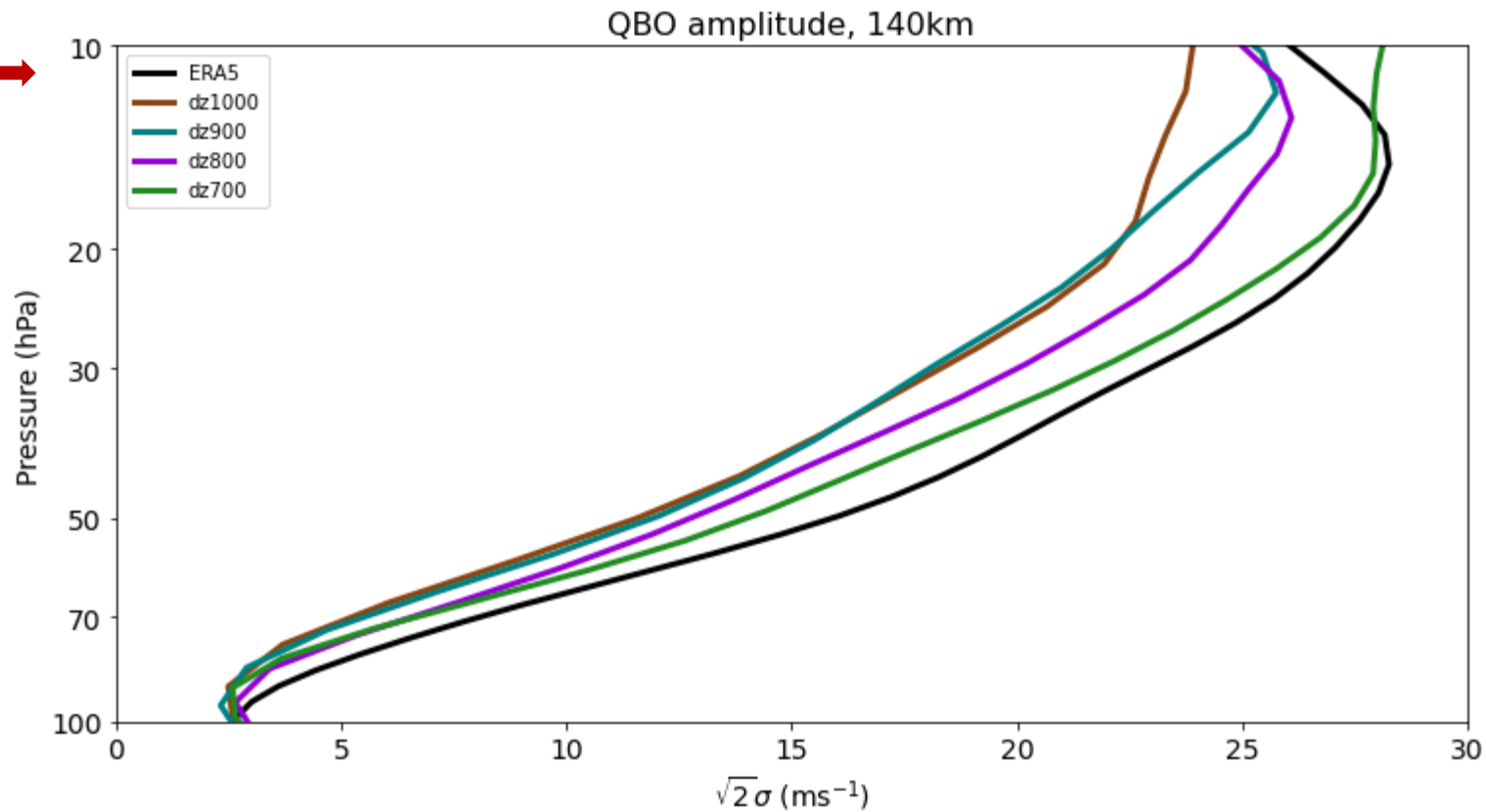
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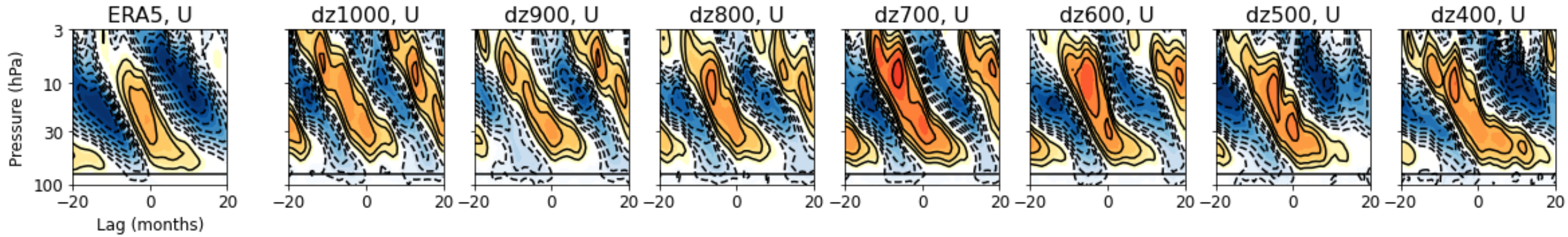
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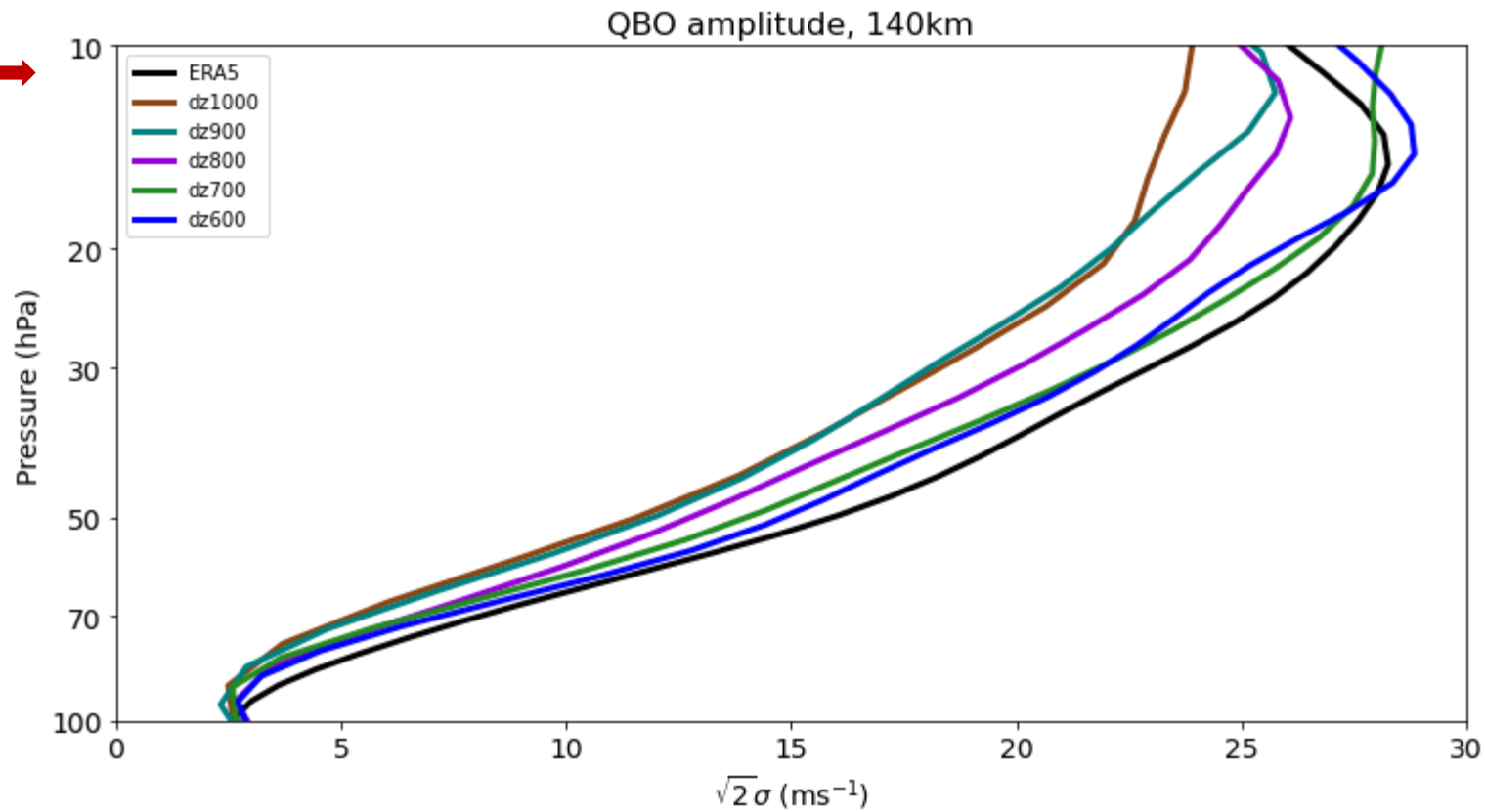
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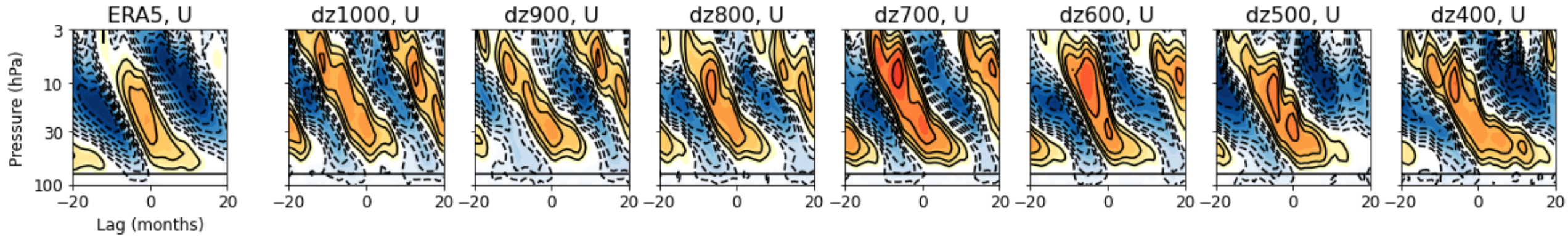
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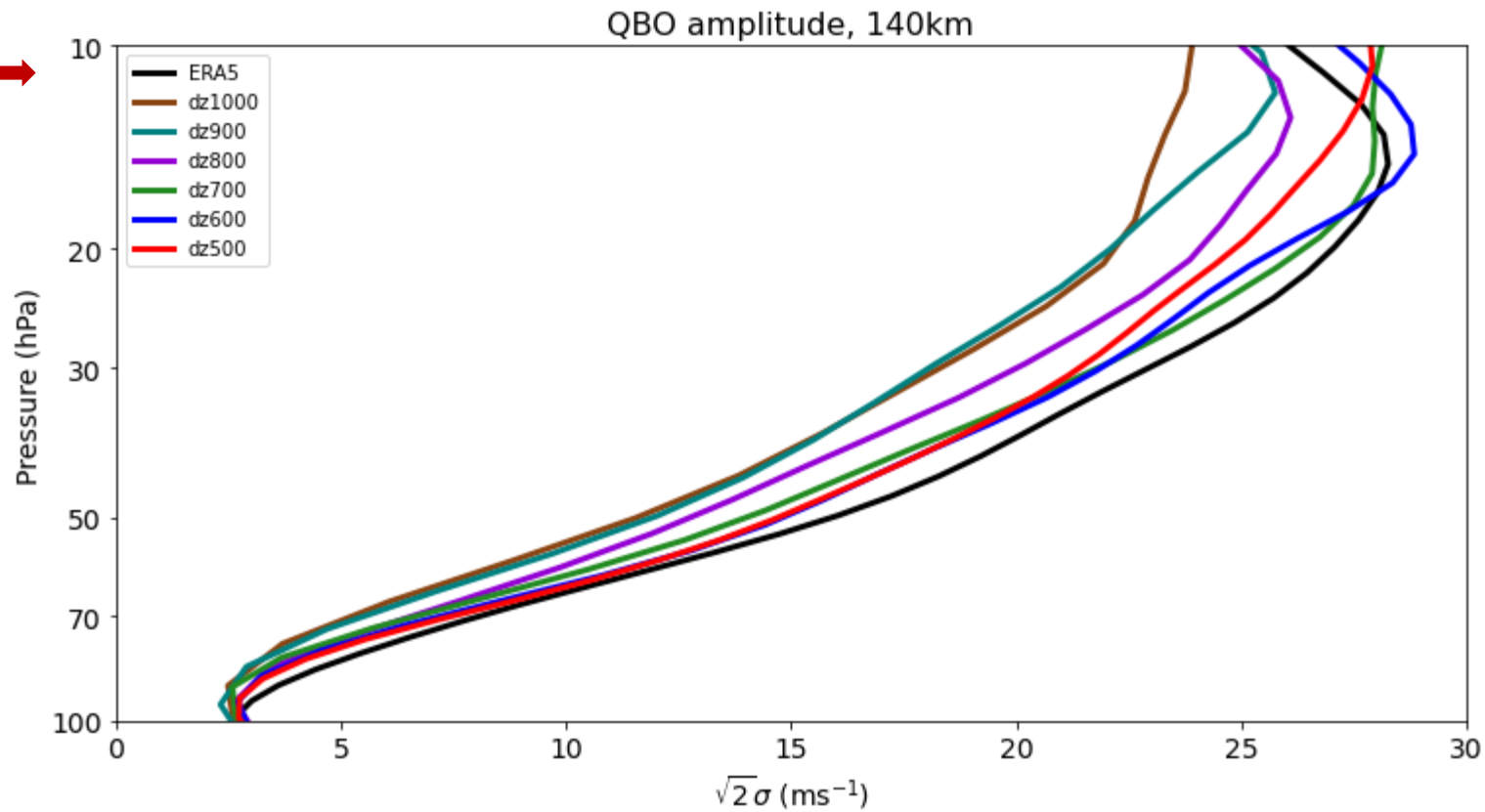
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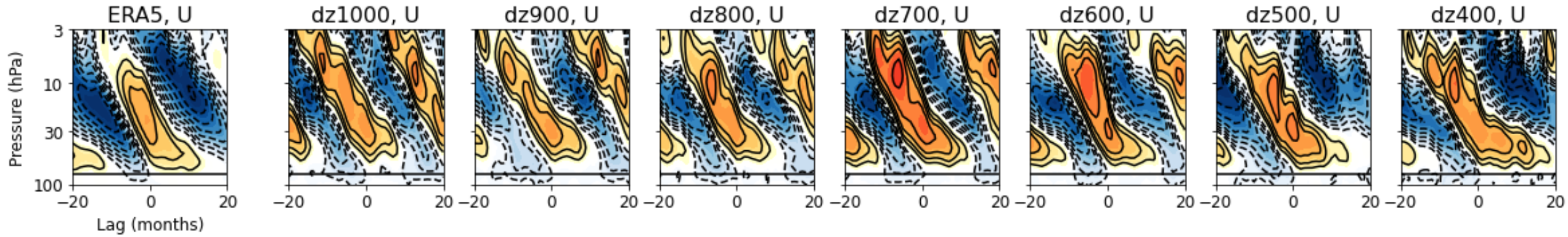
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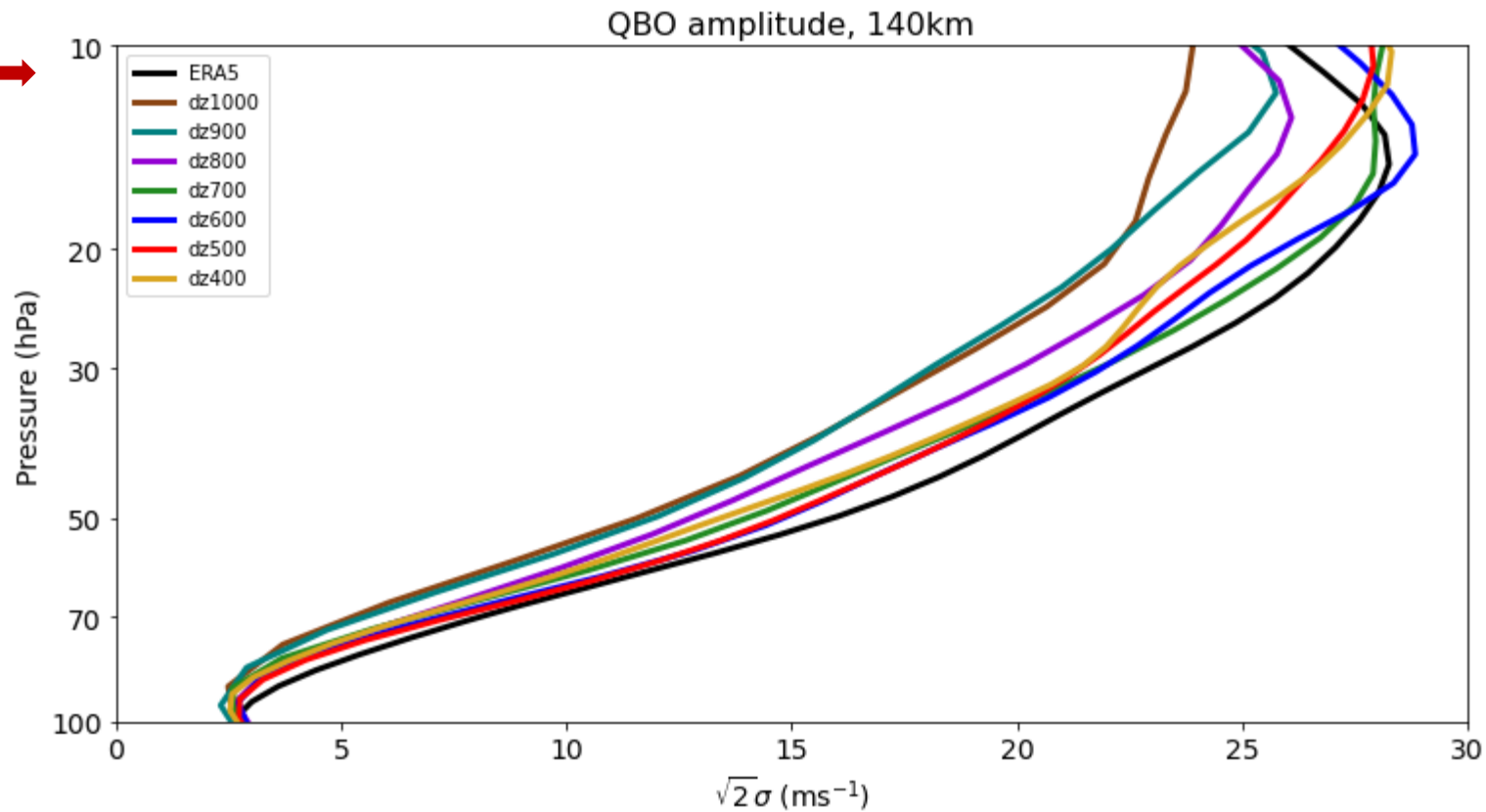
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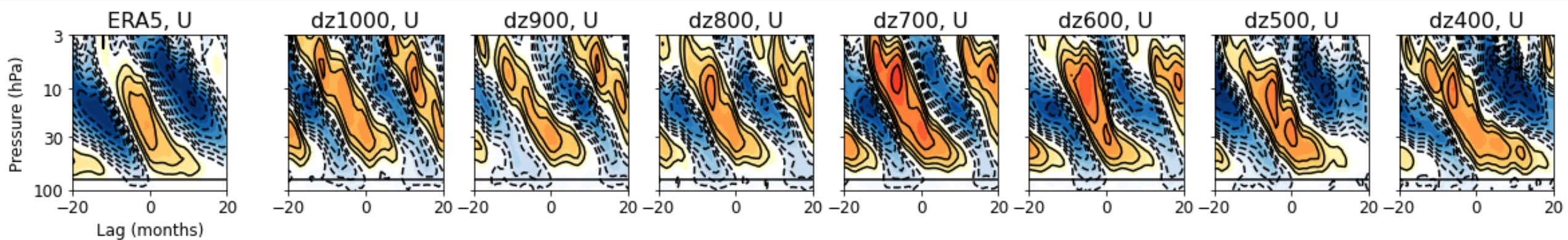
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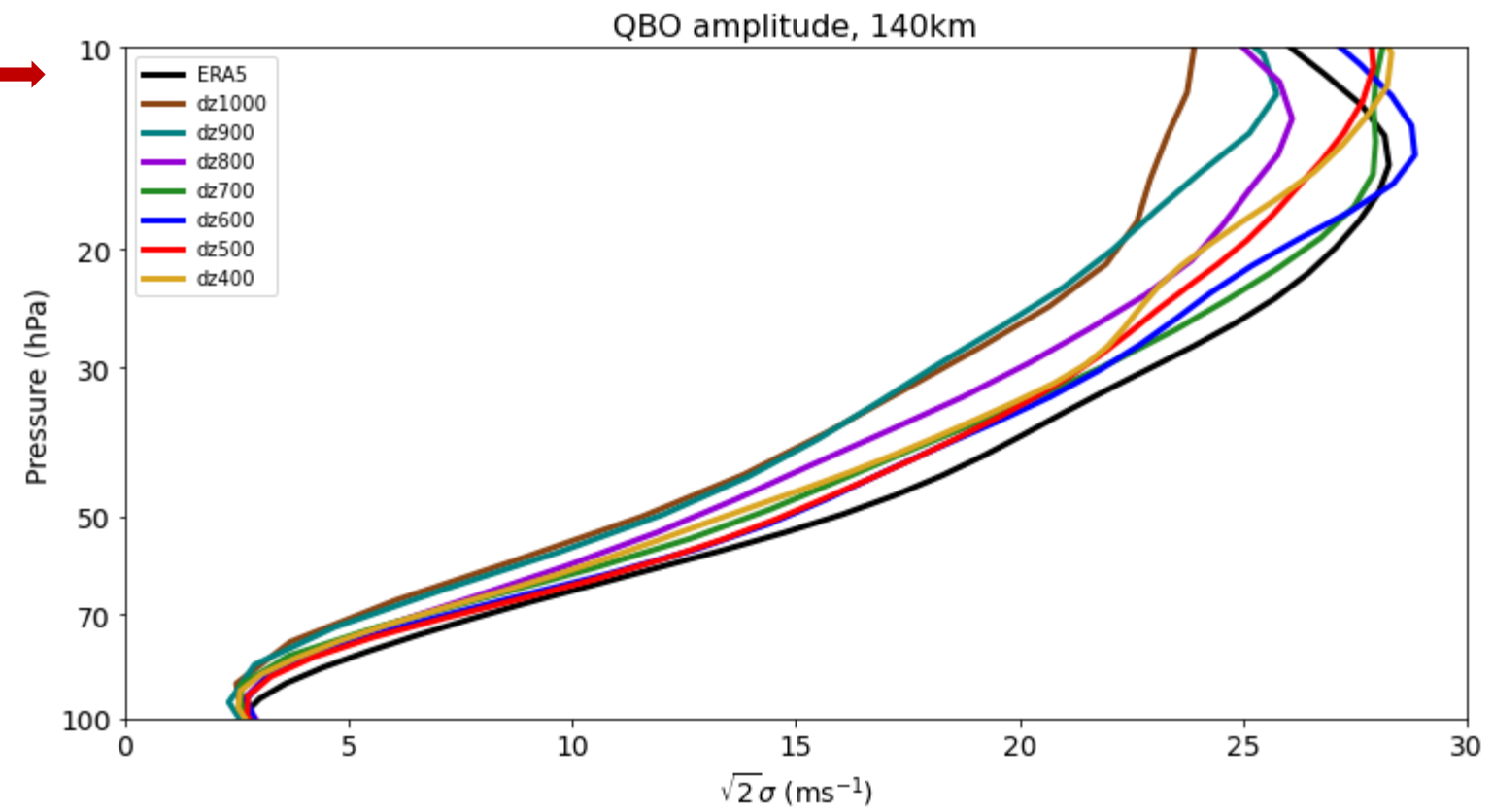


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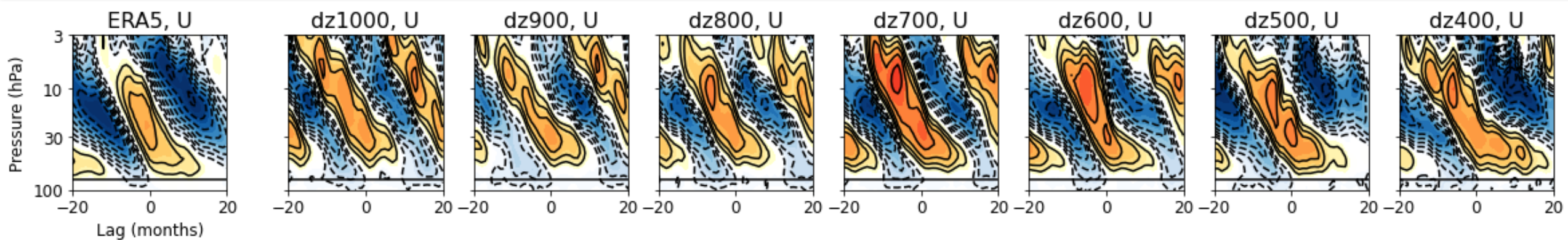


Dunkerton and Delisi QBO amplitude \rightarrow

Resolutions lower than dz700 seem to be deficient in the amplitude of the QBO

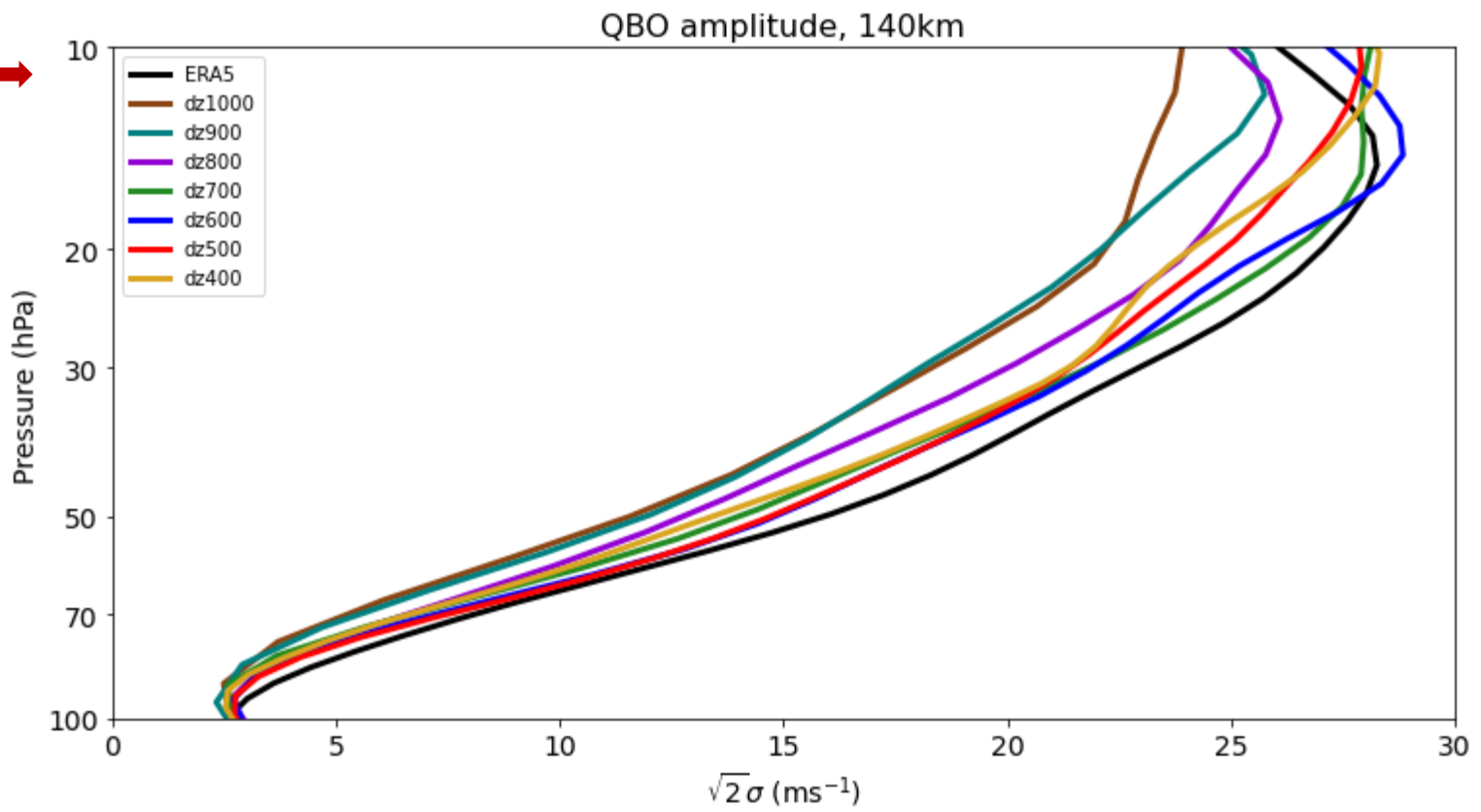


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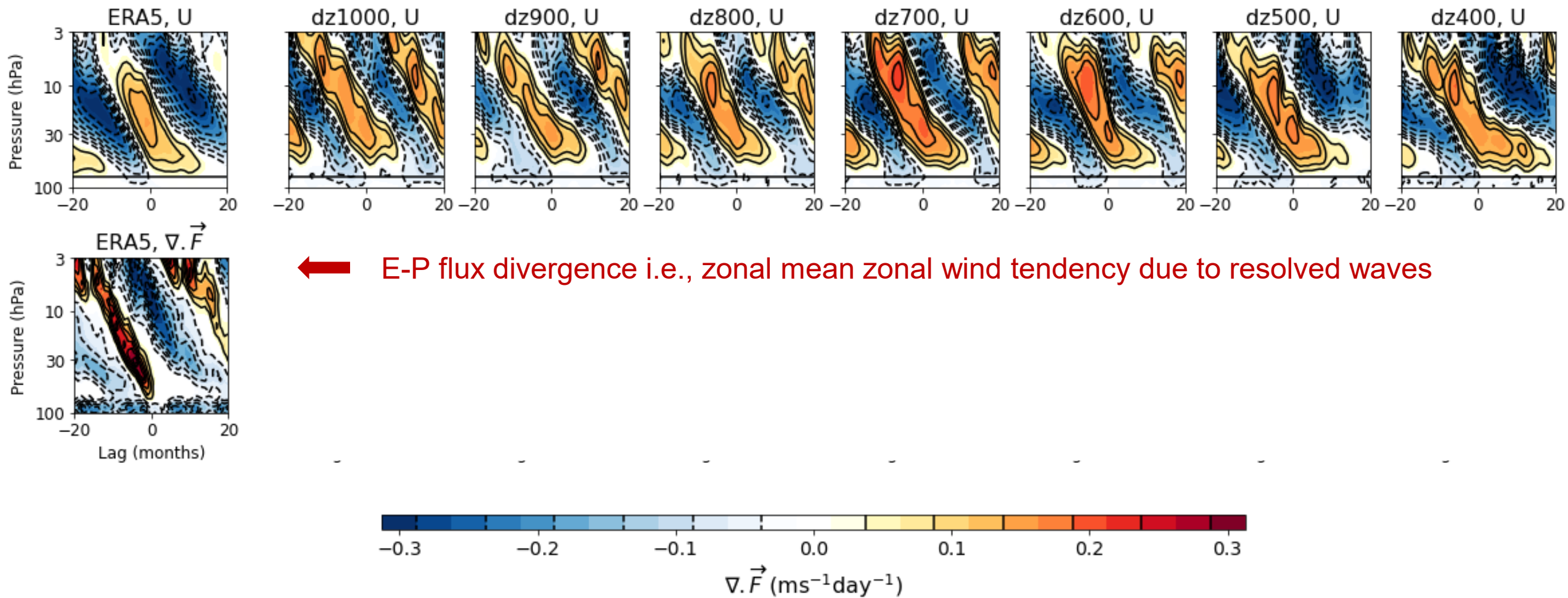
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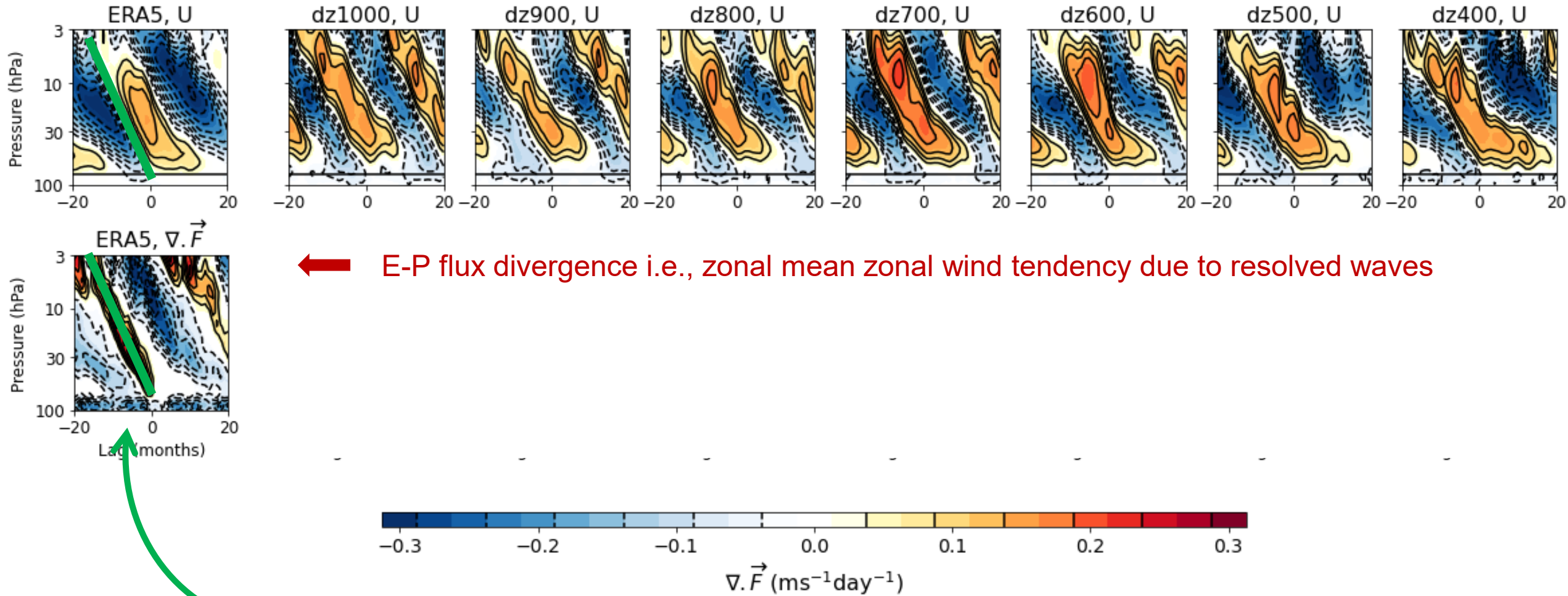


What about the processes driving the QBO?

The influence of grid spacing on the QBO



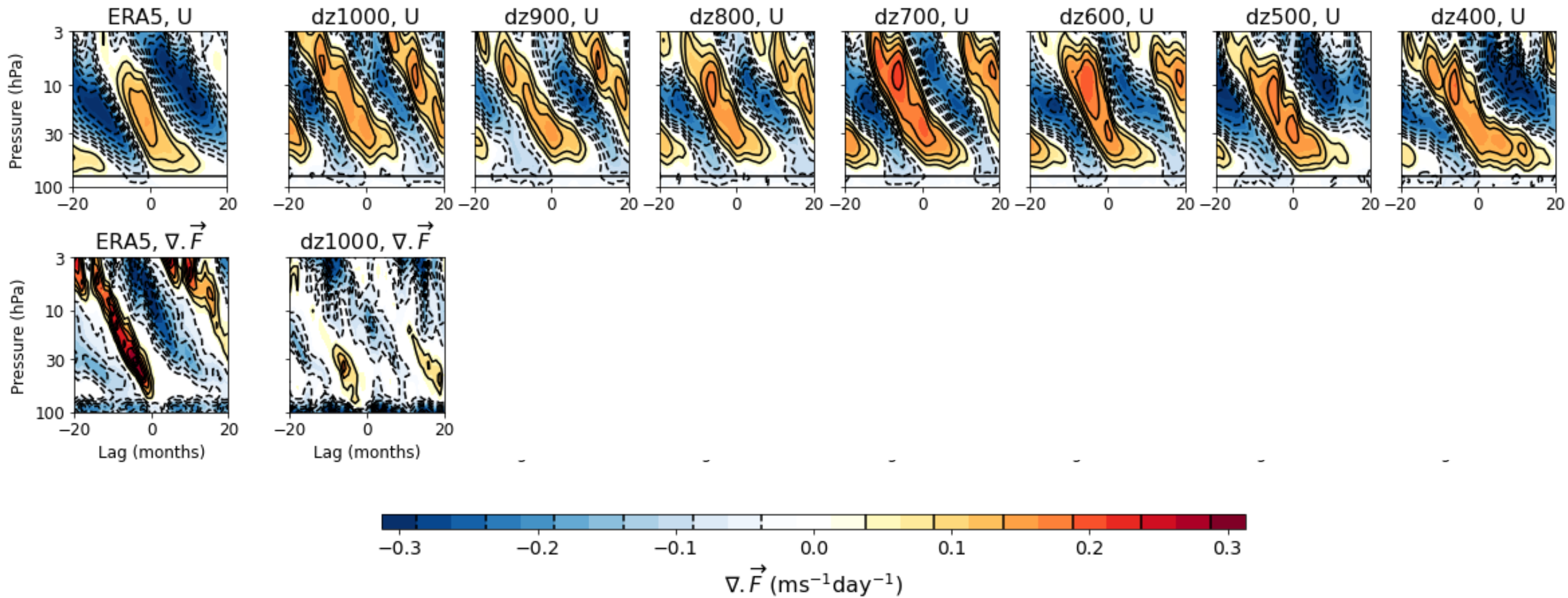
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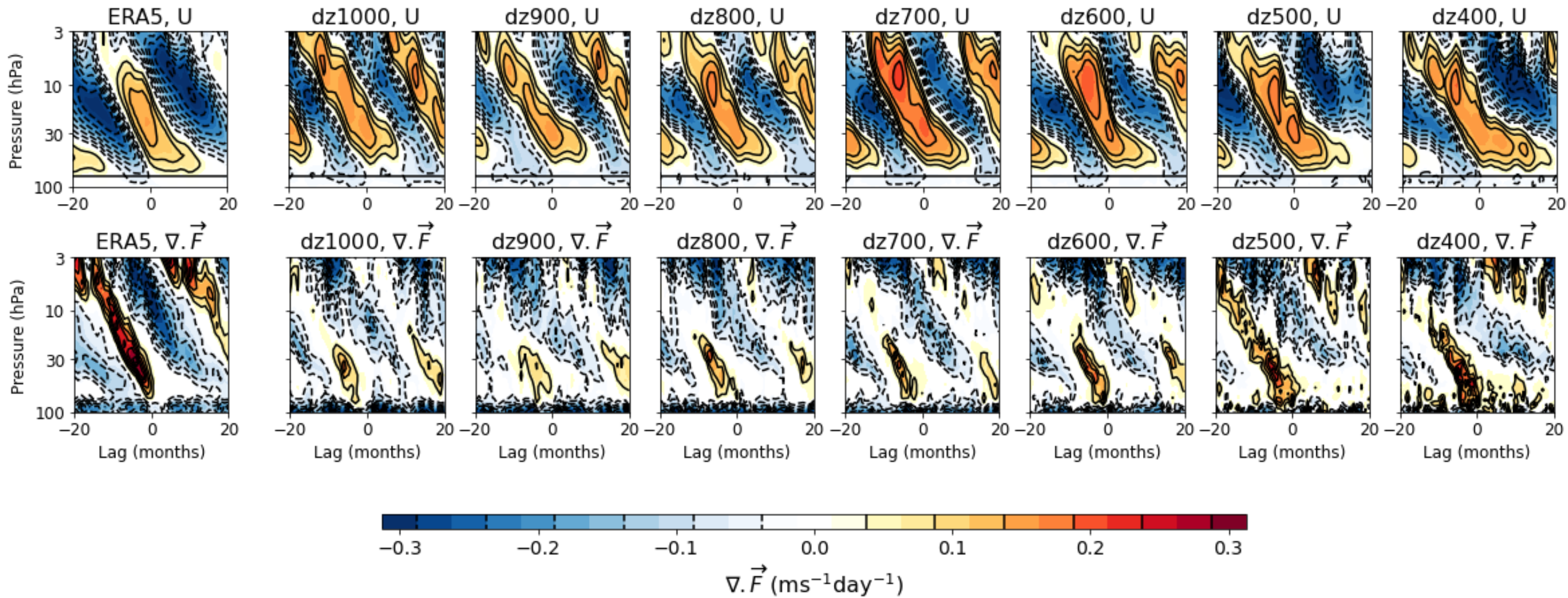
← E-P flux divergence i.e., zonal mean zonal wind tendency due to resolved waves

Resolved waves (in particular Kelvin waves) play an important role in driving the descending westerly phase of the QBO

The influence of grid spacing on the QBO

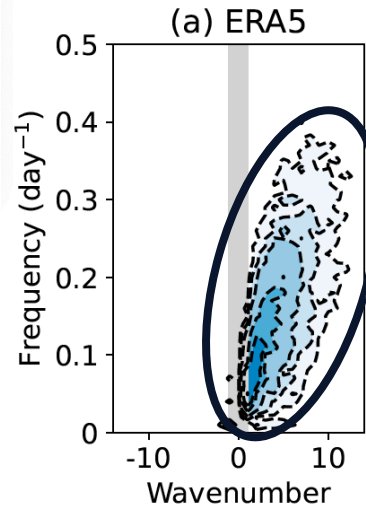


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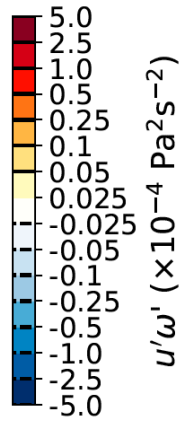
As we go to higher resolution, we see more and more of a role for the resolved waves in driving the descending westerly phase of the QBO. Improved representation of Kelvin waves

Wave spectra over the 90 days prior to the transition from easterly to westerly

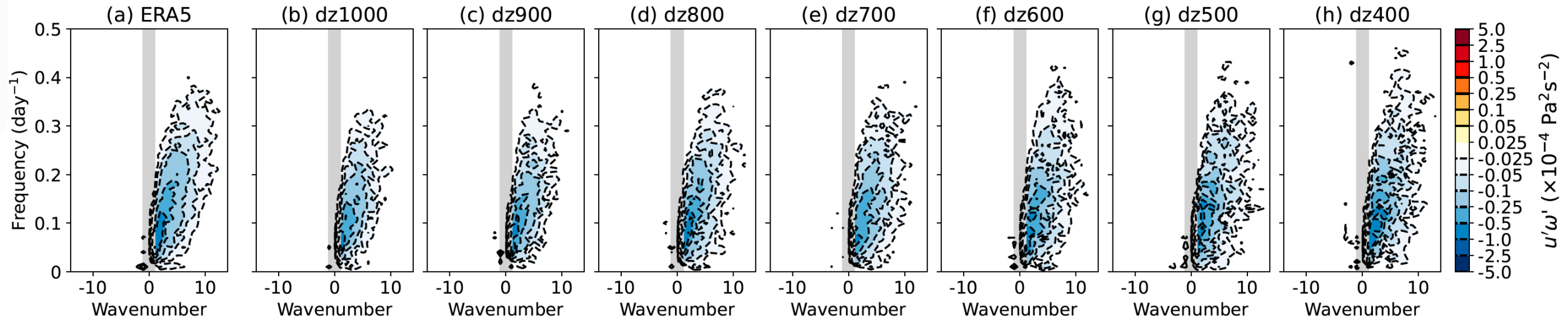


← Vertical eddy momentum flux of waves that are symmetric about the equator at 50hPa

↑ Upward flux of westerly momentum due to Kelvin waves

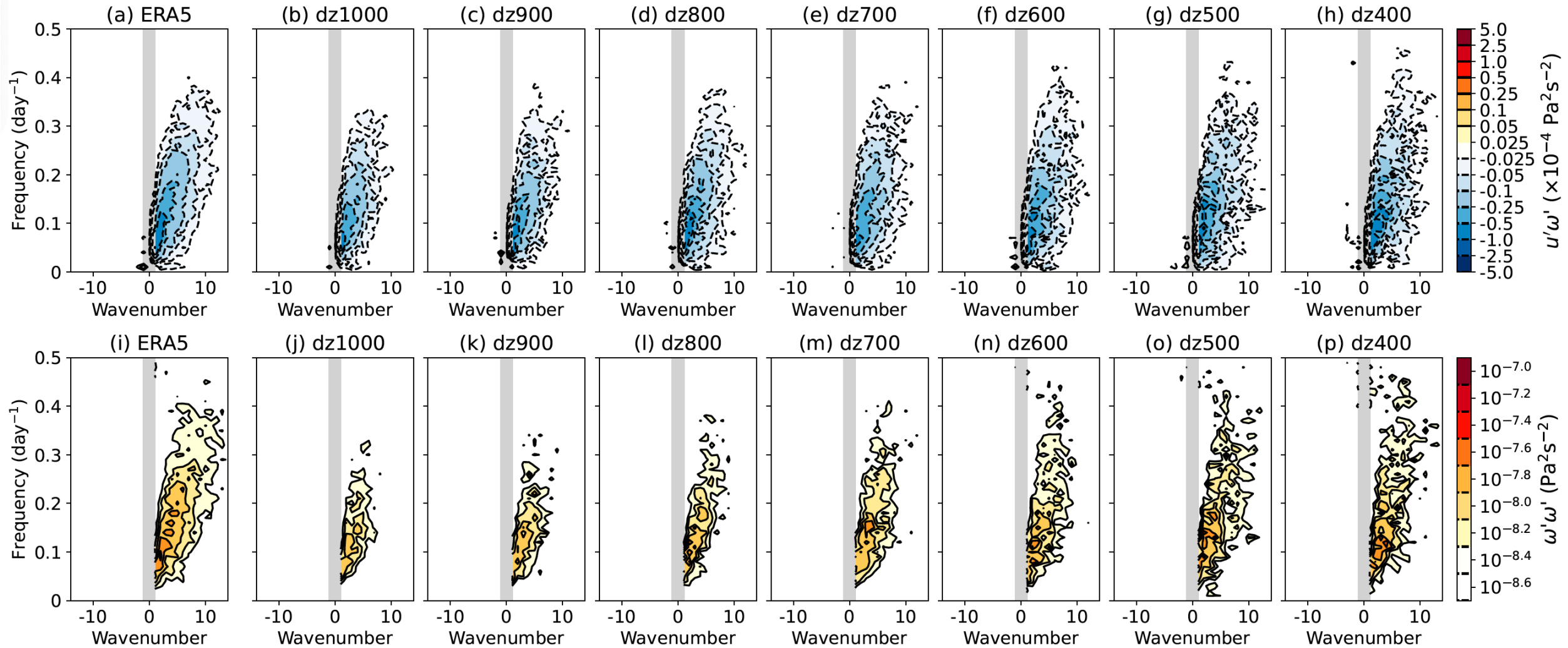


Wave spectra over the 90 days prior to the transition from easterly to westerly



Improved representation of the Kelvin wave momentum flux with resolution

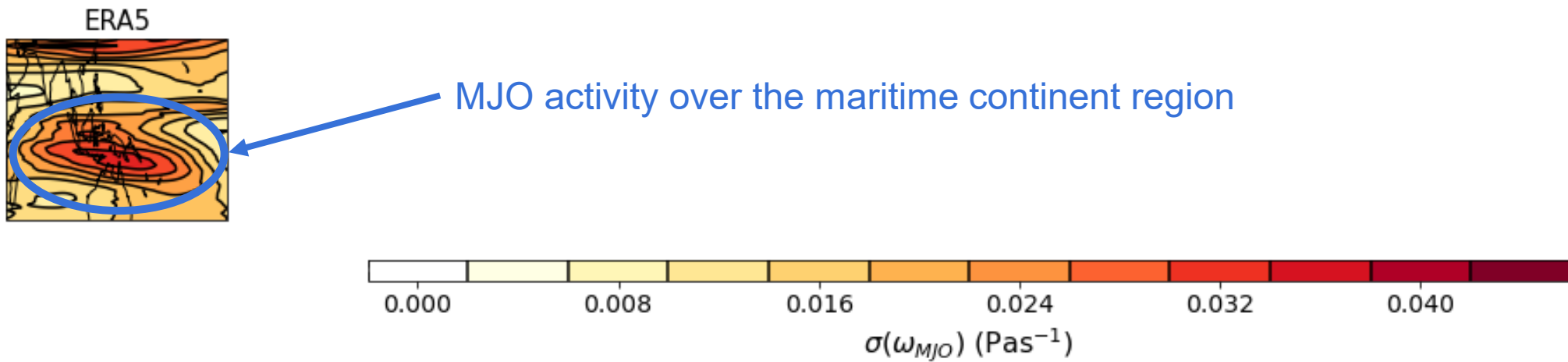
Wave spectra over the 90 days prior to the transition from easterly to westerly



Symmetric vertical velocity power spectra i.e., a measure of the amplitude of the waves

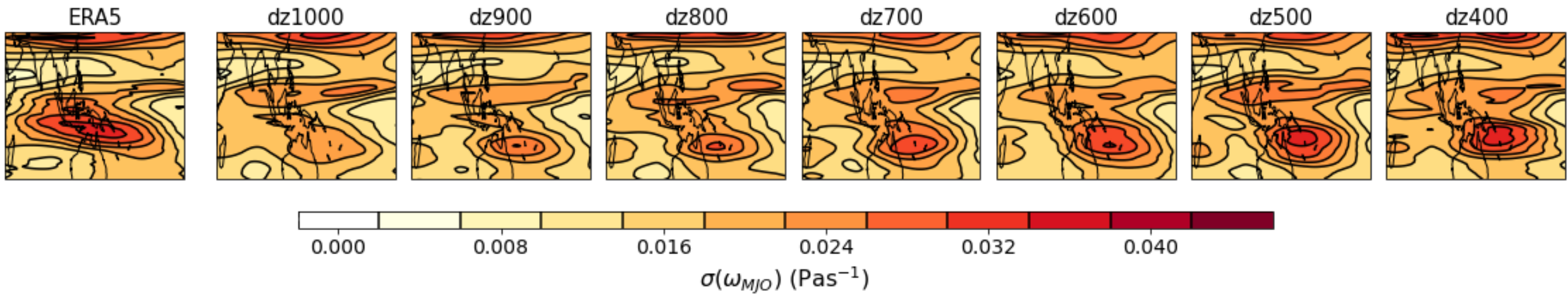
Tropical waves in general

Standard deviation of MJO filtered (k=1-5, period=20-100days) 500hPa vertical velocity



Tropical waves in general

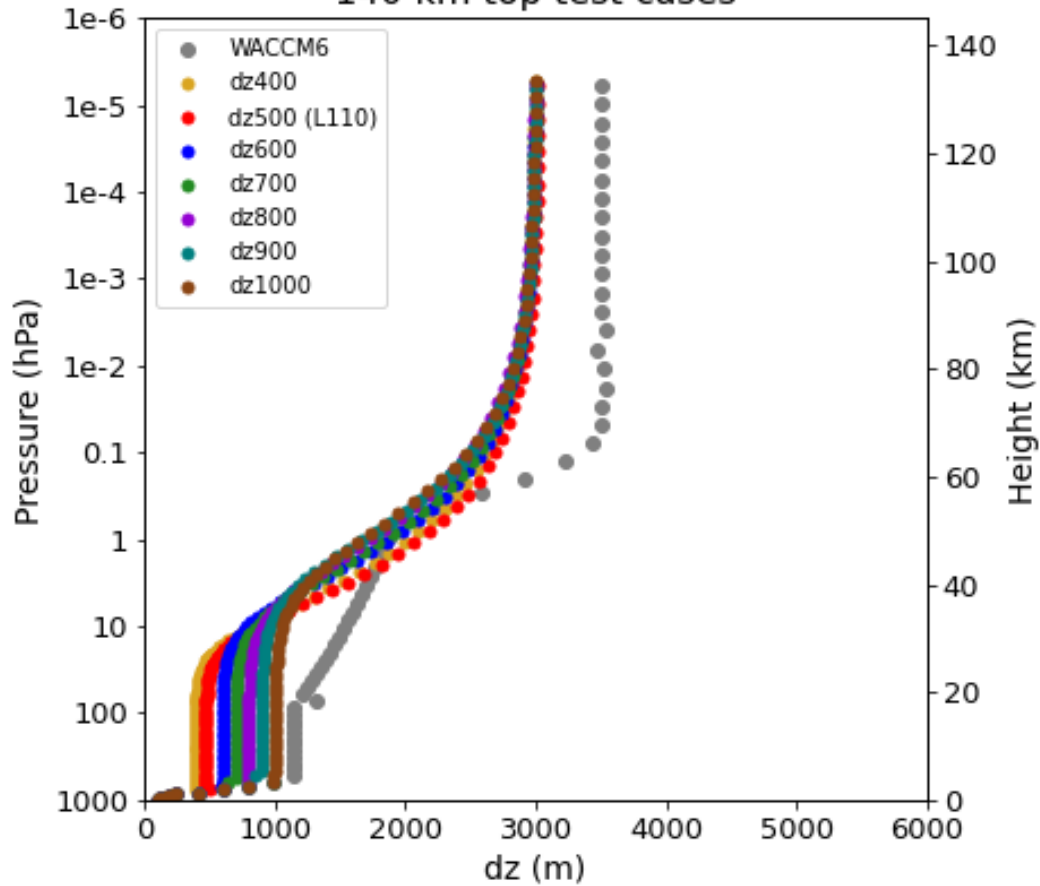
Standard deviation of MJO filtered (k=1-5, period=20-100days) 500hPa vertical velocity



More vertical velocity variations on the time and spatial scales of the MJO as we go to higher resolution

The vertical resolution task team work

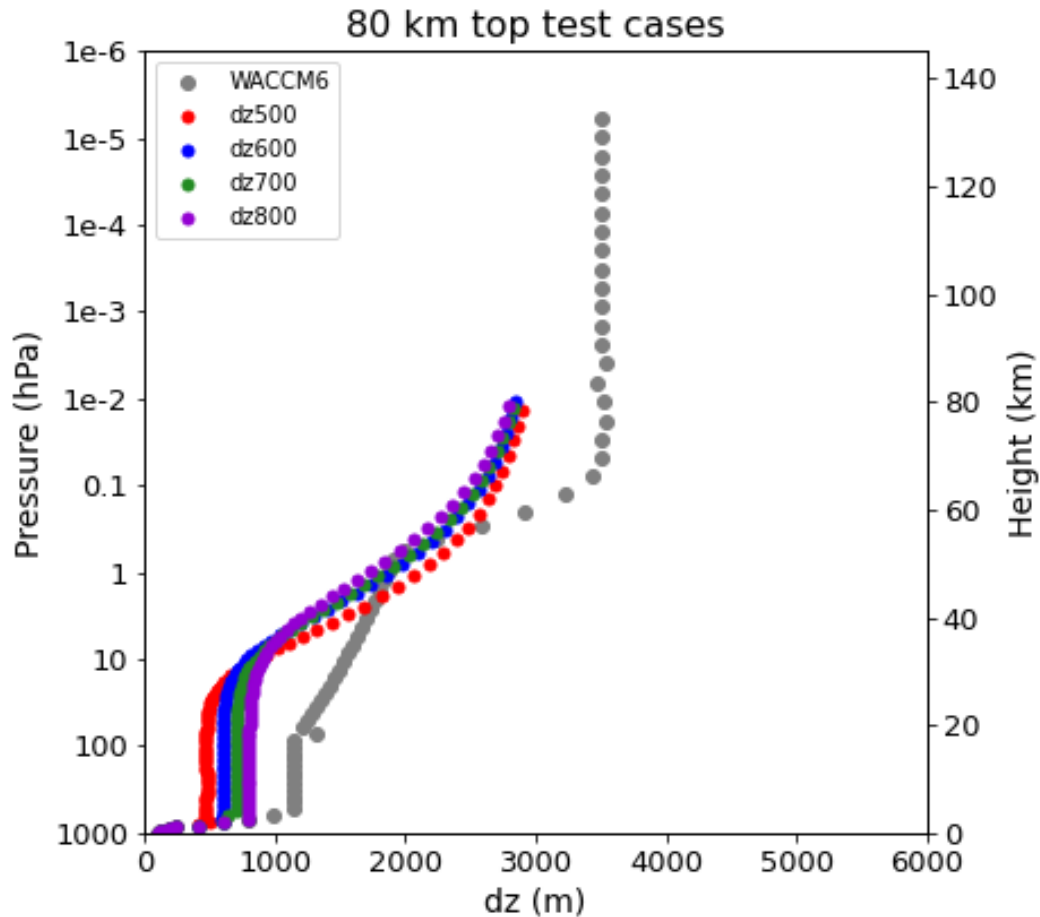
140 km top test cases



How much does the vertical grid spacing in the free troposphere and lower stratosphere impact on the QBO and other things?

It impacts on the wave driving of the QBO other aspects of tropical waves (things are better with dz=500m)

The vertical resolution task team work

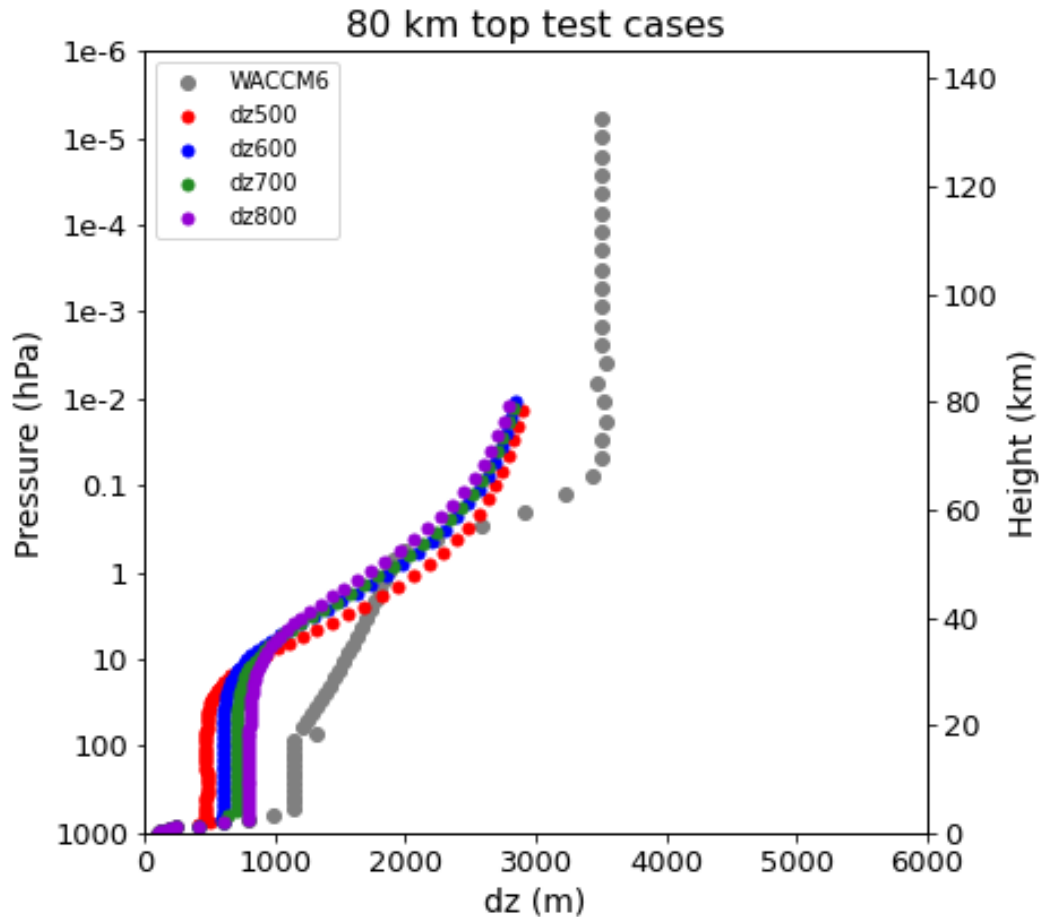


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What happens if we lower the model top to 80km?

The vertical resolution task team work



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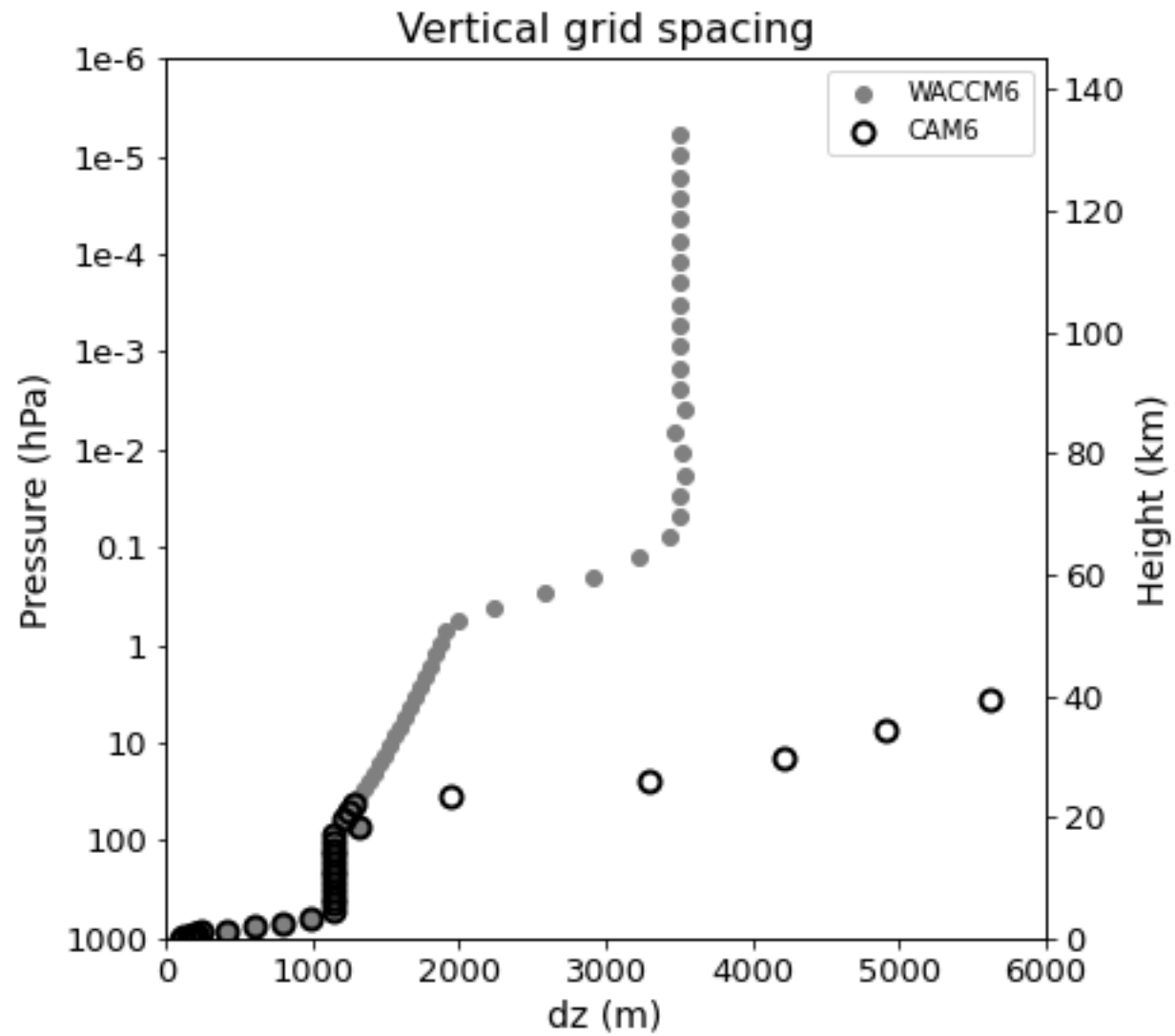
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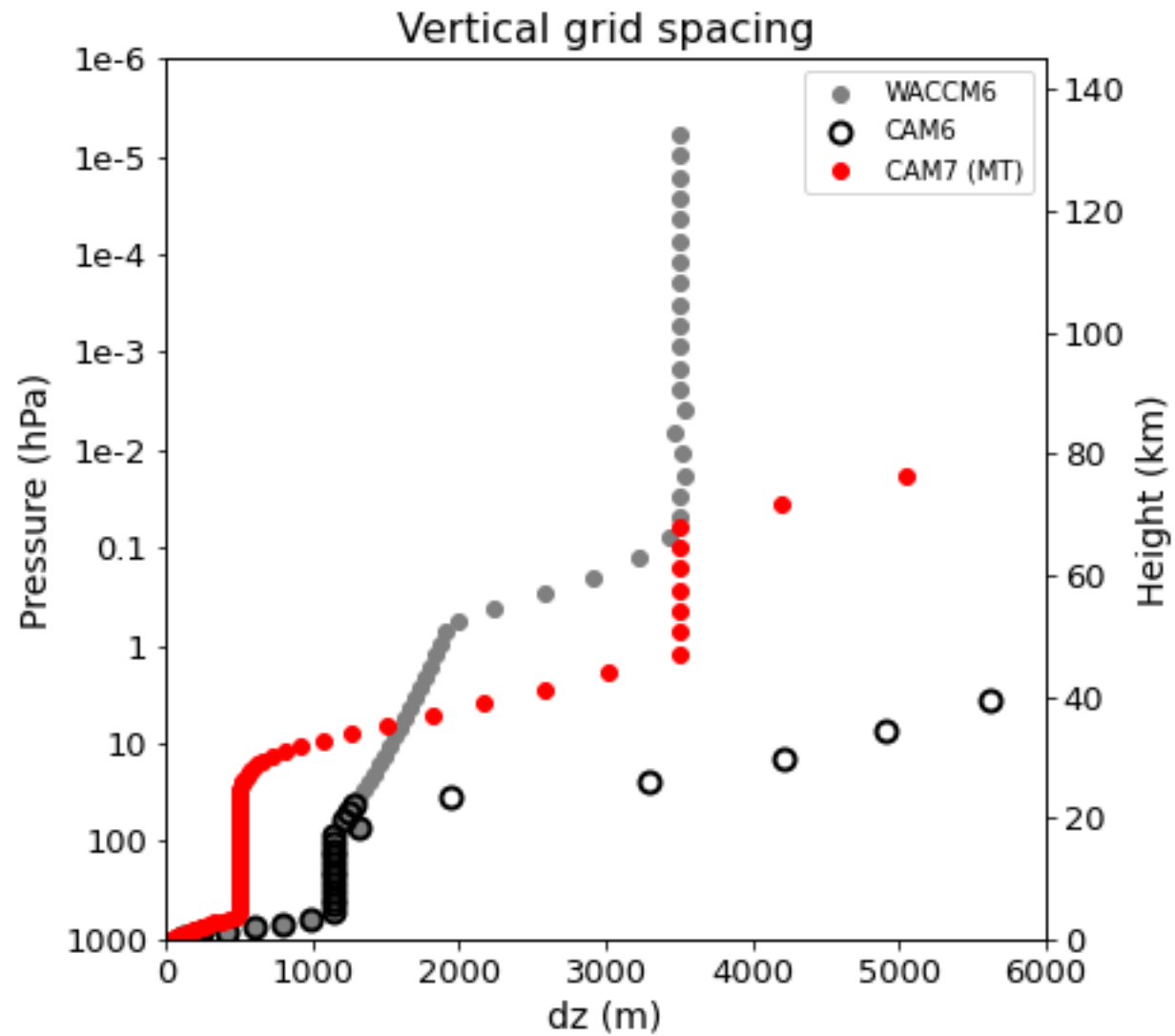
Not a lot

The QBO still looks good and other things like stratospheric polar vortex variability or tropospheric circulation don't change noticeably

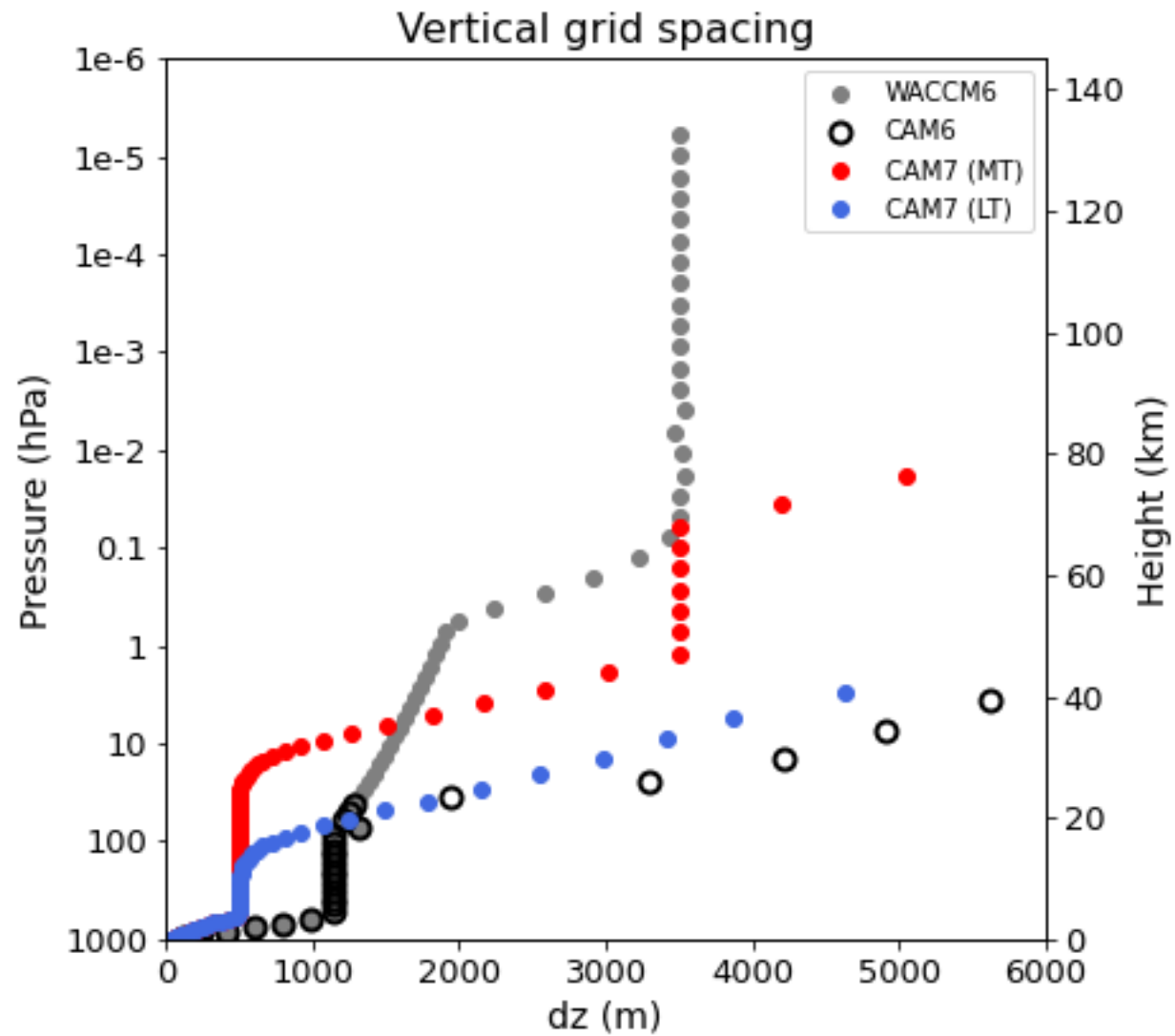
The final grid



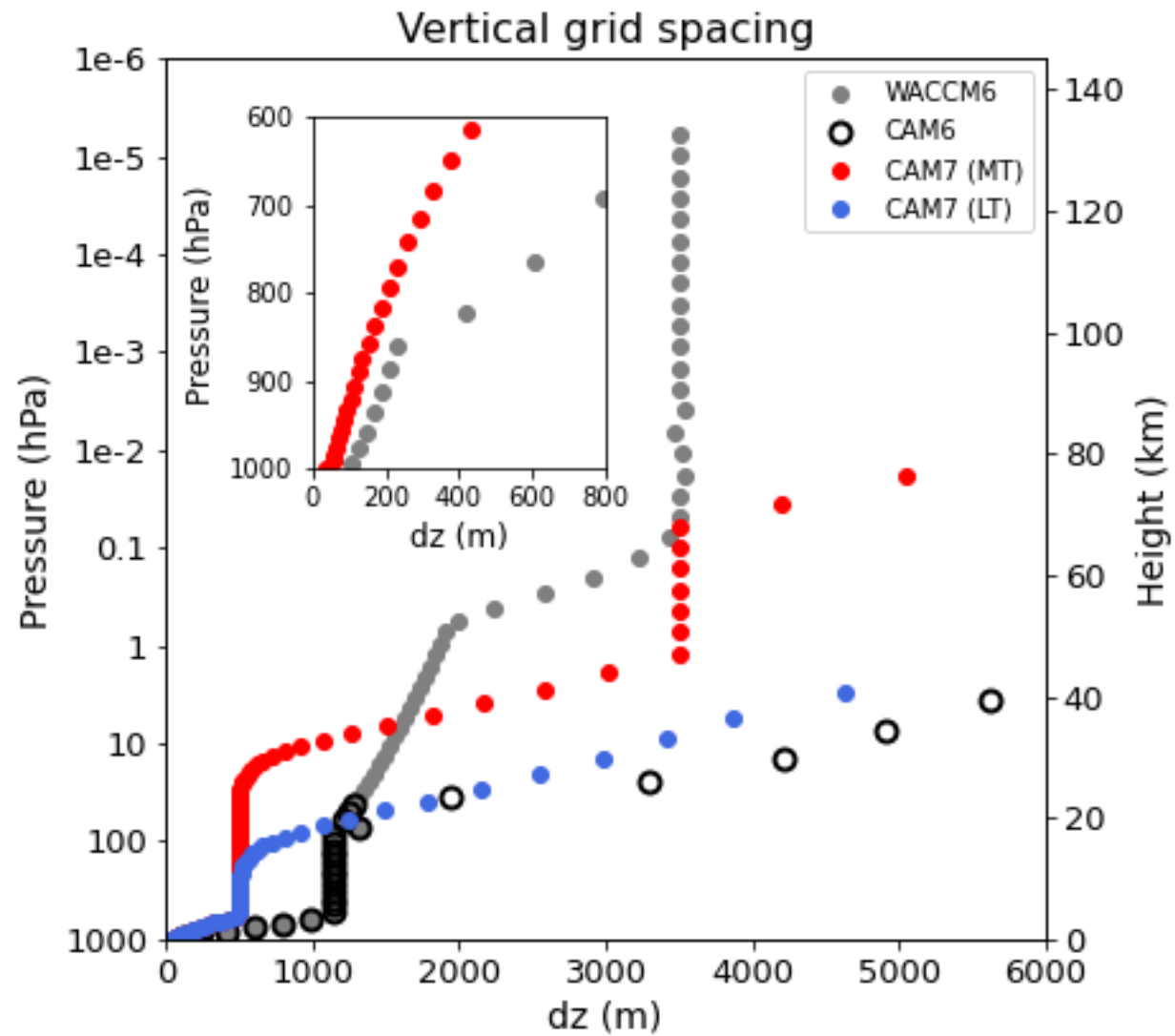
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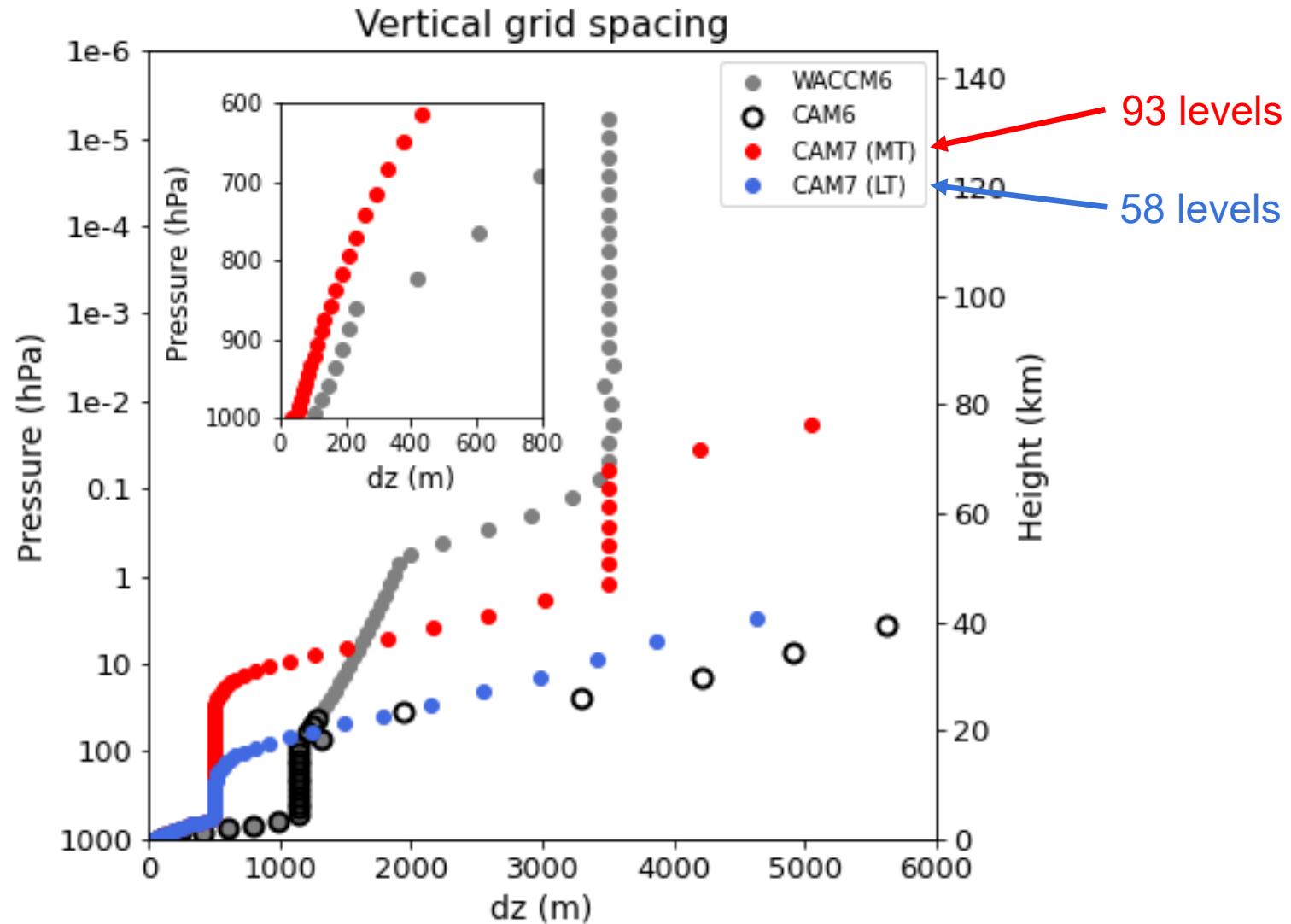
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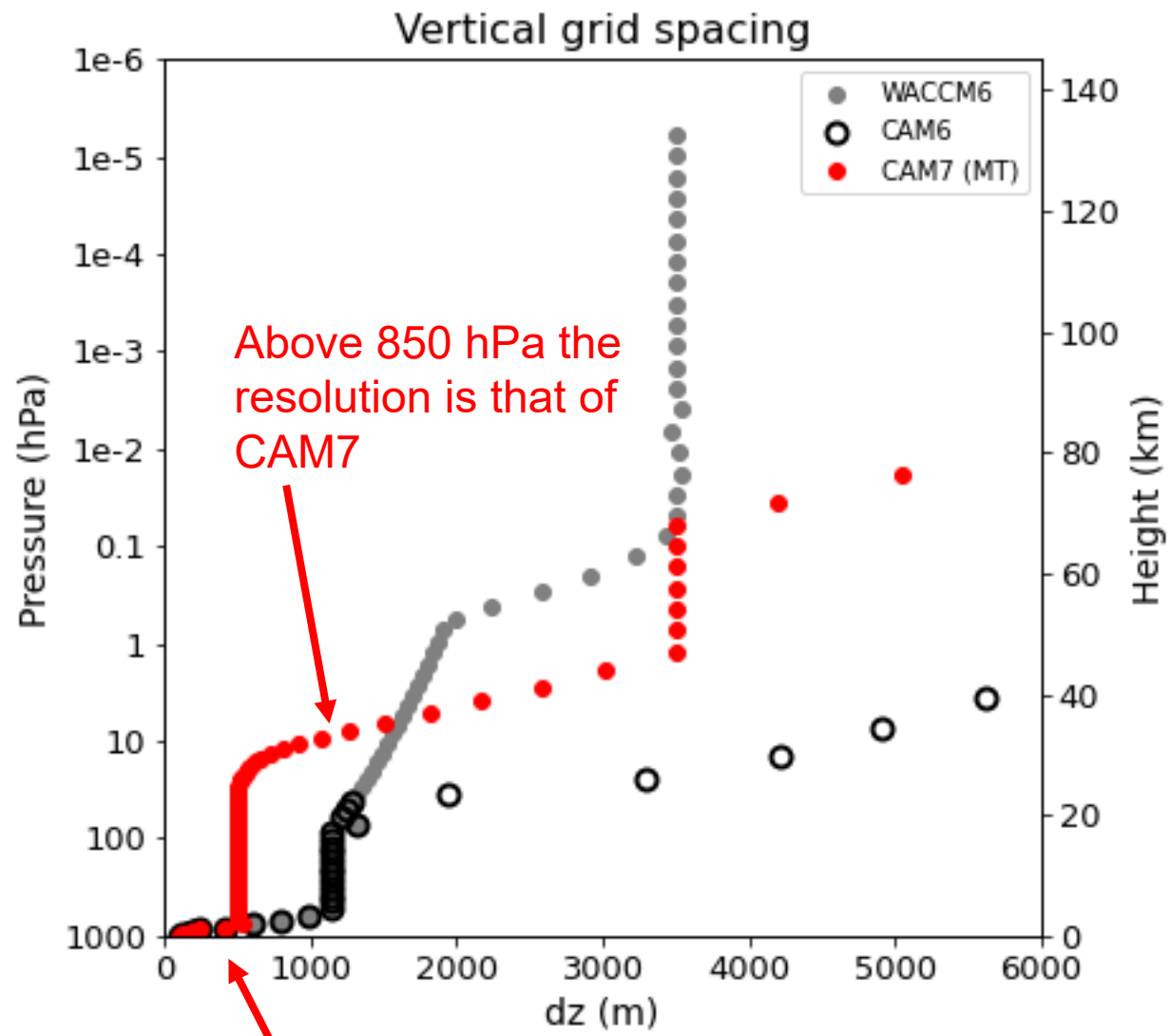
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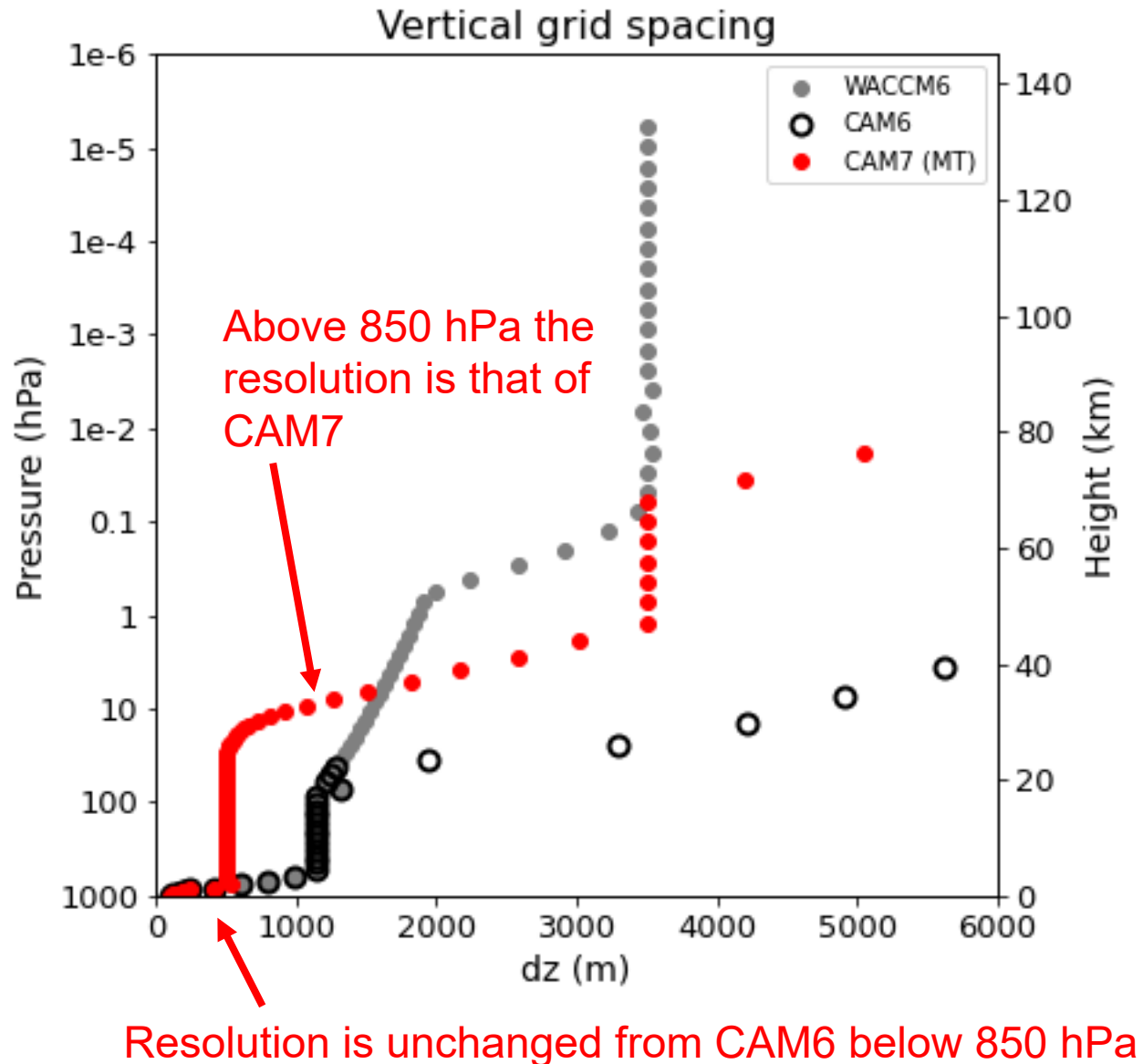


Intermediate tests with the L83 configuration



Resolution is unchanged from CAM6 below 850 hPa

Intermediate tests with the L83 configuration

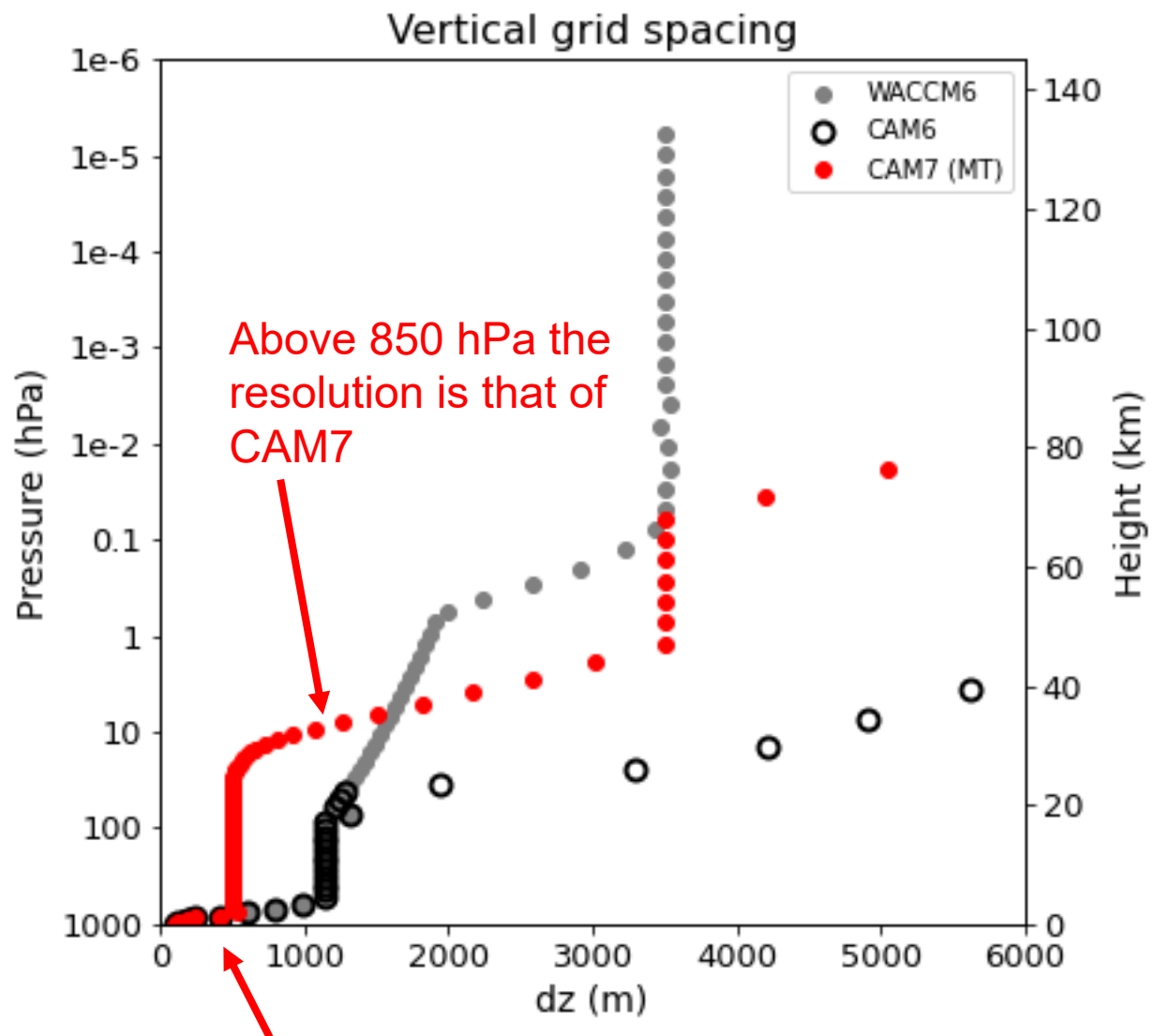


Free running simulations using CVCWG resources.
FV dycore and CAM6 physics.

- piControl (105 years)
- Historical → SSP370 (1850-2100, 3 members)
- AMIP (1979-2020, 3 members)
- Various AMIPs with QBO nudging for QBOi

Simpson et al, in prep

Intermediate tests with the L83 configuration



Free running simulations using CVCWG resources.
FV dycore and CAM6 physics.

- piControl (105 years)
- Historical → SSP370 (1850-2100, 3 members)
- AMIP (1979-2020, 3 members)
- Various AMIPs with QBO nudging for QBOi

Simpson et al, in prep

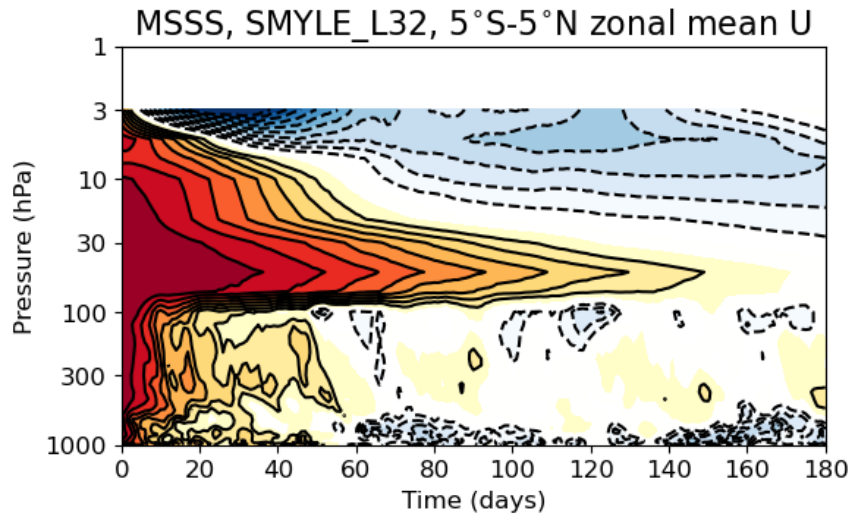
- Initialized S2S predictions.
 - Nov 1st, Sept 1st, Feb 1st
 - 1970 to 2020
 - 6 months



DeFlorio et al, in prep

QBO skill

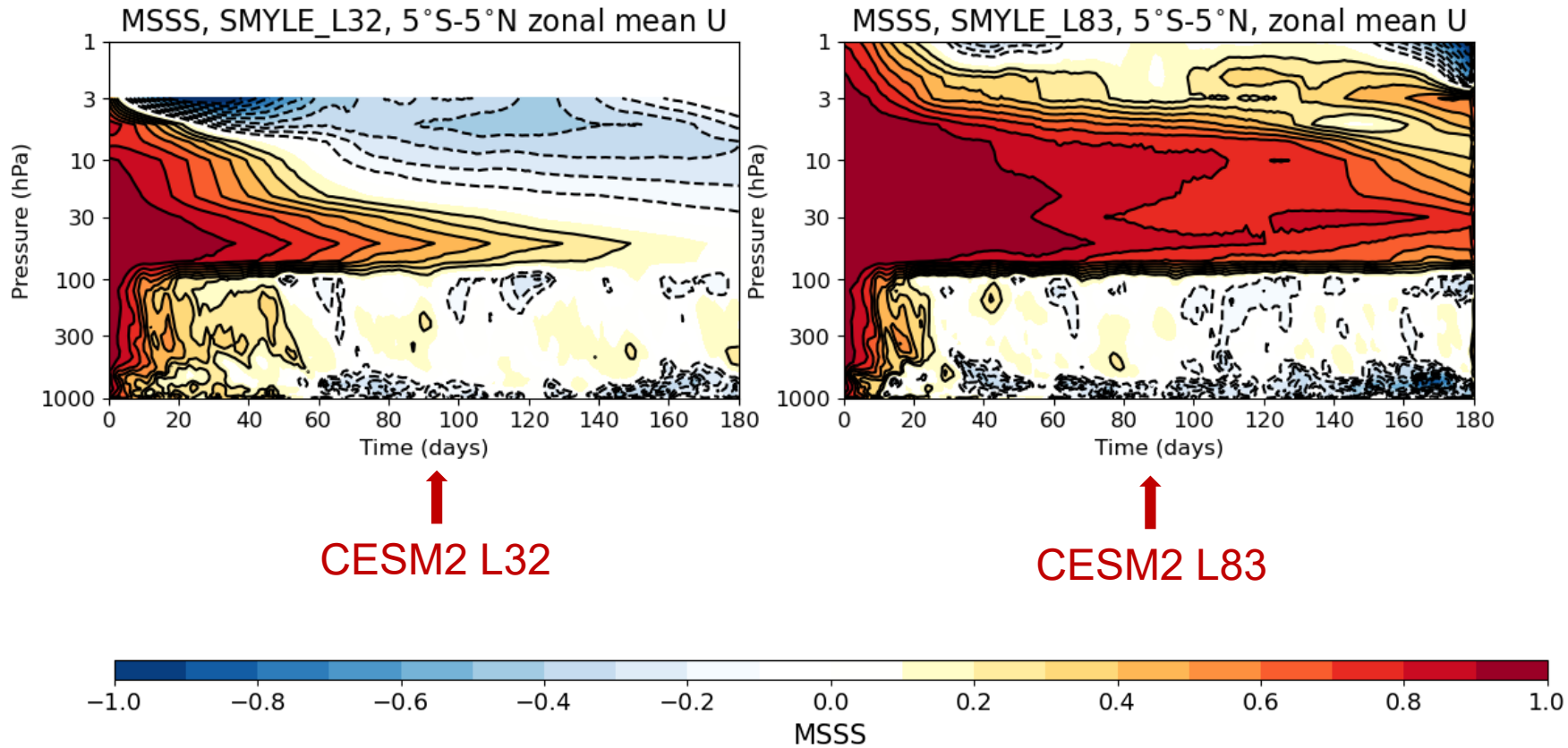
Mean Squared Skill Score for 5S-5N zonal mean zonal wind predictions as a function of lead time after Nov 1st initialization
(after removing a lead dependent climatology)



Mean Squared Skill Score
1 = perfect
0 = same skill as climatology
<0 = worse than climatology

QBO skill

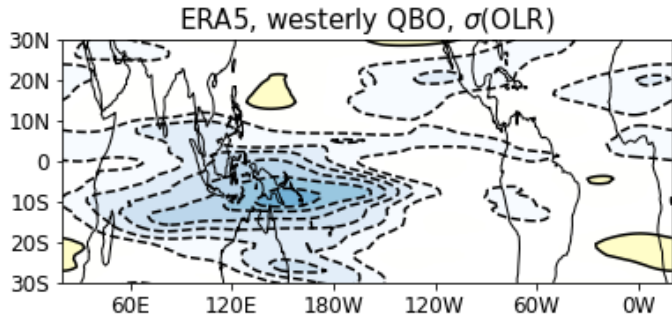
Mean Squared Skill Score for 5S-5N zonal mean zonal wind predictions as a function of lead time after Nov 1st initialization
(after removing a lead dependent climatology)



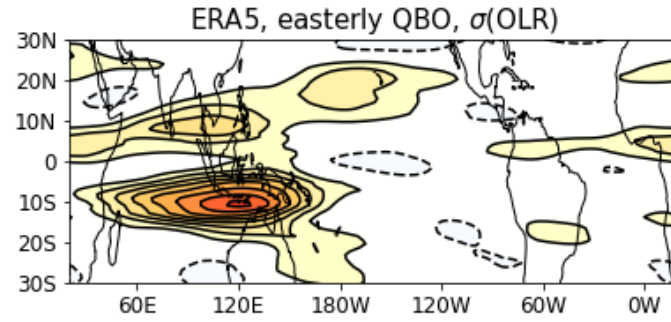
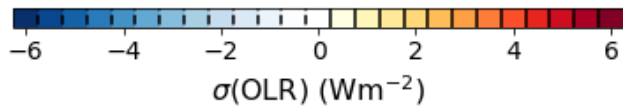
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QBO composites of MJO filtered OLR in initialized predictions

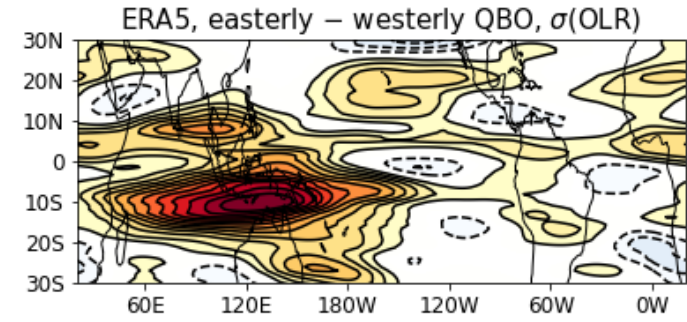
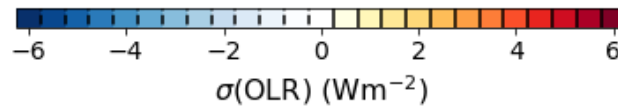
ERA5



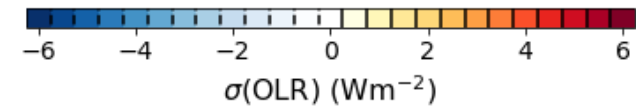
↑
Westerly QBO minus climatology



↑
Easterly QBO minus climatology

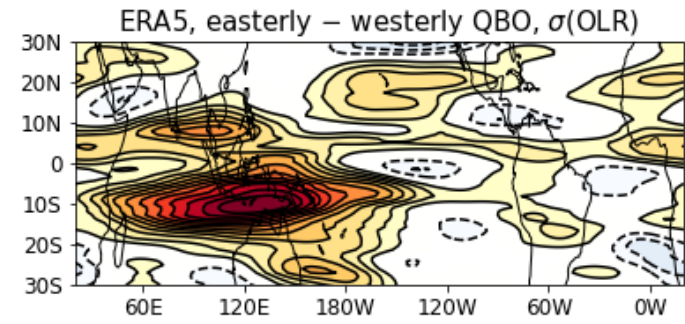
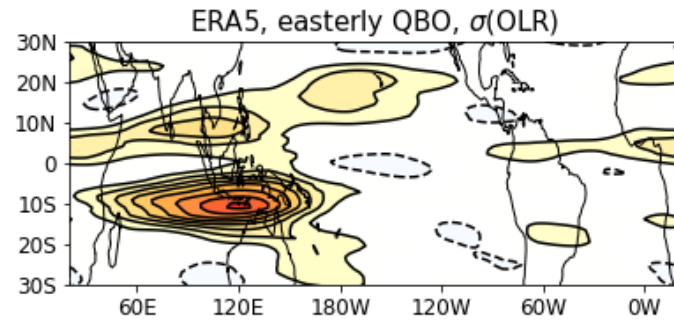
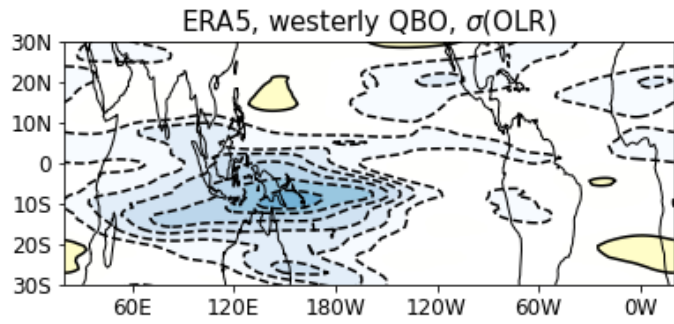


↑
Easterly minus Westerly

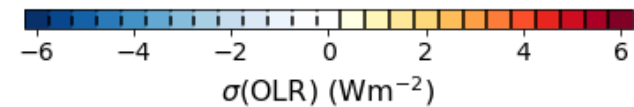
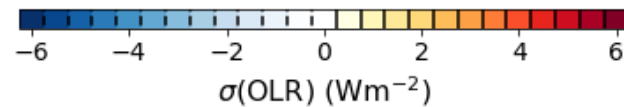
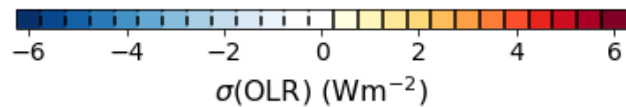
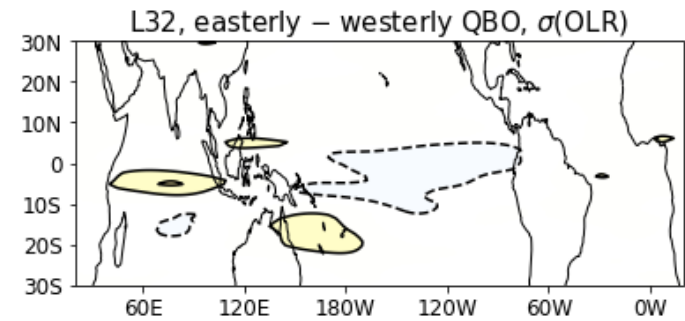
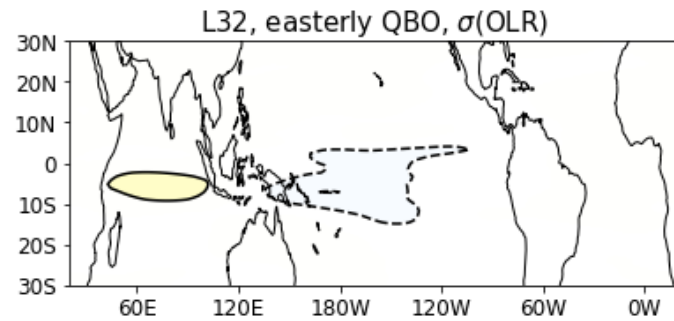
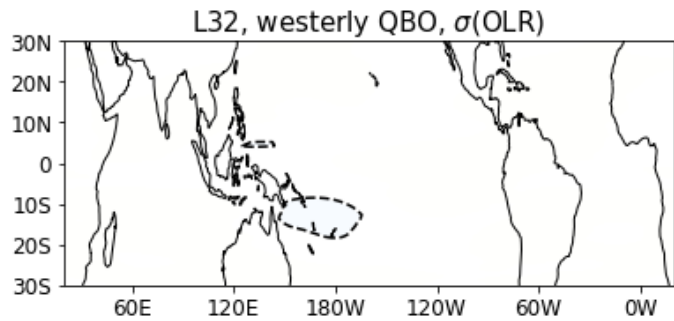


QBO composites of MJO filtered OLR in initialized predictions

ERA5

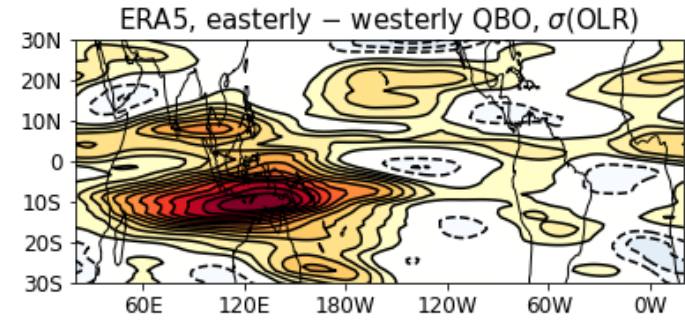
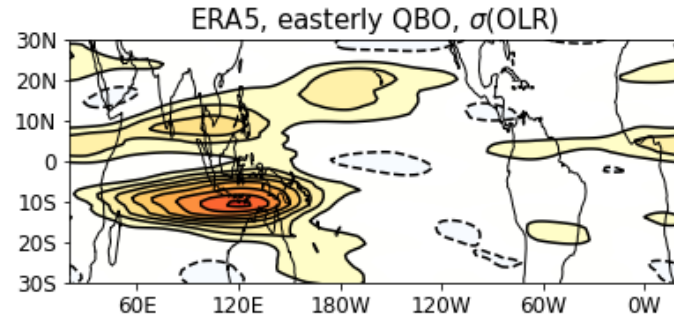
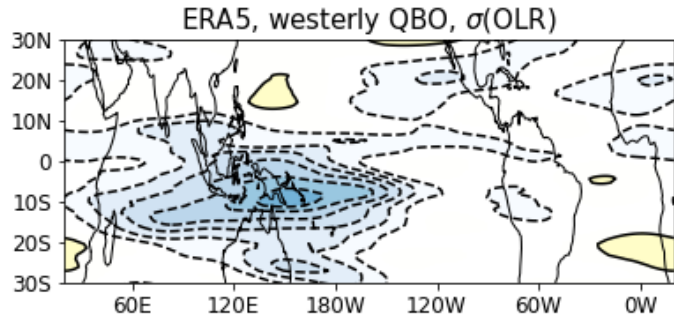


L32

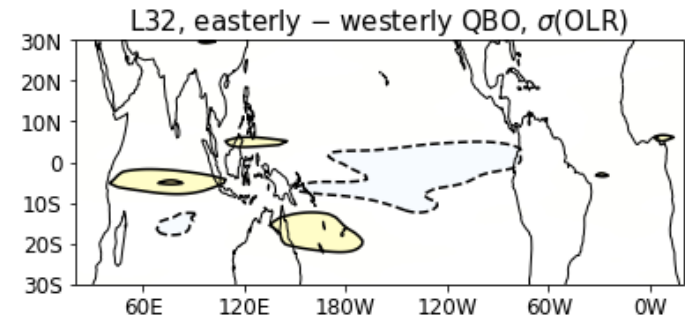
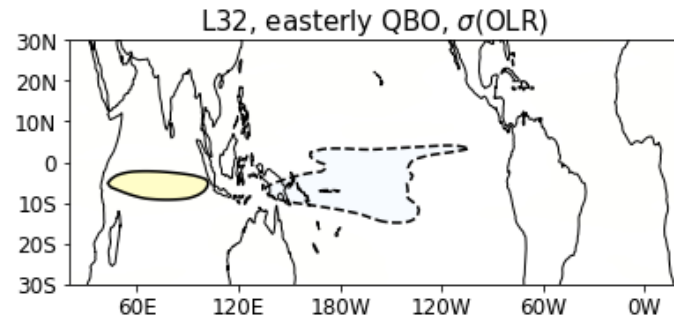
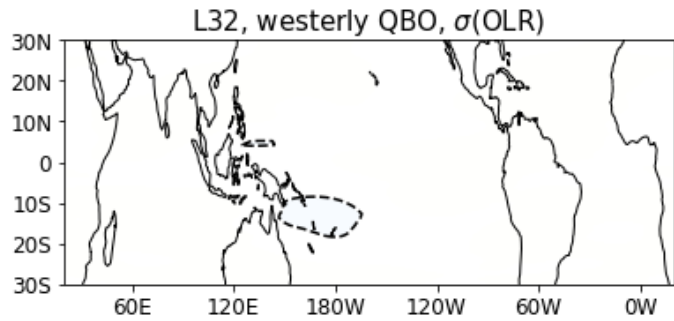


QBO composites of MJO filtered OLR in initialized predictions

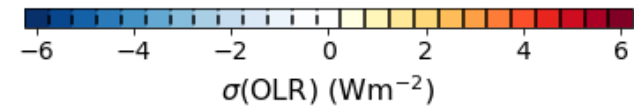
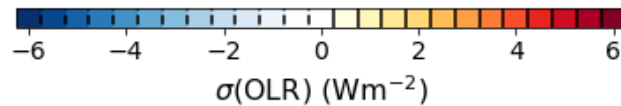
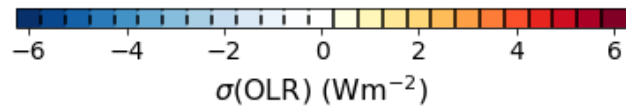
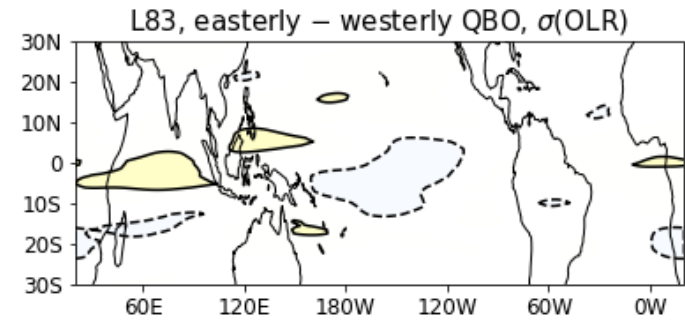
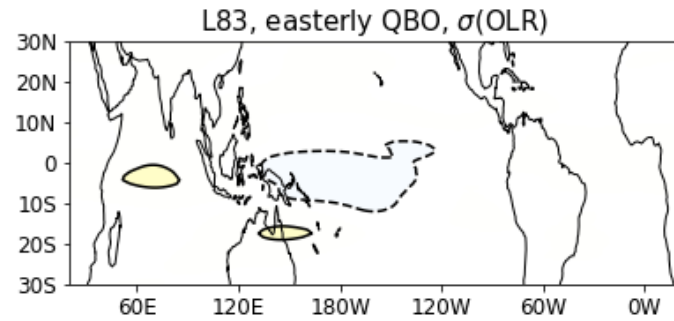
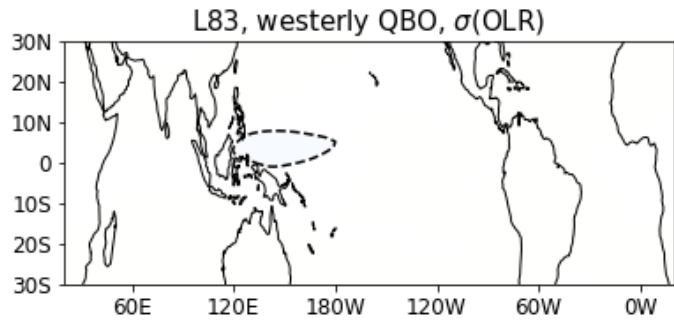
ERA5



L32



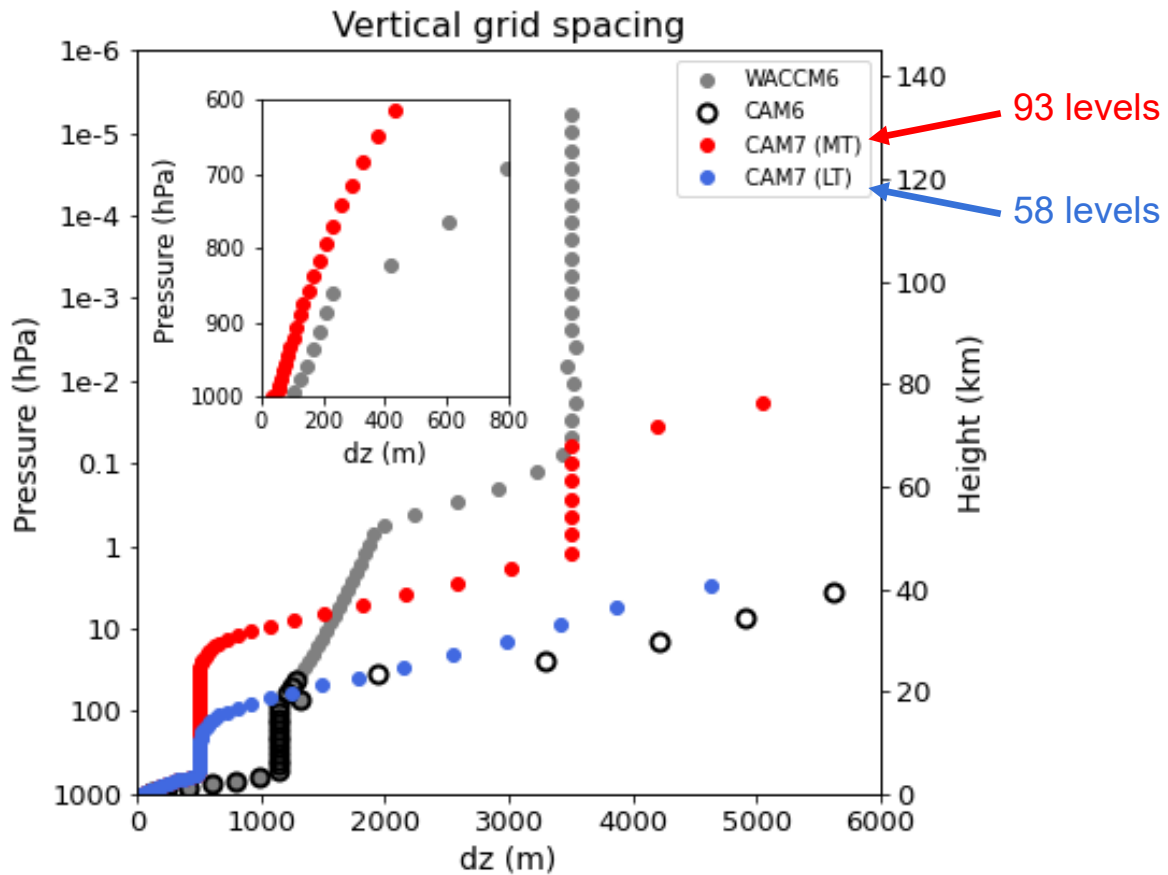
L83



Conclusions

Conclusions

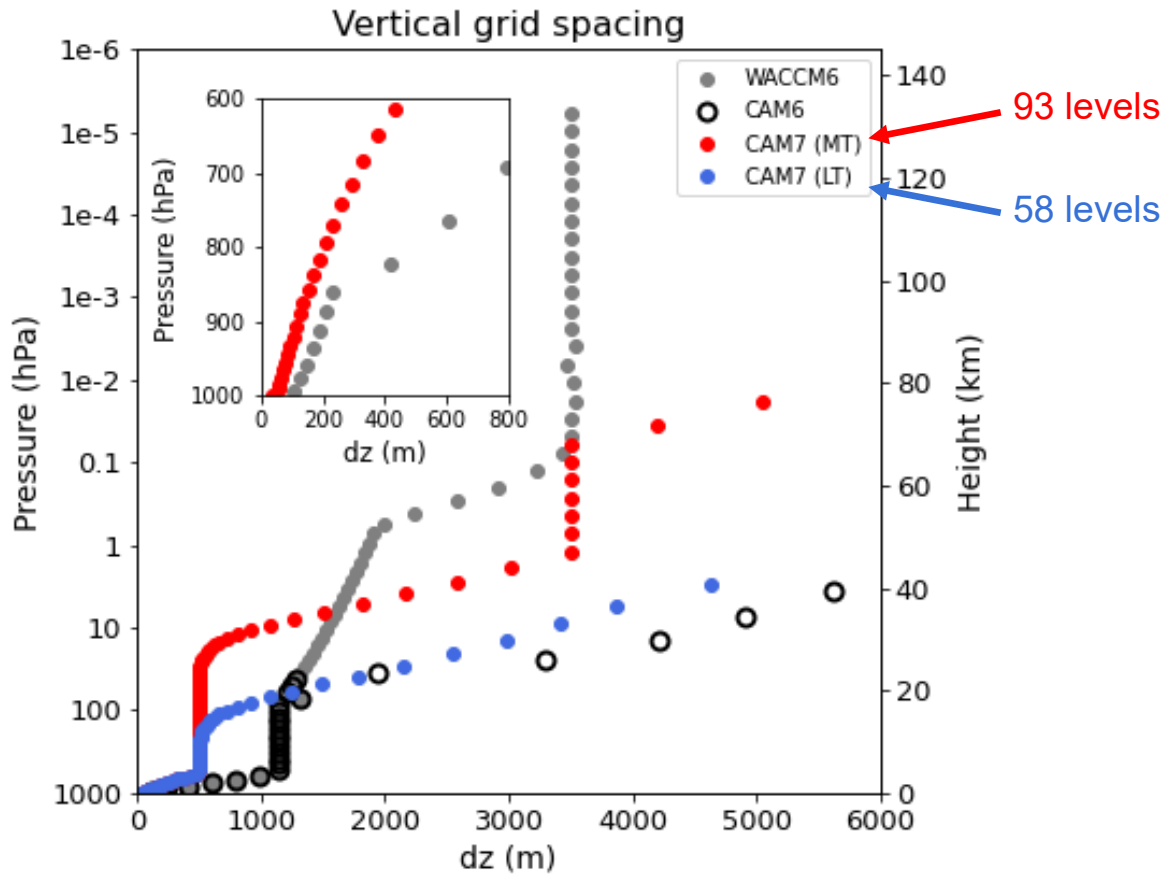
- These are the new grids for CAM7



Conclusions

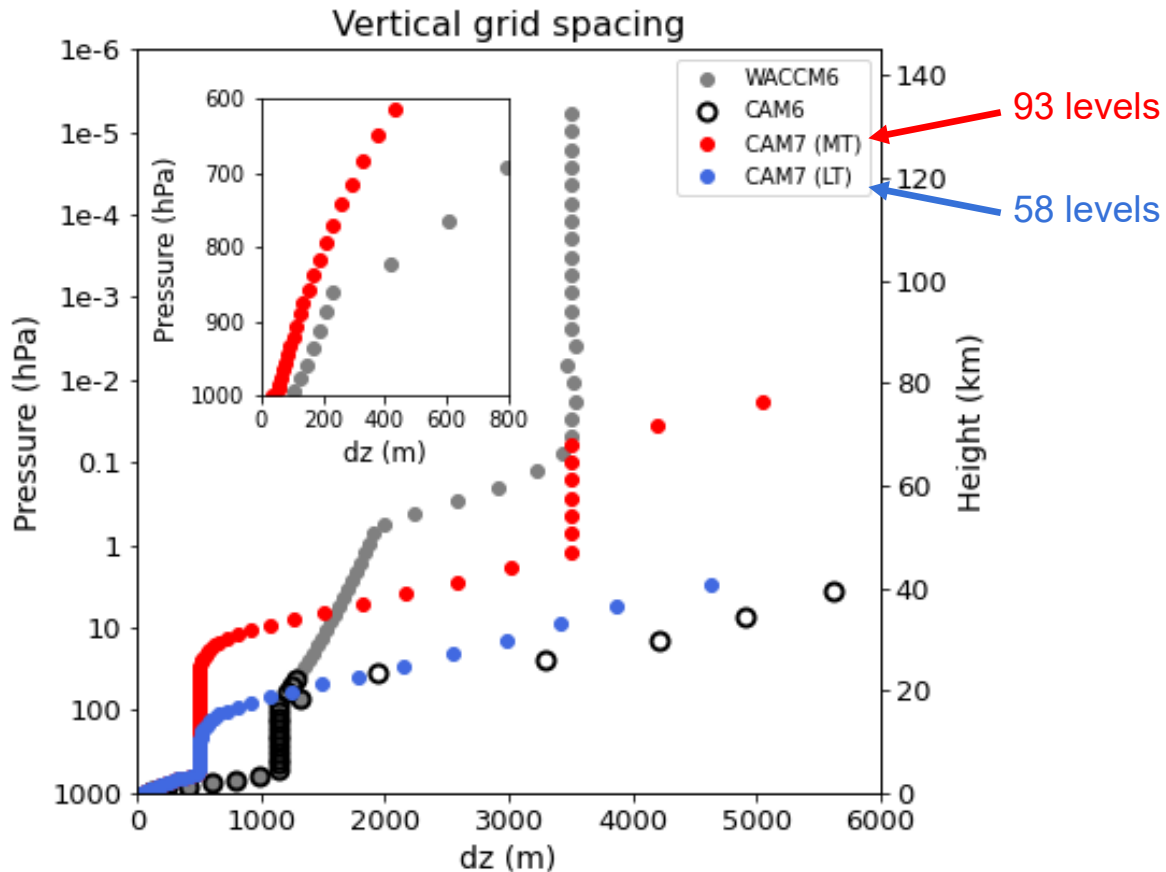
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- The mid-top resolution allows us to capture the QBO and associated wave driving processes well



Conclusions

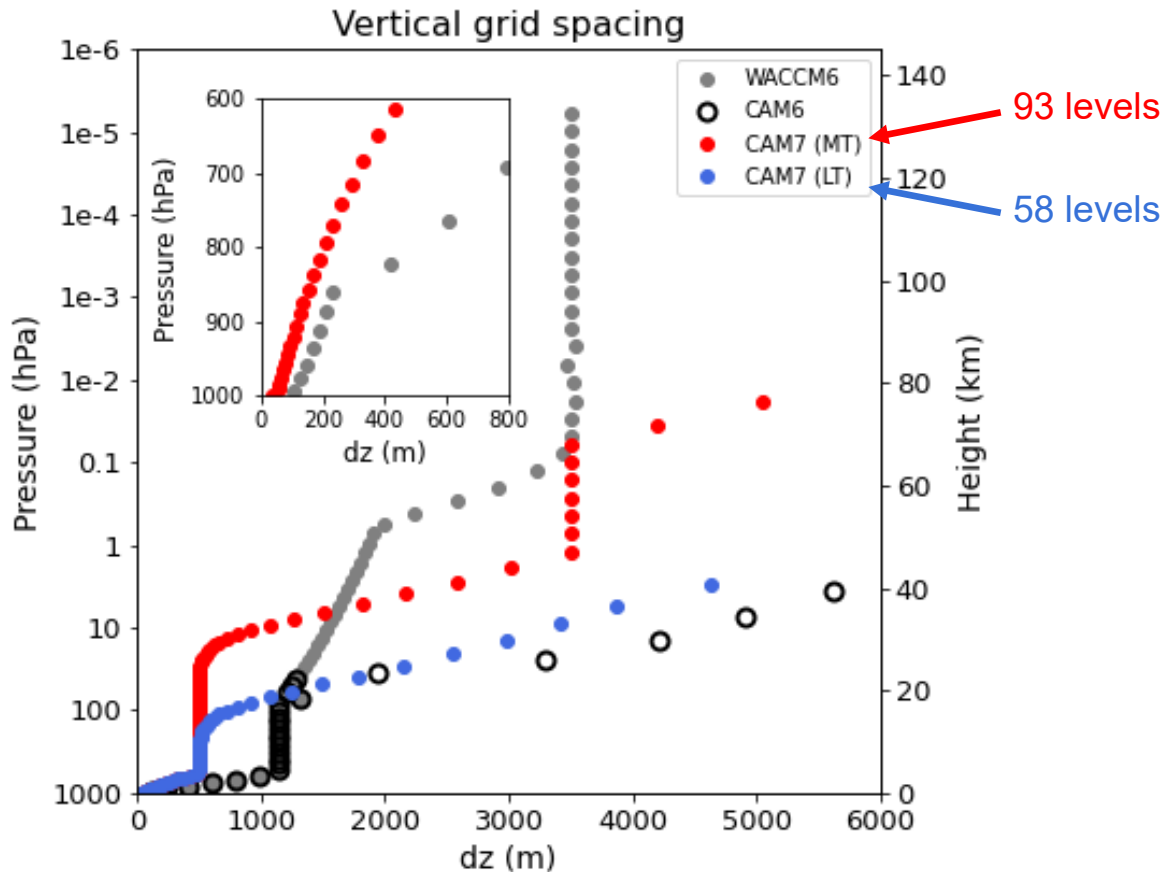
- These are the new grids for CAM7



- The mid-top resolution allows us to capture the QBO and associated wave driving processes well
- There are also improvements in various aspects of the tropical waves.

Conclusions

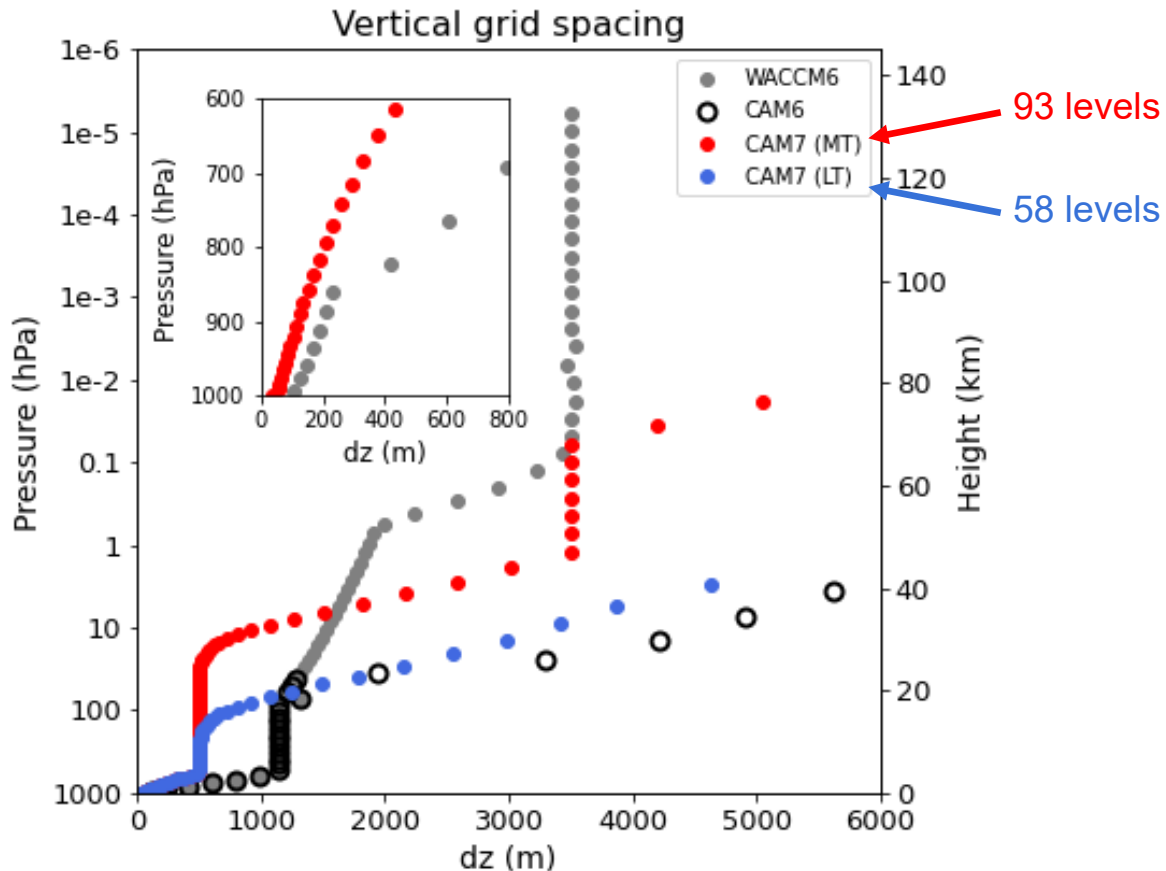
- These are the new grids for CAM7



- The mid-top resolution allows us to capture the QBO and associated wave driving processes well
- There are also improvements in various aspects of the tropical waves.
- Free running and S2S simulations will become available soon where only the free tropospheric and stratospheric resolution are changed.

Conclusions

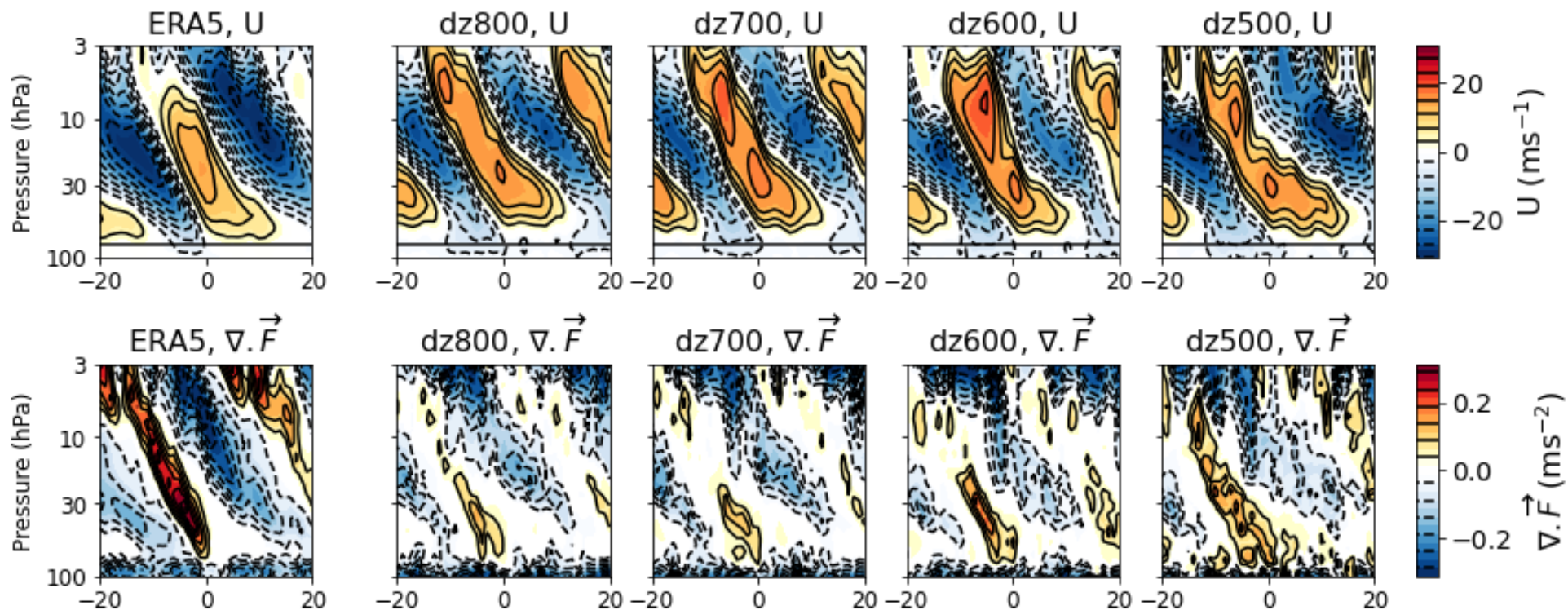
- These are the new grids for CAM7



- The mid-top resolution allows us to capture the QBO and associated wave driving processes well
- There are also improvements in various aspects of the tropical waves.
- Free running and S2S simulations will become available soon where only the free tropospheric and stratospheric resolution are changed.
- Despite having a great QBO, we still are not capturing the QBO-MJO connection. But at least we have one of the pieces there.

Extra Slides

QBO composites with an 80 km top



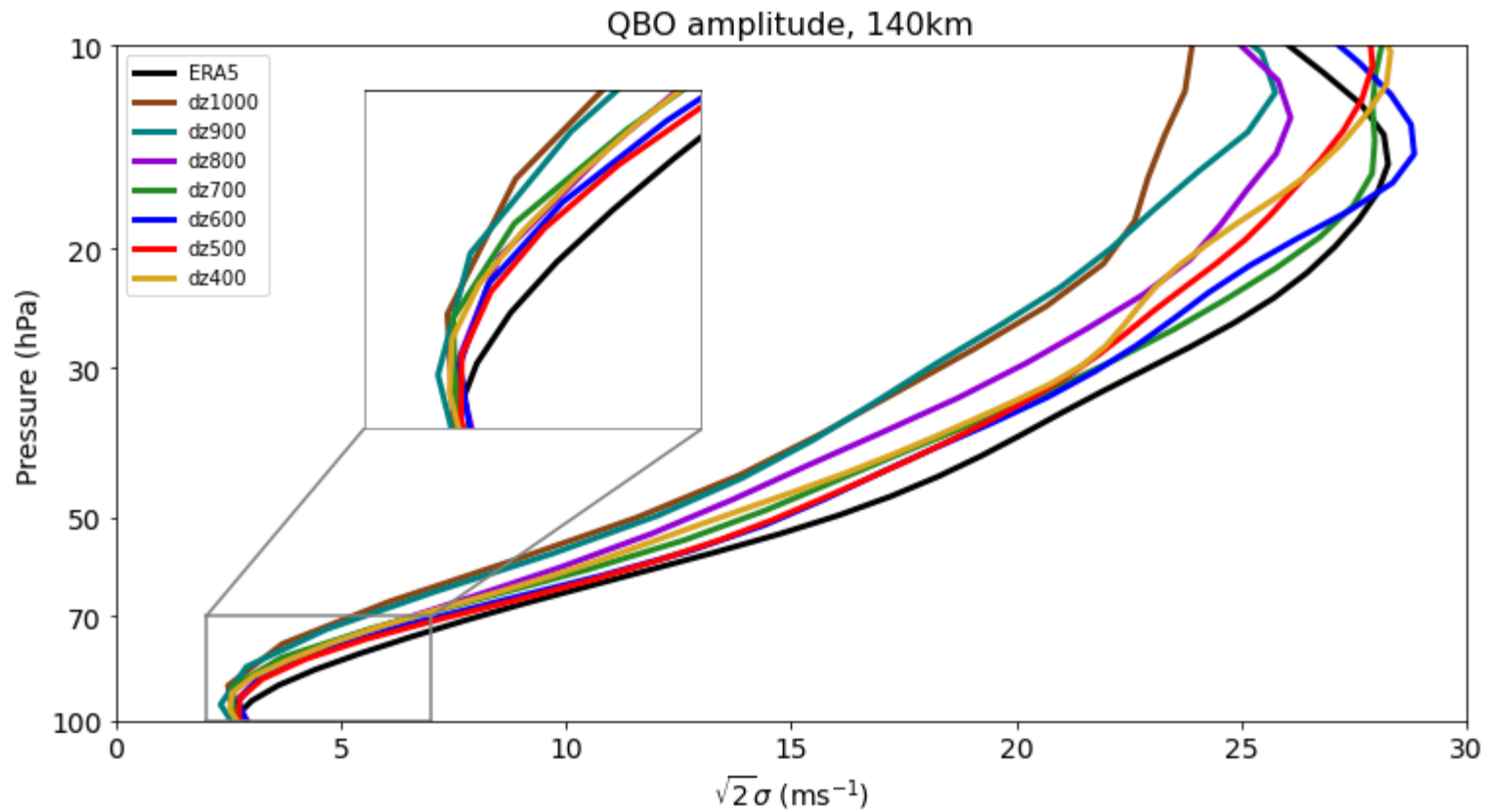
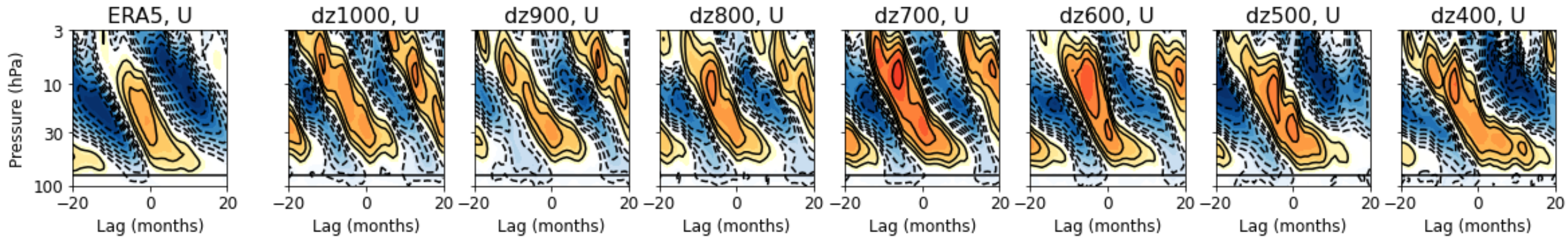
We can still have a good QBO with the 80 km top

← Increase in wave driving with resolution

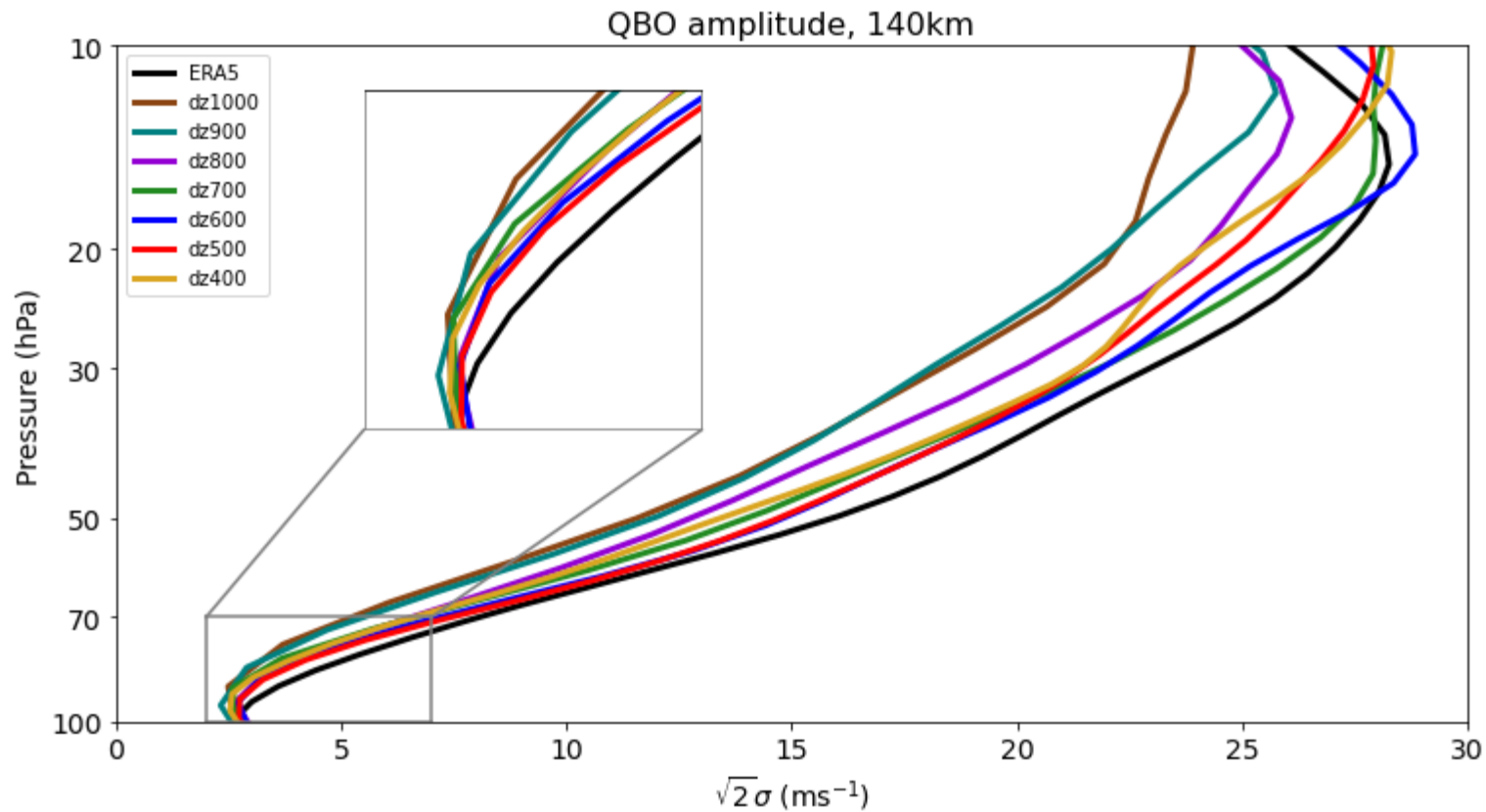
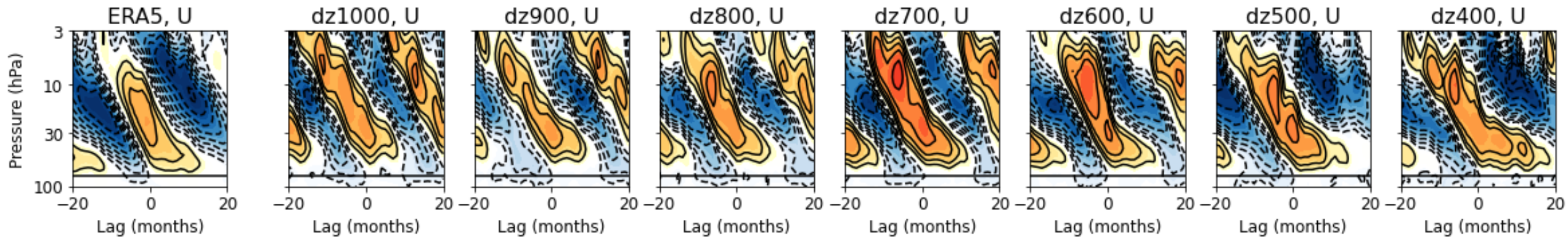
Other things like stratospheric polar vortex variability or tropospheric circulation don't change noticeably

Given the improvements in the representation of the wave driving of the QBO it was decided on dz=500

The influence of grid spacing on the QBO

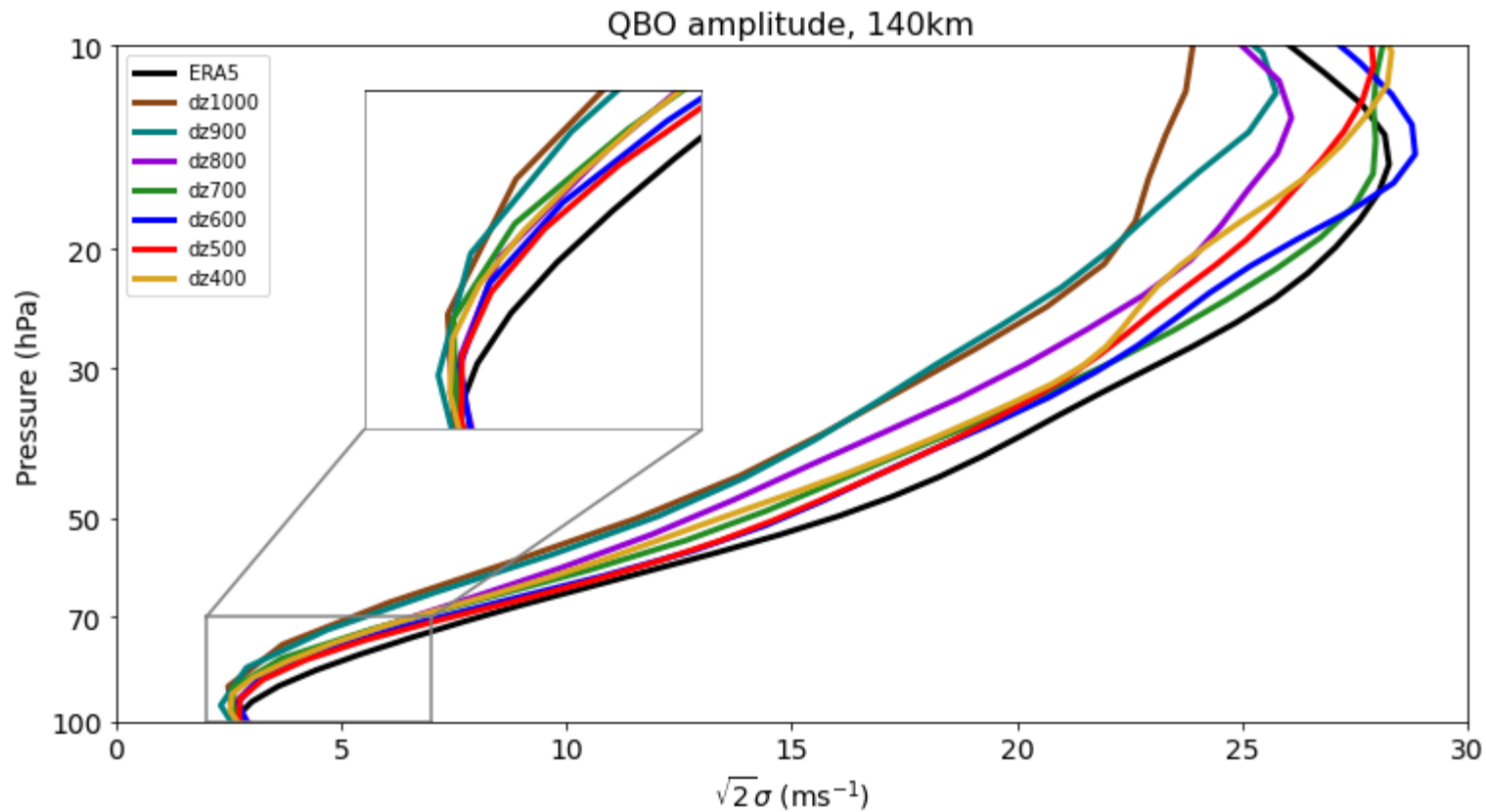
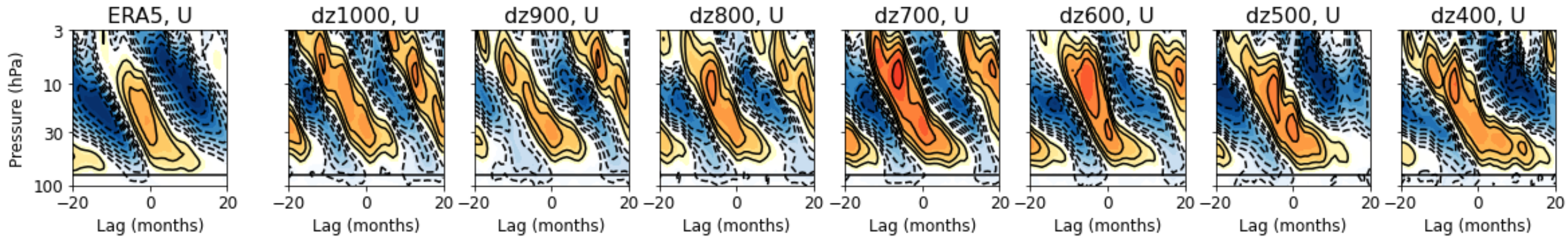


The influence of grid spacing on the QBO



Resolutions lower than dz700 seem to be deficient in the amplitude of the QBO

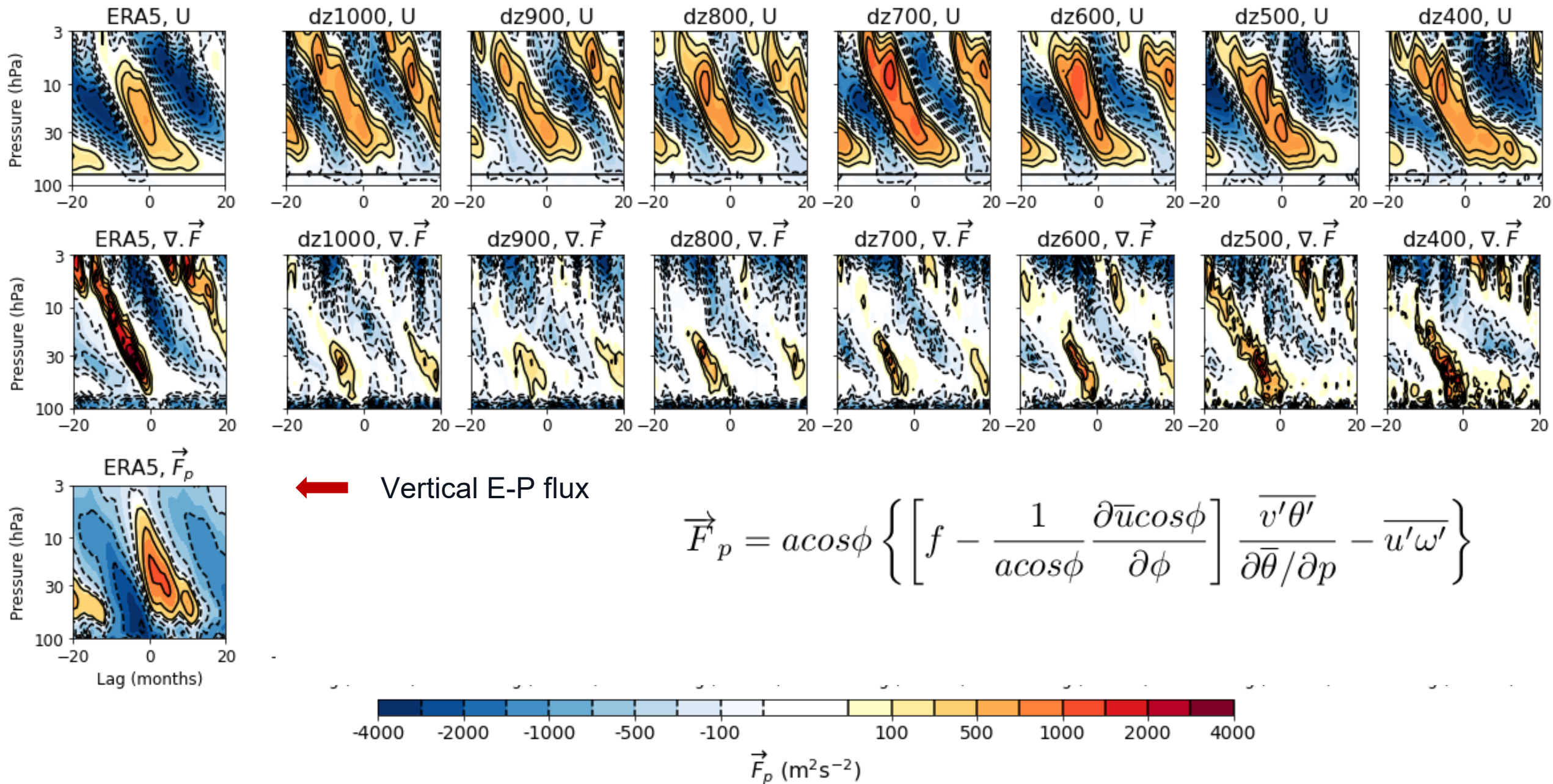
The influence of grid spacing on the QBO



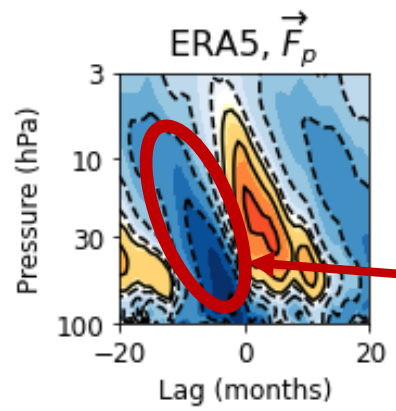
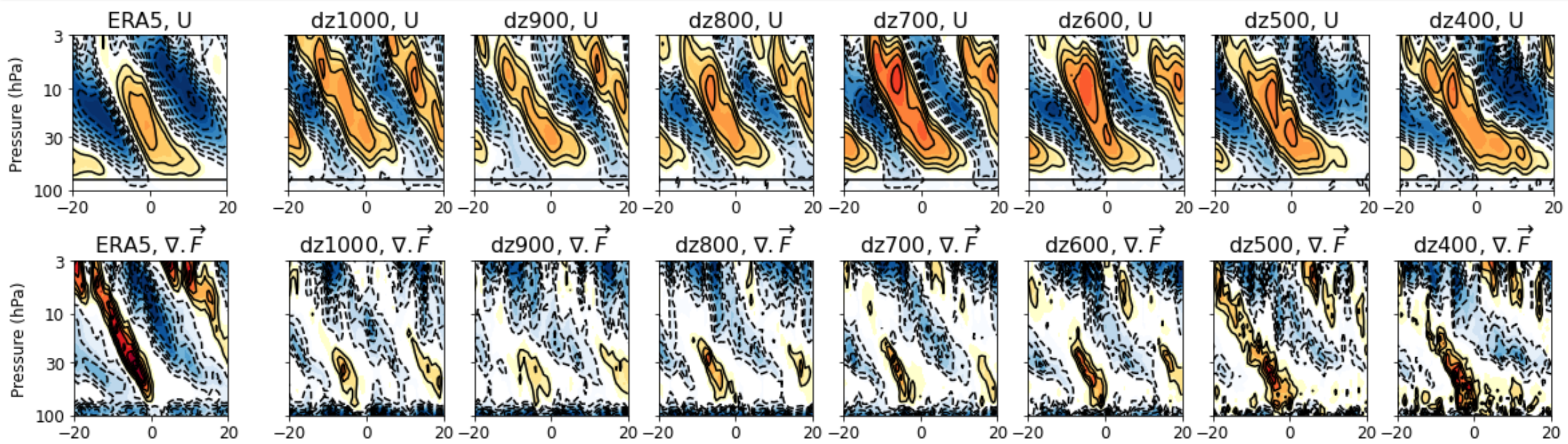
Resolutions lower than dz700 seem to be deficient in the amplitude of the QBO

What about the processes driving the QBO?

The influence of grid spacing on the QBO



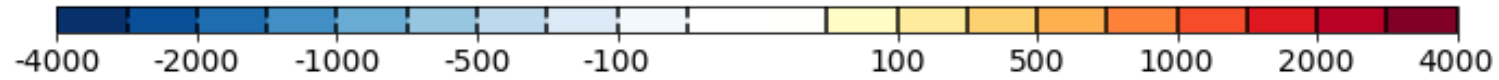
The influence of grid spacing on the QBO



← Vertical E-P flux

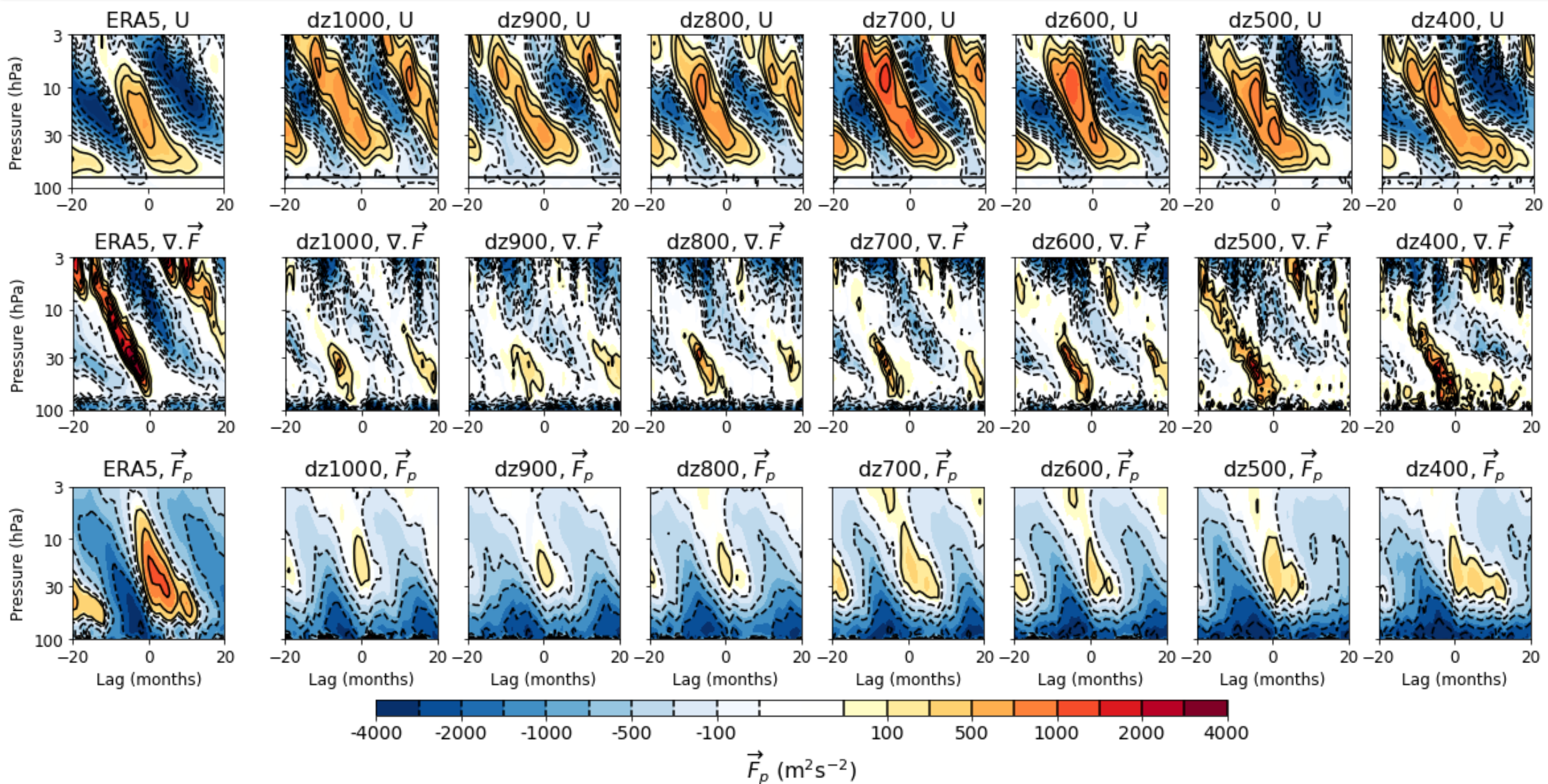
Upward propagation of Kelvin Wave activity transporting westerly momentum upward

$$\vec{F}_p = a \cos \phi \left\{ \left[f - \frac{1}{a \cos \phi} \frac{\partial \bar{u} \cos \phi}{\partial \phi} \right] \frac{\overline{v' \theta'}}{\partial \bar{\theta} / \partial p} - \overline{u' \omega'} \right\}$$

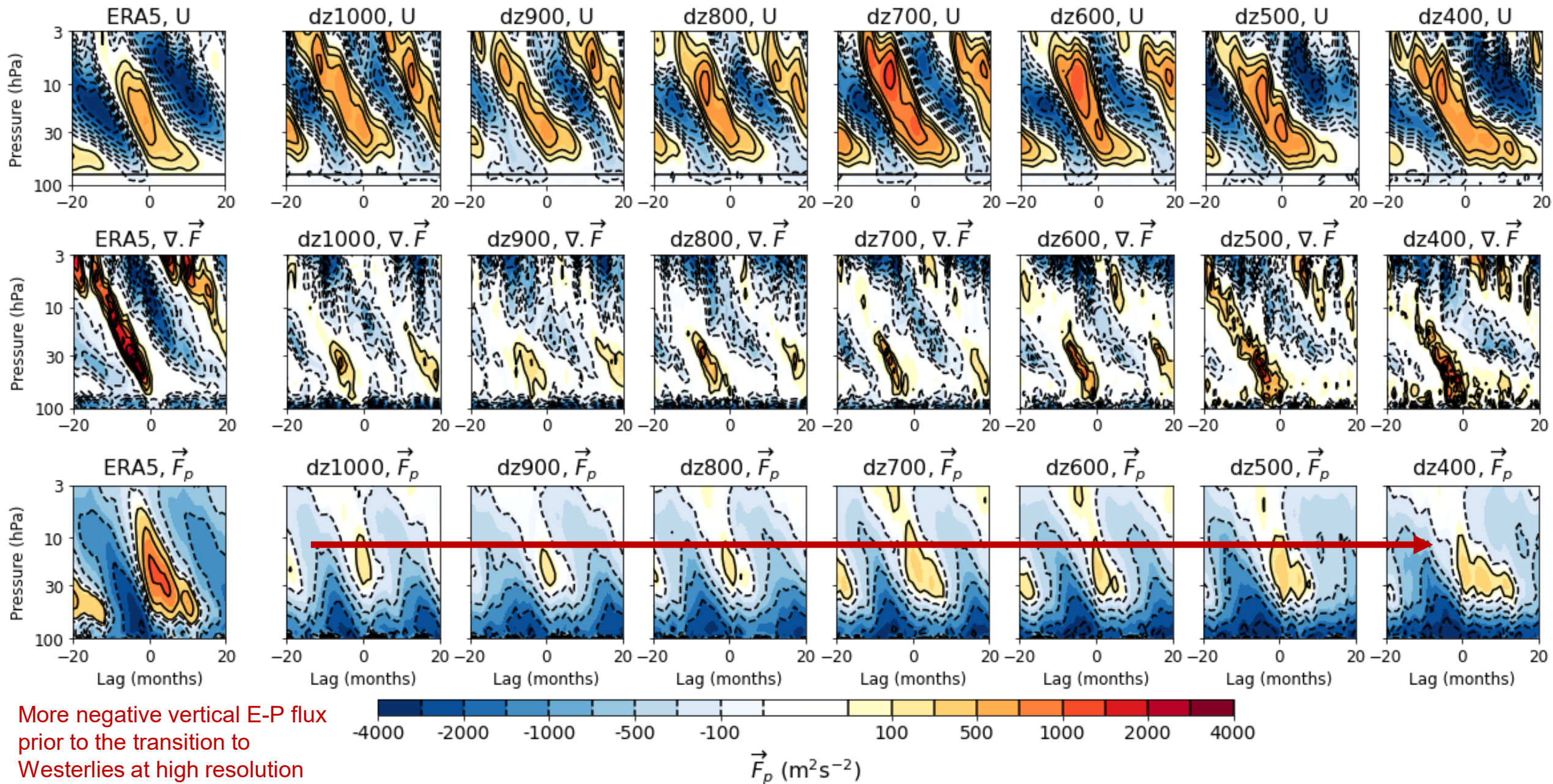


\vec{F}_p ($m^2 s^{-2}$)

The influence of grid spacing on the QBO

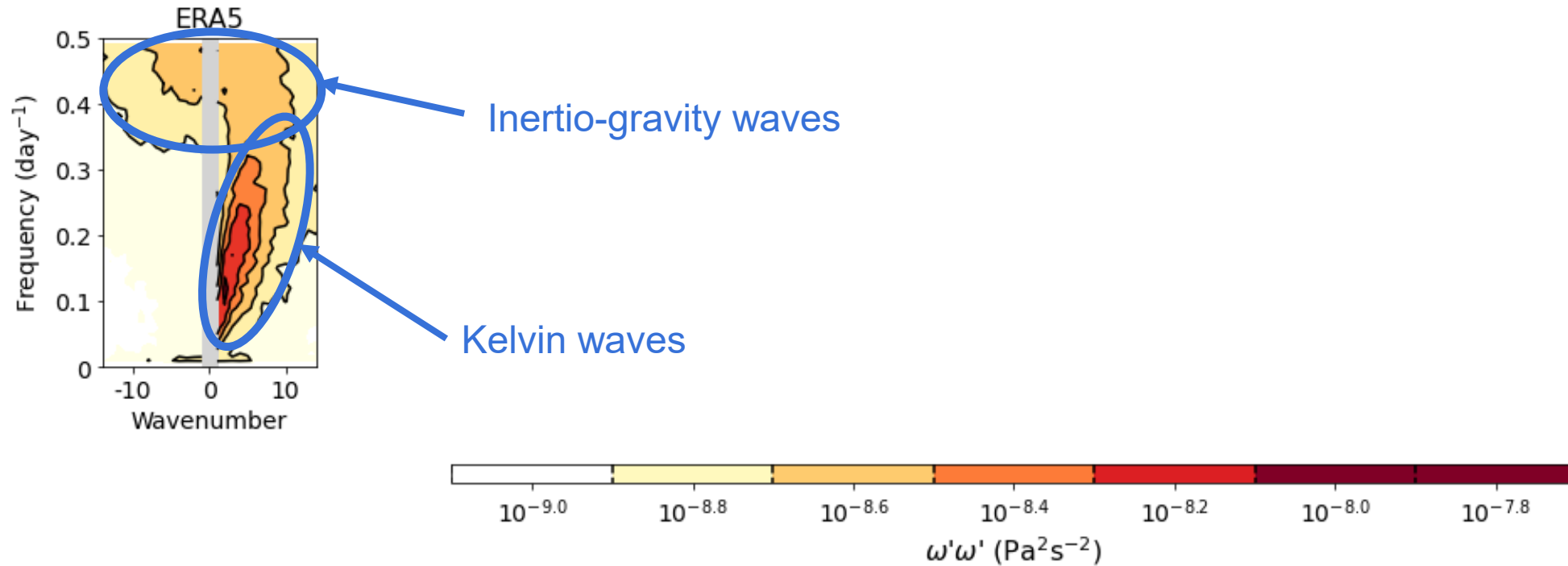


The influence of grid spacing on the QBO



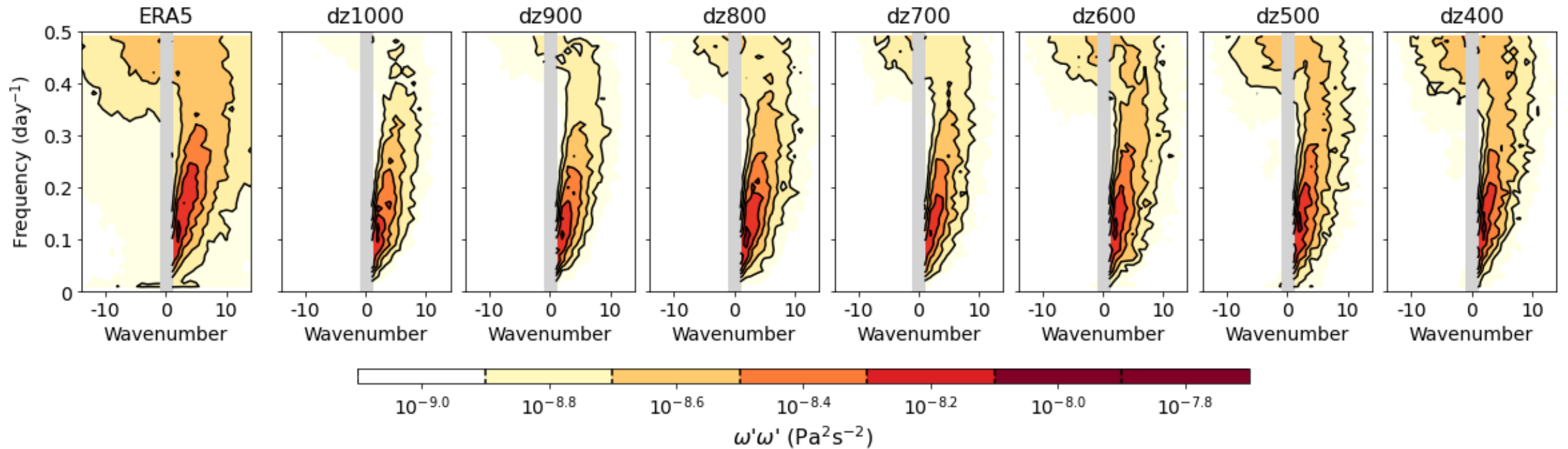
Tropical waves in general

50hPa vertical velocity, 5S-5N, symmetric component



Tropical waves in general

50hPa vertical velocity, 5S-5N, symmetric component

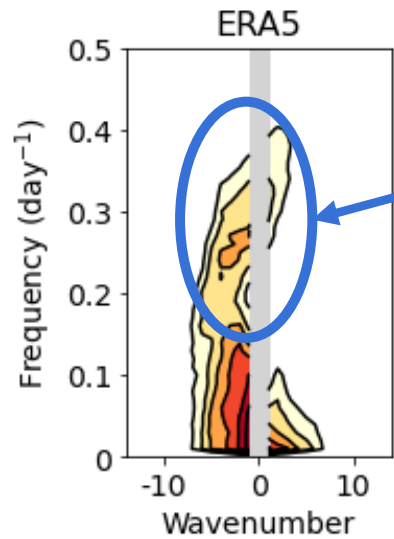


More lower stratospheric Kelvin waves and Inertio-gravity waves as you go to higher resolution.

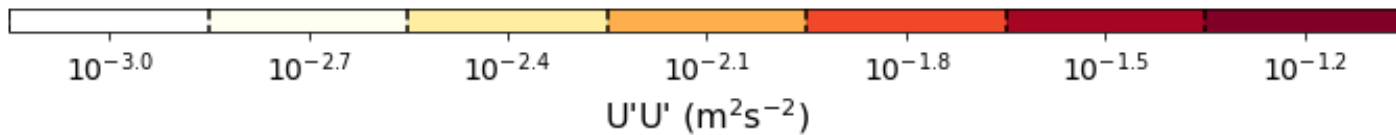
An improvement when comparing with ERA5

Tropical waves in general

50hPa zonal wind, 15S-15N, antisymmetric component

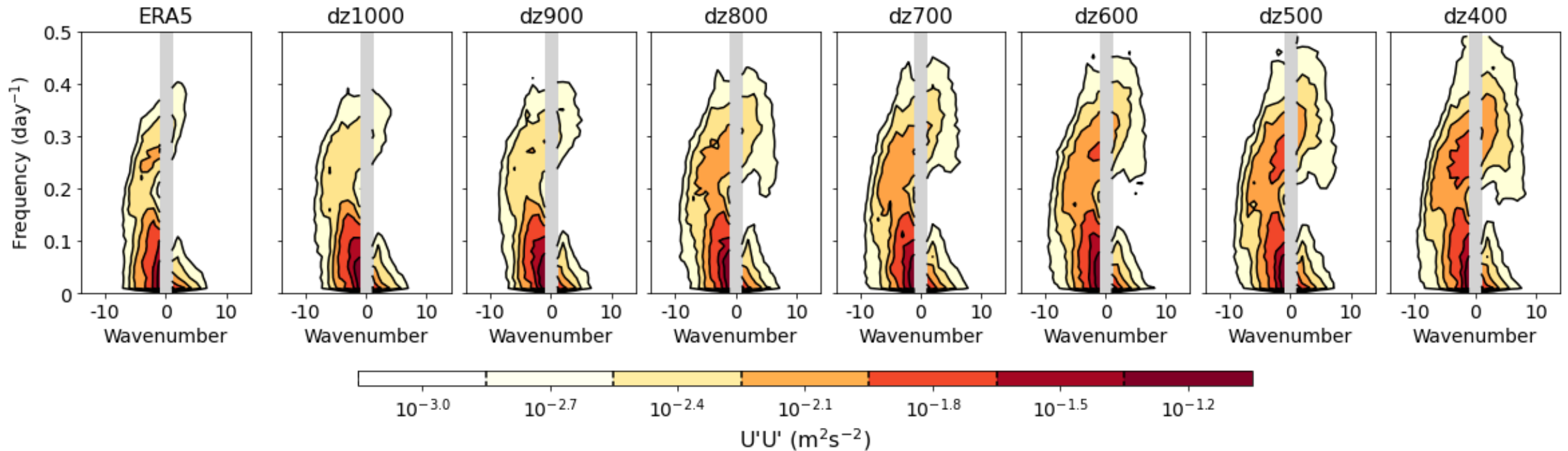


Mixed Rossby-Gravity waves



Tropical waves in general

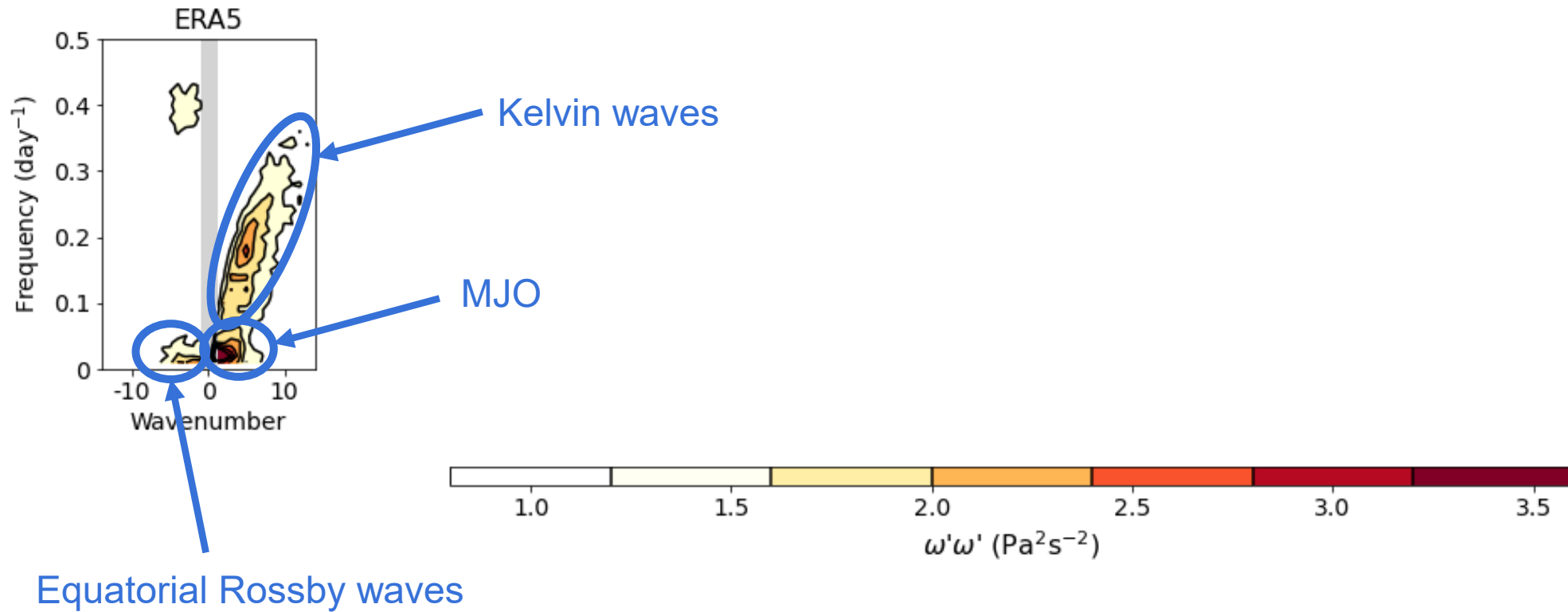
50hPa zonal wind, 15S-15N, antisymmetric component



We get a lot more mixed-Rossby wave activity as we go to higher resolution
Not necessarily a good thing if we compare to ERA5

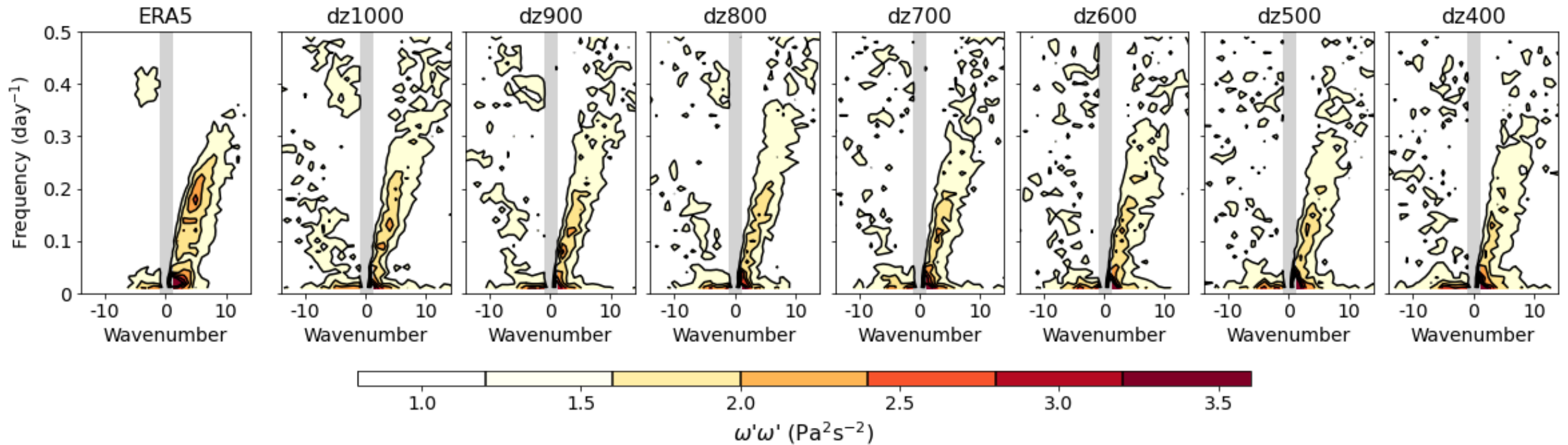
Tropical waves in general

500hPa zonal wind, 5S-5N, symmetric component



Tropical waves in general

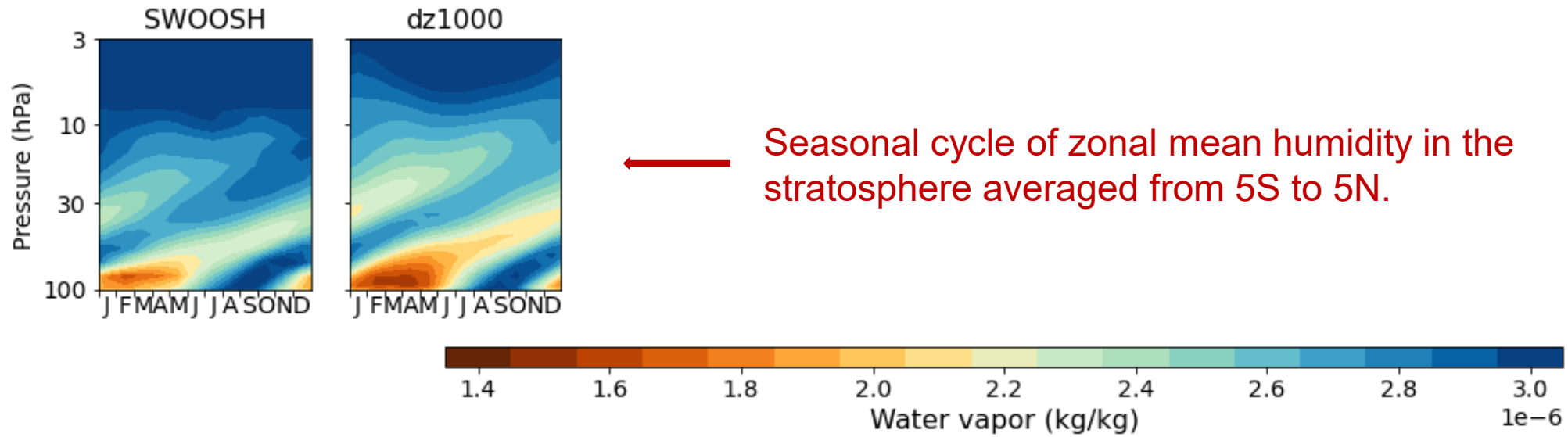
500hPa zonal wind, 5S-5N, symmetric component



Not too much change. Maybe a little more activity in the MJO region at higher resolution.

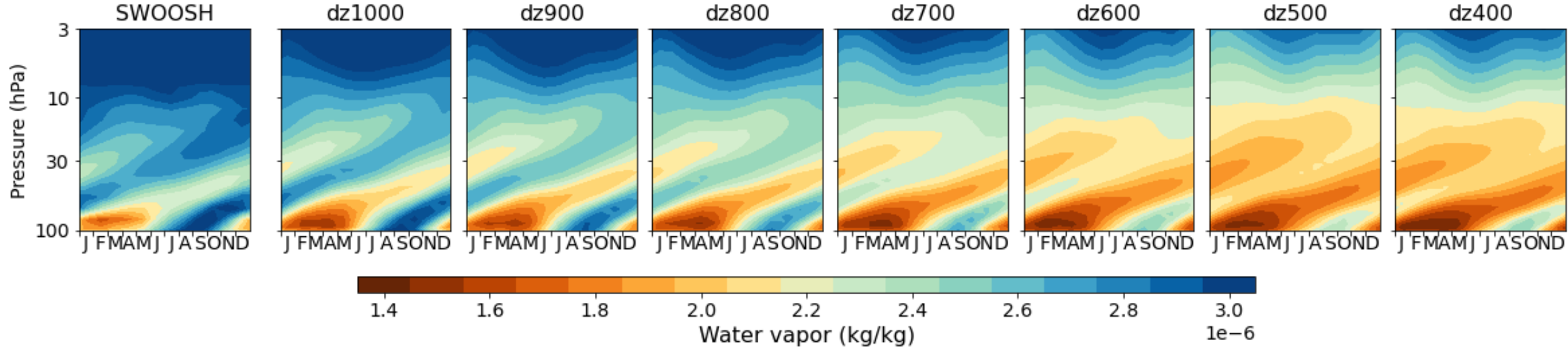
Stratospheric water vapor

Water vapor tape recorder climatology, 5S-5SN



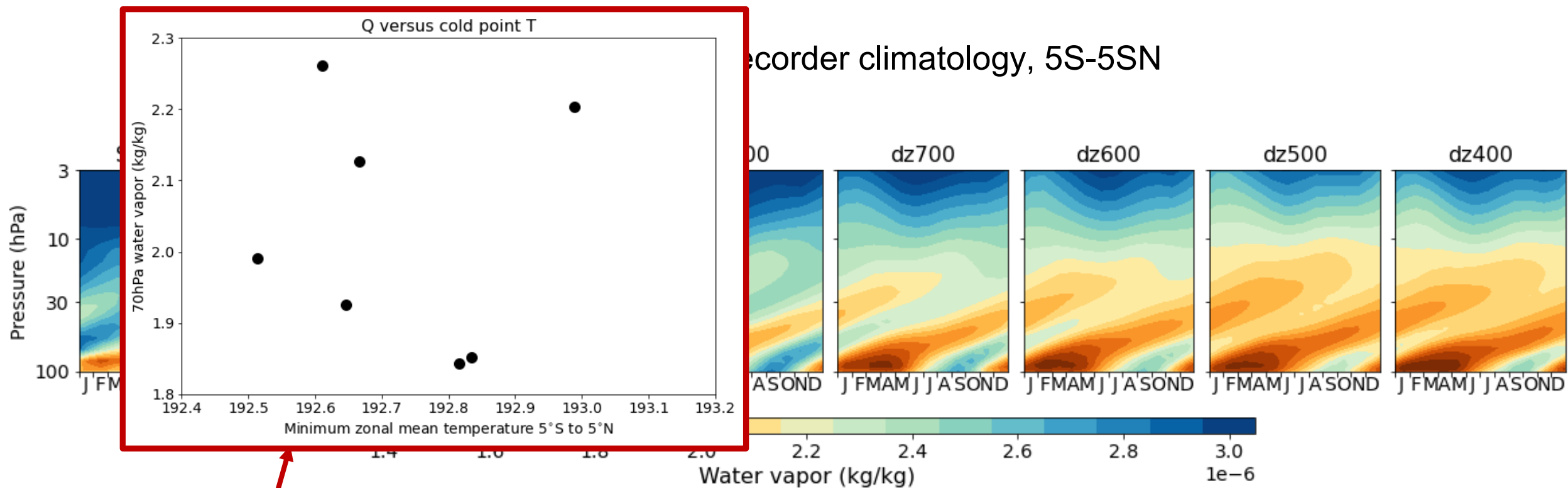
Stratospheric water vapor

Water vapor tape recorder climatology, 5S-5SN



Stratosphere gets drier with increasing resolution (not a good thing)

Stratospheric water vapor



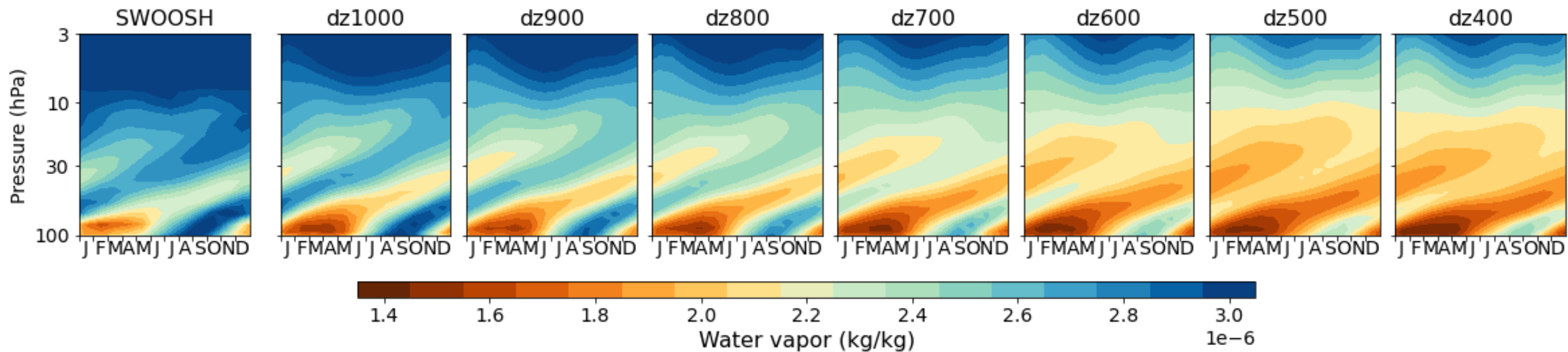
reorder climatology, 5S-5SN

Stratosphere gets drier with increasing resolution (not a good thing)

Water vapor is not correlated with cold point temperature across the simulations

Stratospheric water vapor

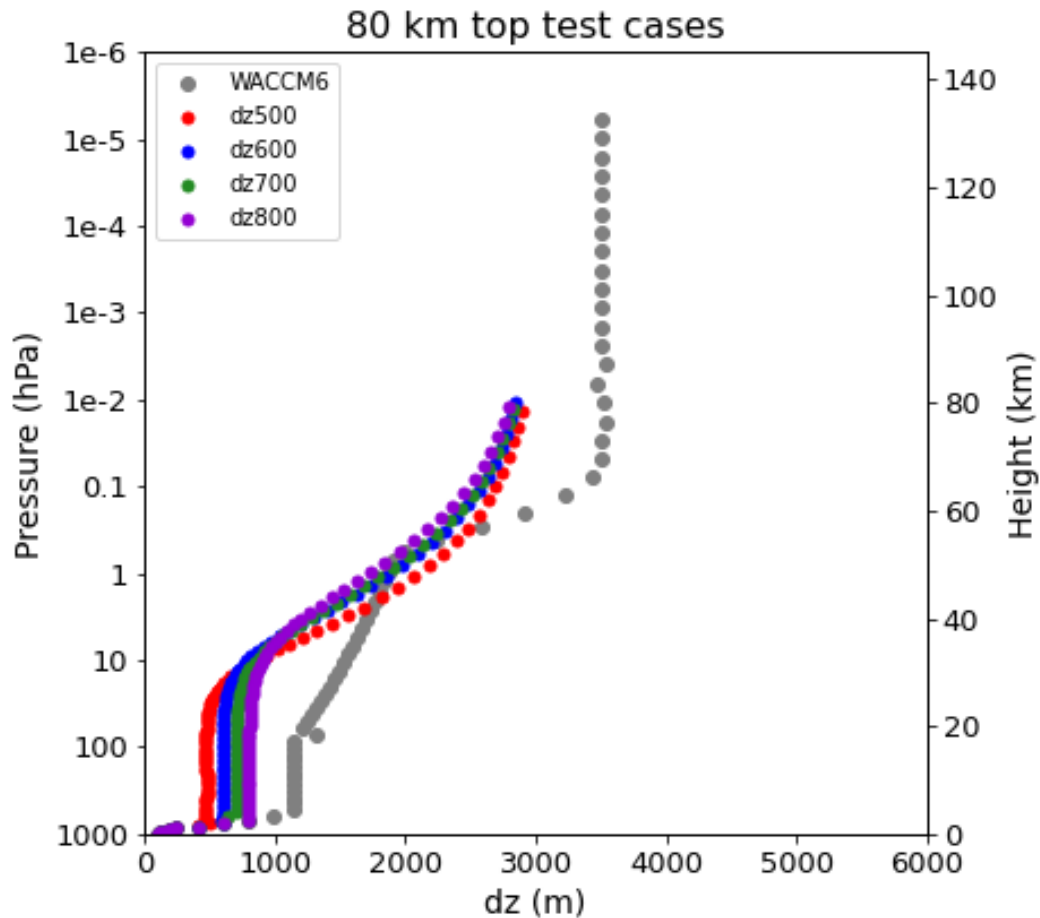
Water vapor tape recorder climatology, 5S-5SN



Stratosphere gets drier with increasing resolution (not a good thing)

But don't worry. This drying in association with increased vertical resolution has been compensated for by other physics changes in CAM7

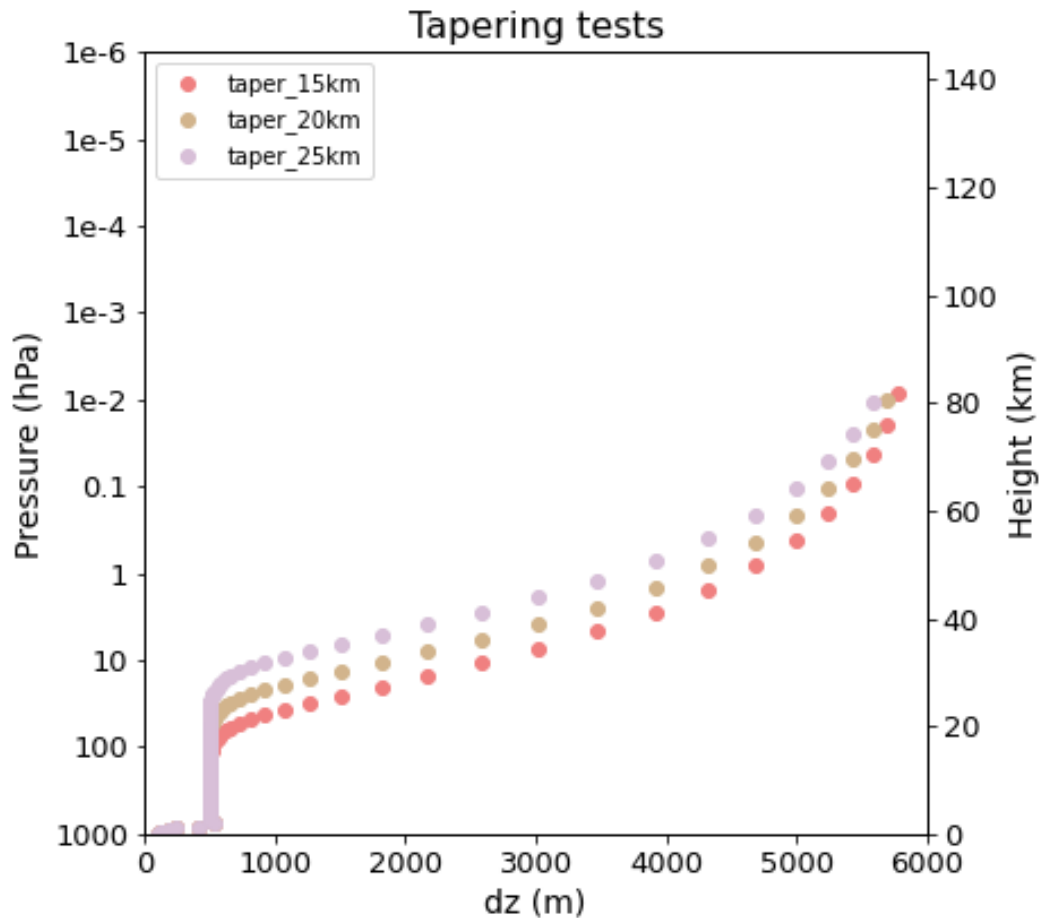
The stages of the vertical resolution task team decision making process



(1) With a top similar to WACCMs (~ 140 km), how much does the vertical grid spacing in the free troposphere and lower stratosphere impact on the QBO and other things?

(2) Can we lower the model top to 80 km without detrimental impacts on the representation of tropospheric and stratospheric climate? Do the QBO results still hold with an 80 km top?

The stages of the vertical resolution task team decision making process

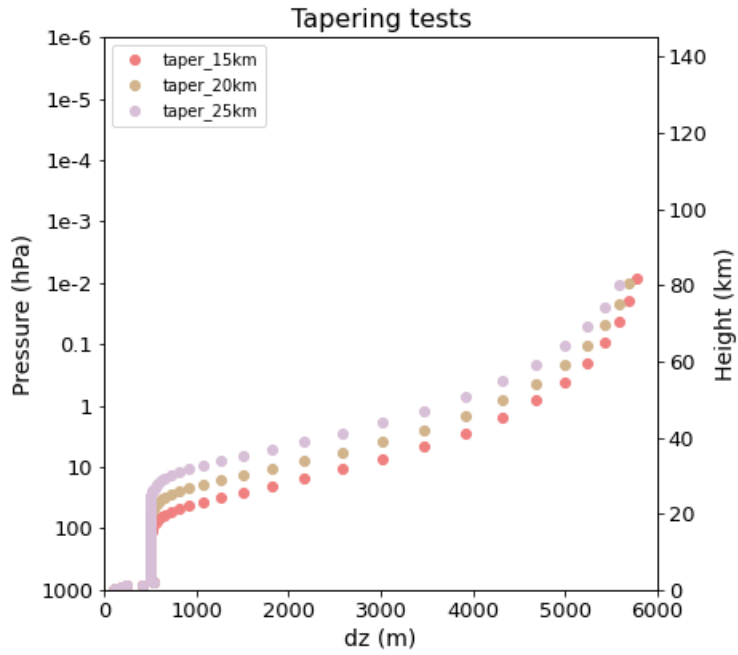


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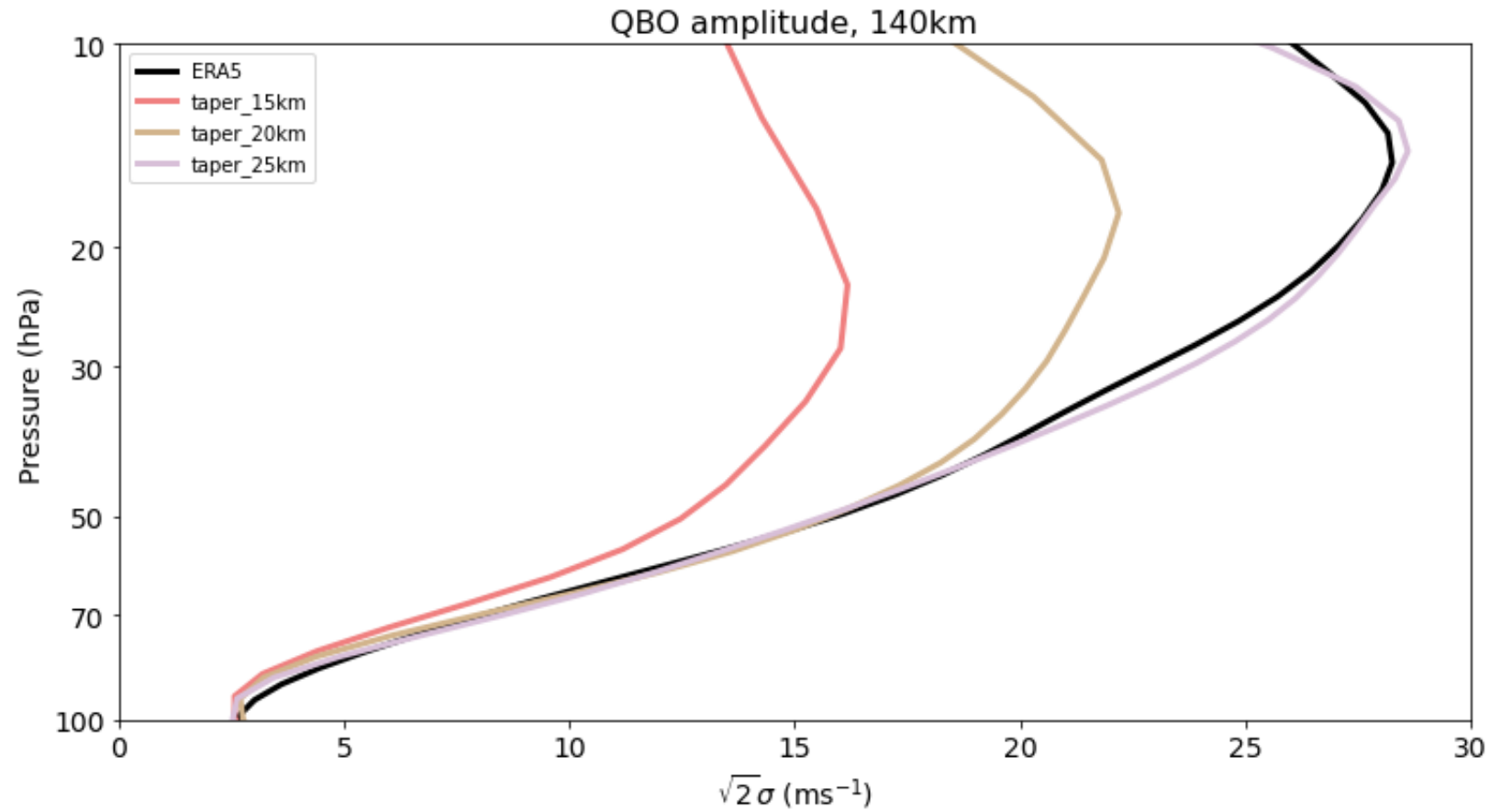
(2) Can we lower the model top to 80 km without detrimental impacts on the representation of tropospheric and stratospheric climate? Do the QBO results still hold with an 80 km top?

(3) How much can we taper the resolution in the stratosphere and still retain the fidelity of the QBO?

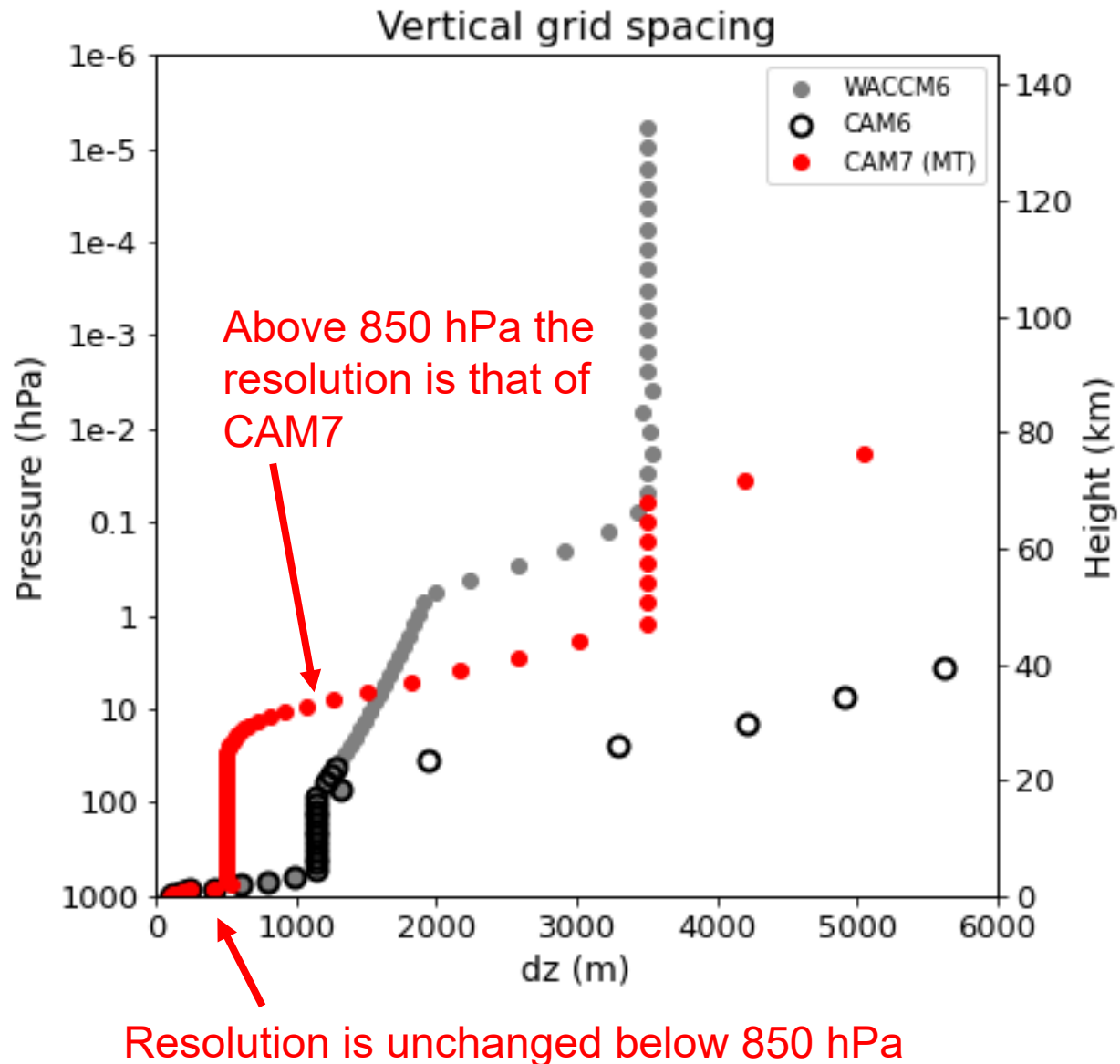
QBO Amplitude



QBO amplitude severely degraded if you taper off the resolution at too low a level



S2S predictions with the 83 level version



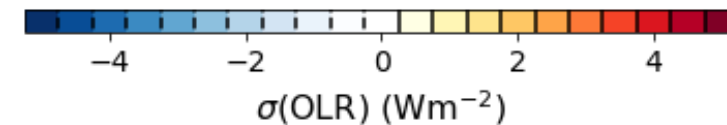
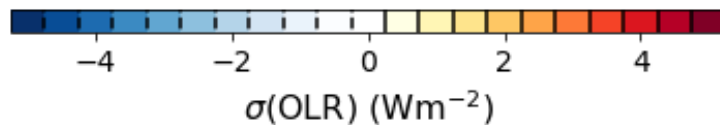
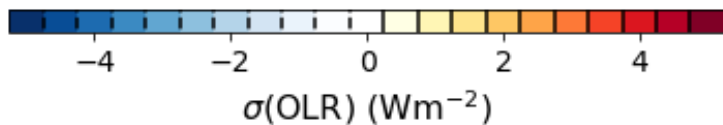
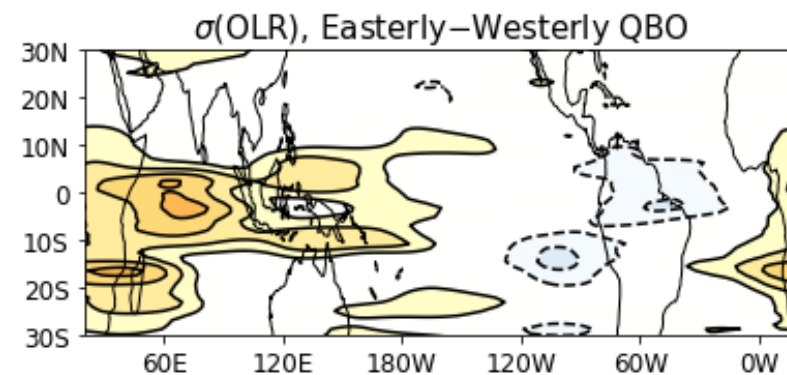
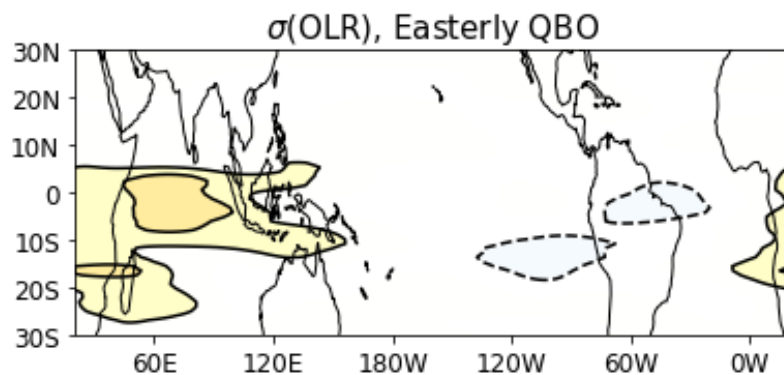
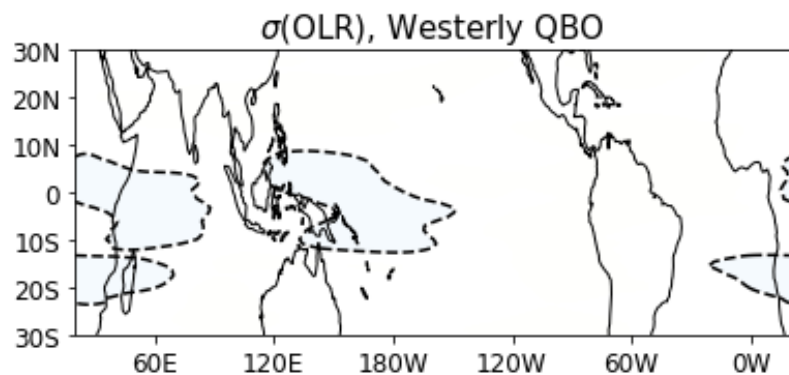
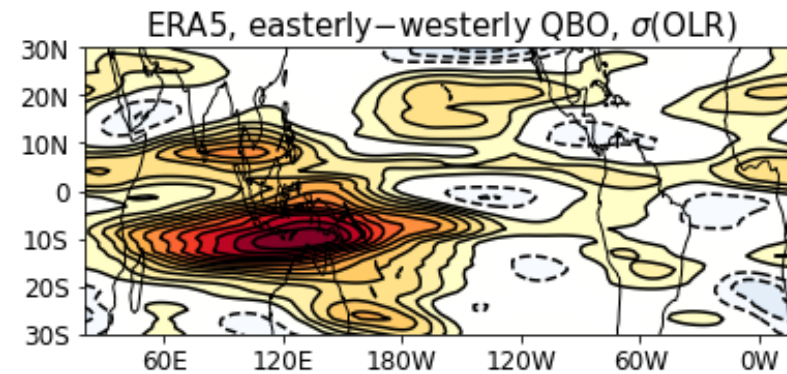
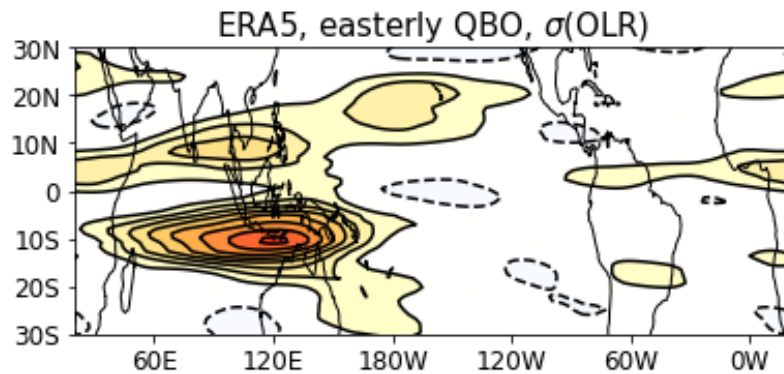
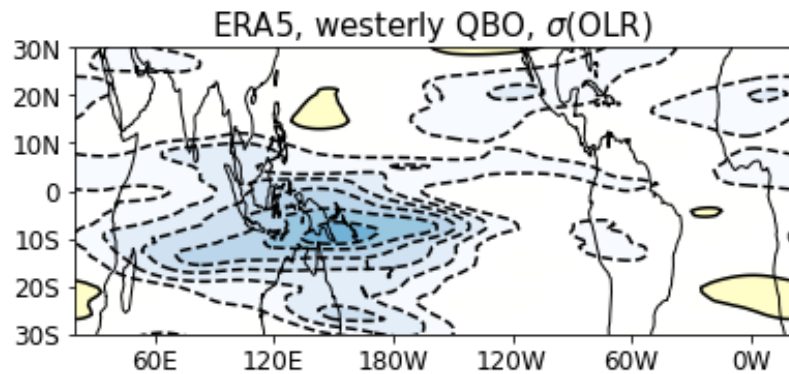
Initialized predictions analogous to the CESM2 SMYLE (Seasonal-to-Multiyear Large Ensemble, Yeager et al 2022)

- Initializations Nov 1st, Sept 1st, Feb 1st
- 1970 to 2020
- 6 months

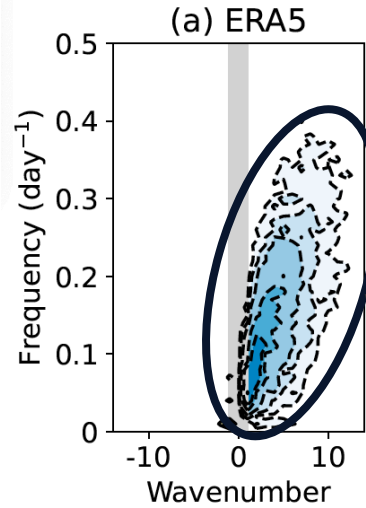
DeFlorio et al, in prep



Do we capture the QBO - MJO connection?

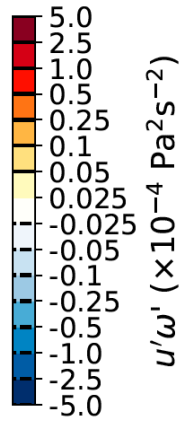


Wave spectra over the 90 days prior to the transition from easterly to westerly

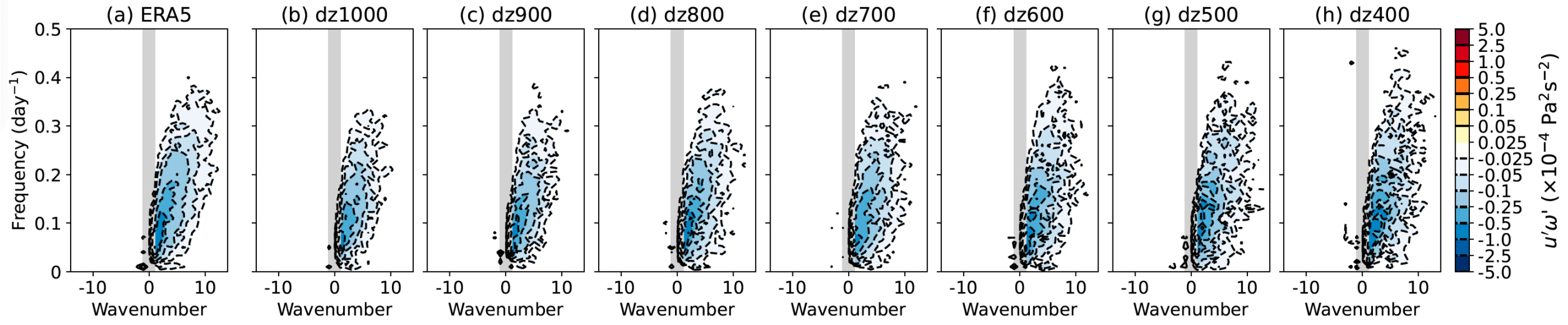


Vertical eddy momentum flux of waves that are symmetric about the equator

Upward flux of westerly momentum due to Kelvin waves

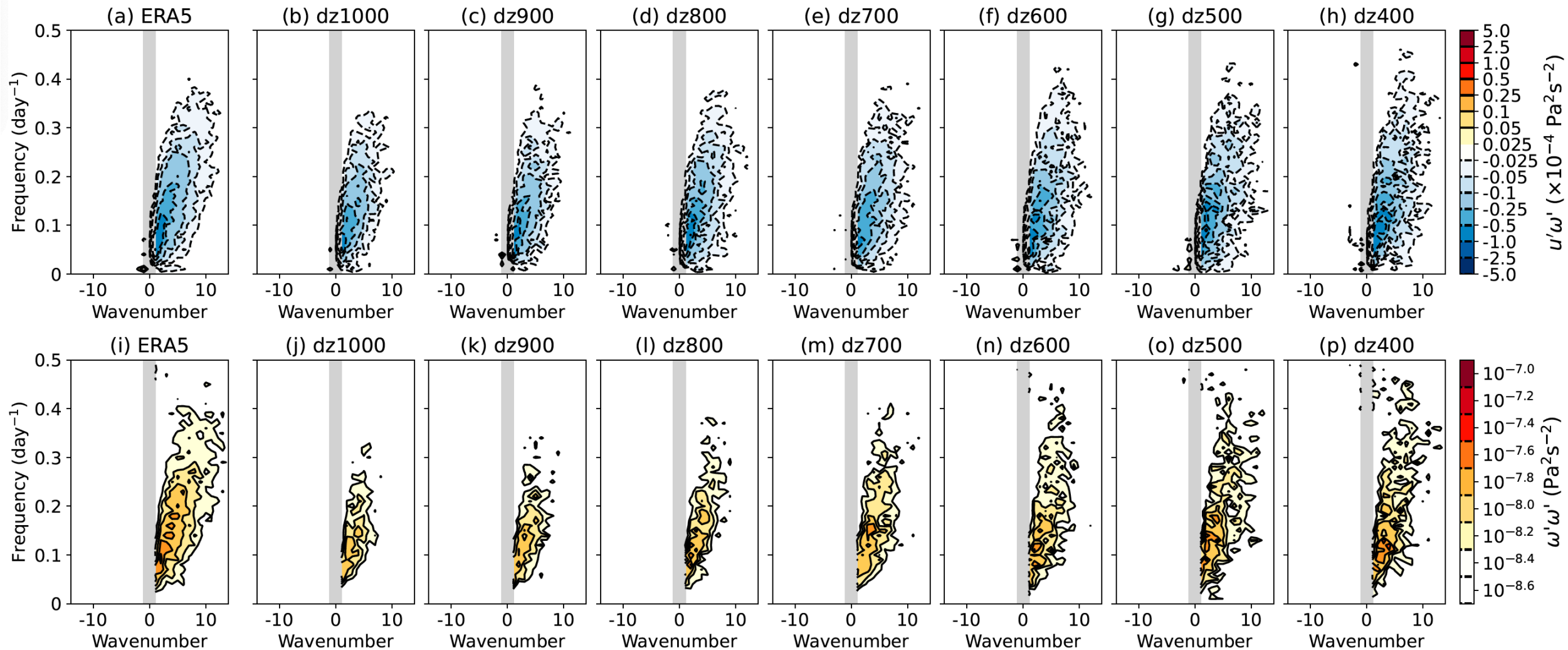


Wave spectra over the 90 days prior to the transition from easterly to westerly



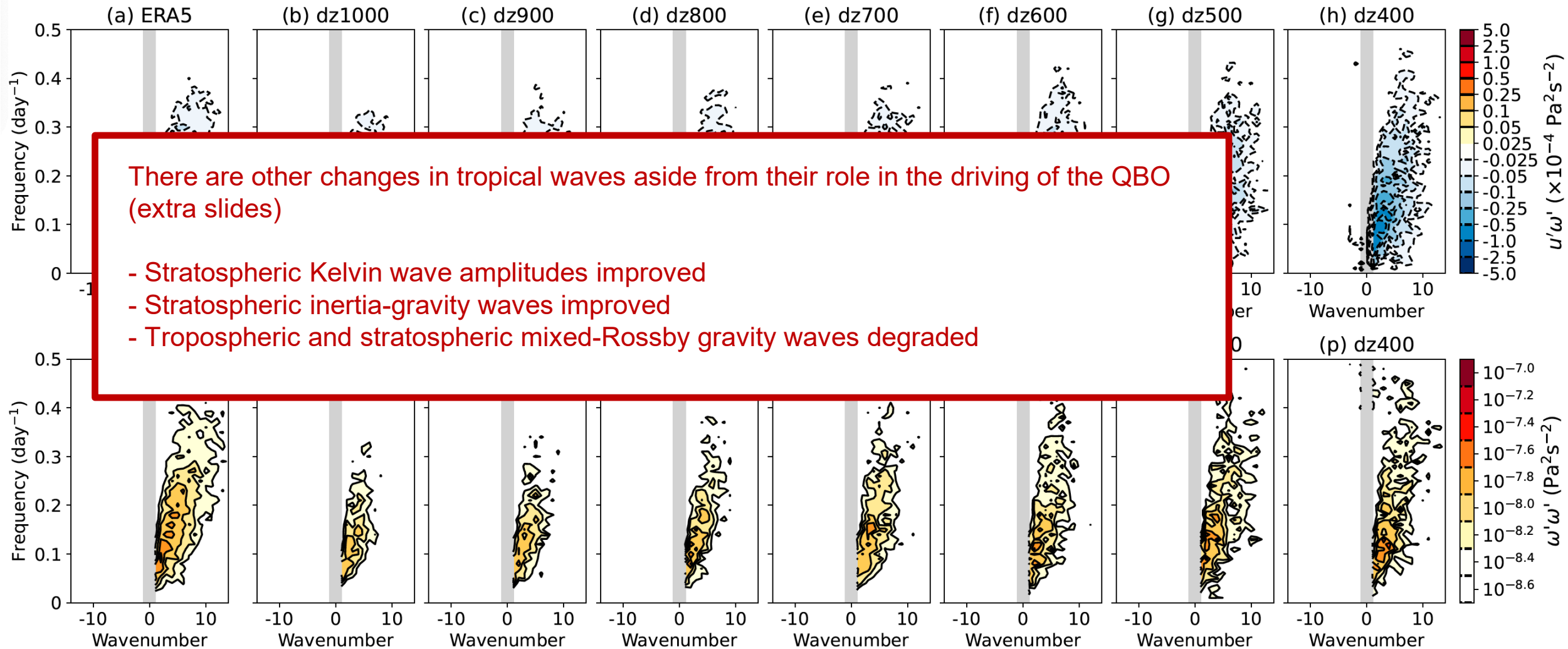
Improved representation of the Kelvin wave momentum flux with resolution

Wave spectra over the 90 days prior to the transition from easterly to westerly



Symmetric vertical velocity power spectra i.e., a measure of the amplitude of the waves

Wave spectra over the 90 days prior to the transition from easterly to westerly



Symmetric vertical velocity power spectra i.e., a measure of the amplitude of the waves