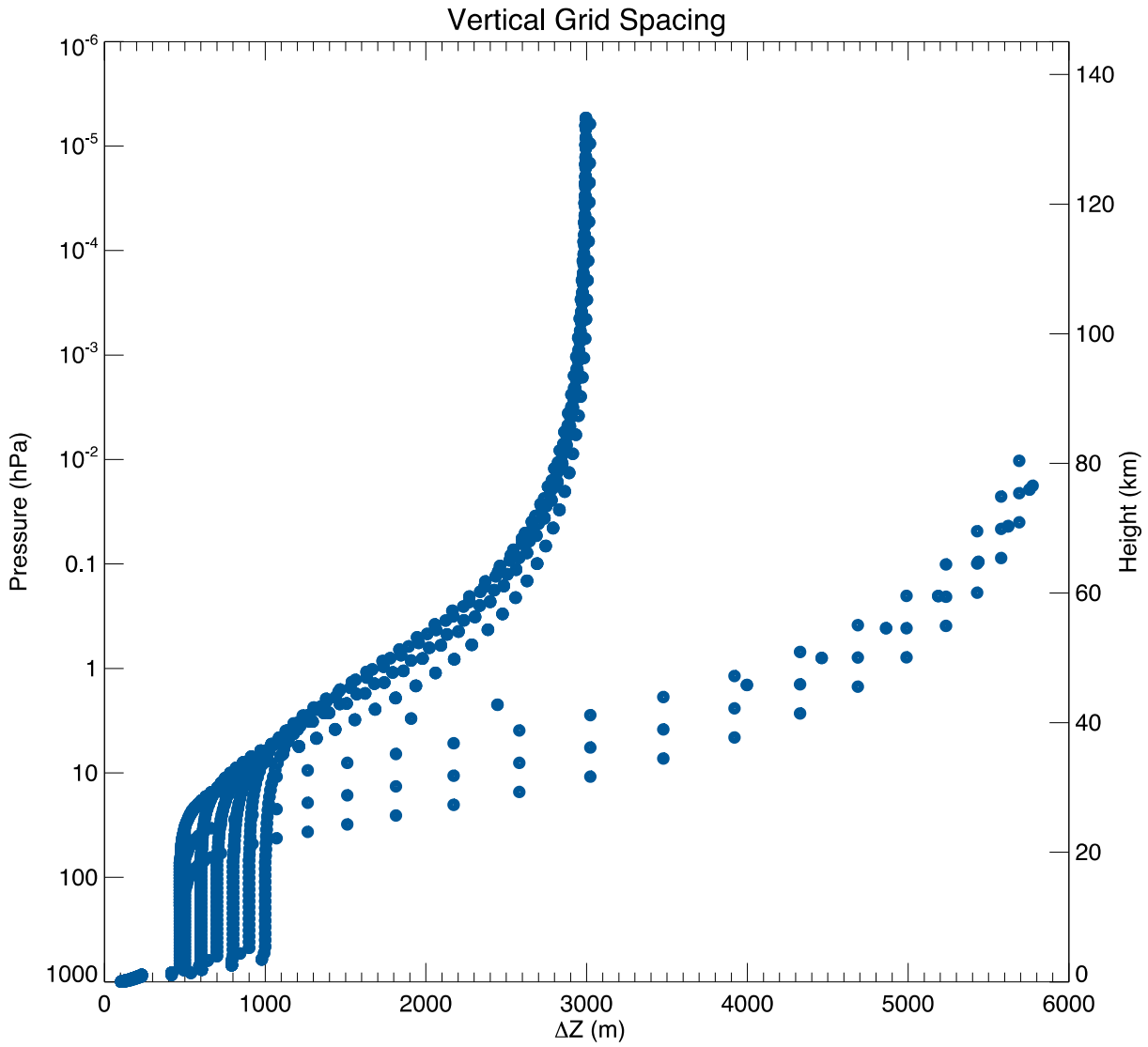
Investigations into the vertical resolution for the next "workhorse" version of CESM

Isla Simpson

Task Team (in alphabetical order):

Julio Bacmeister, Julie Caron, Nick Davis, Rolando Garcia, Cecile Hannay, Christiane Jablonowski, Peter Lauritzen, Brian Medeiros, Rich Neale, Lorenzo Polvani, Yaga Richter, Simone Tilmes



June, 2020

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The Task…

Investigate possible grid configurations for the next generation “workhorse” version of CESM i.e., the model that will be run for CMIP7 and will be released to the community in CESM3 and will be used for the next 5-10 years. This will be a model that does not extend as high as WACCM, but extends higher than CAM and has a grid structure with improvements in vertical resolution in the free troposphere and stratosphere and the boundary layer in order to capture features of interest.

- Recommend a specific top height with justification (expectation ~80km)
- Recommend a specific number of levels (expectation ~80), along with their spacing, with justification
- (secondary) recommend a ”mid-level” height and resolution for cheaper simulation/tuning purposes.

Motivation

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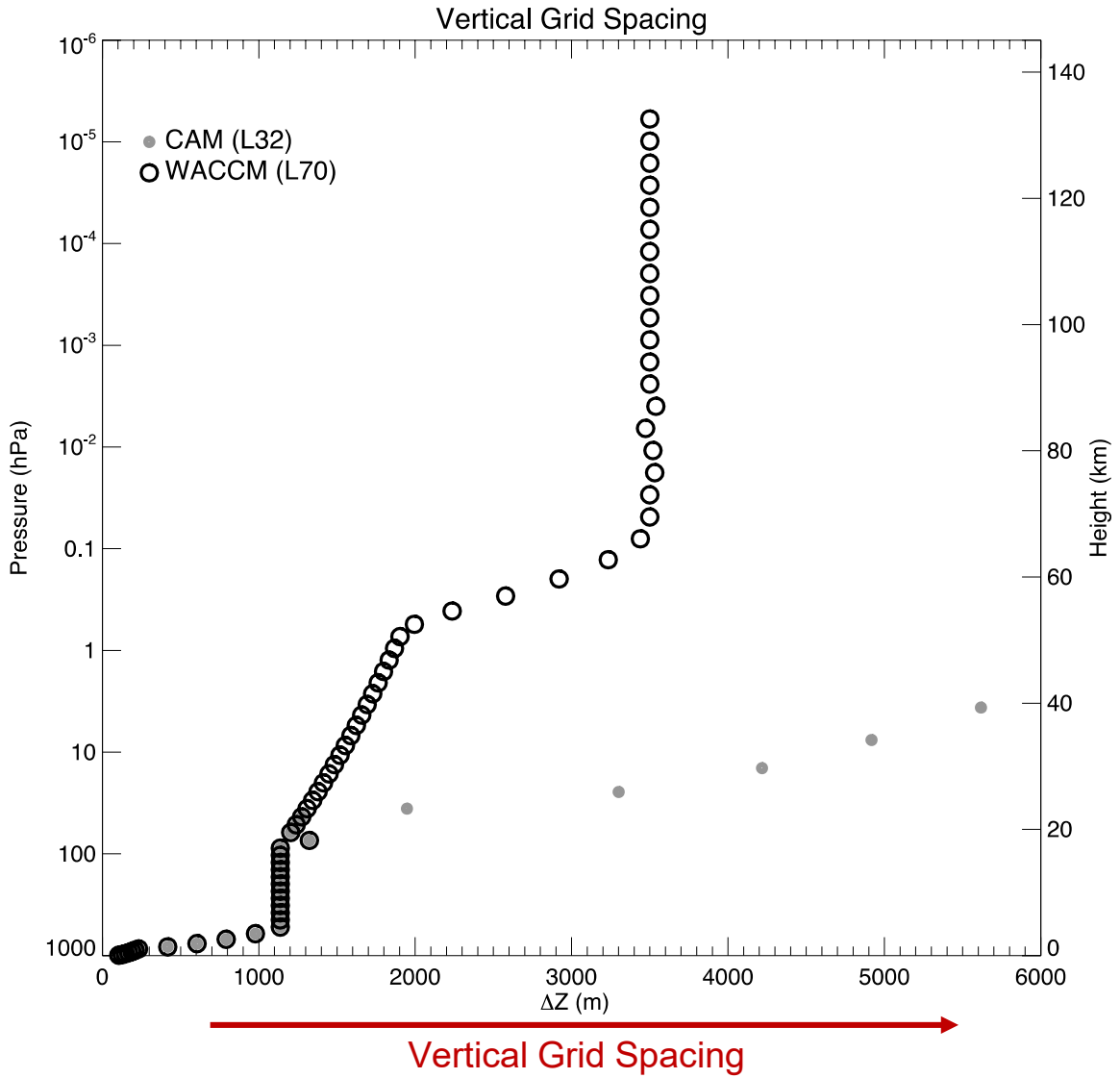

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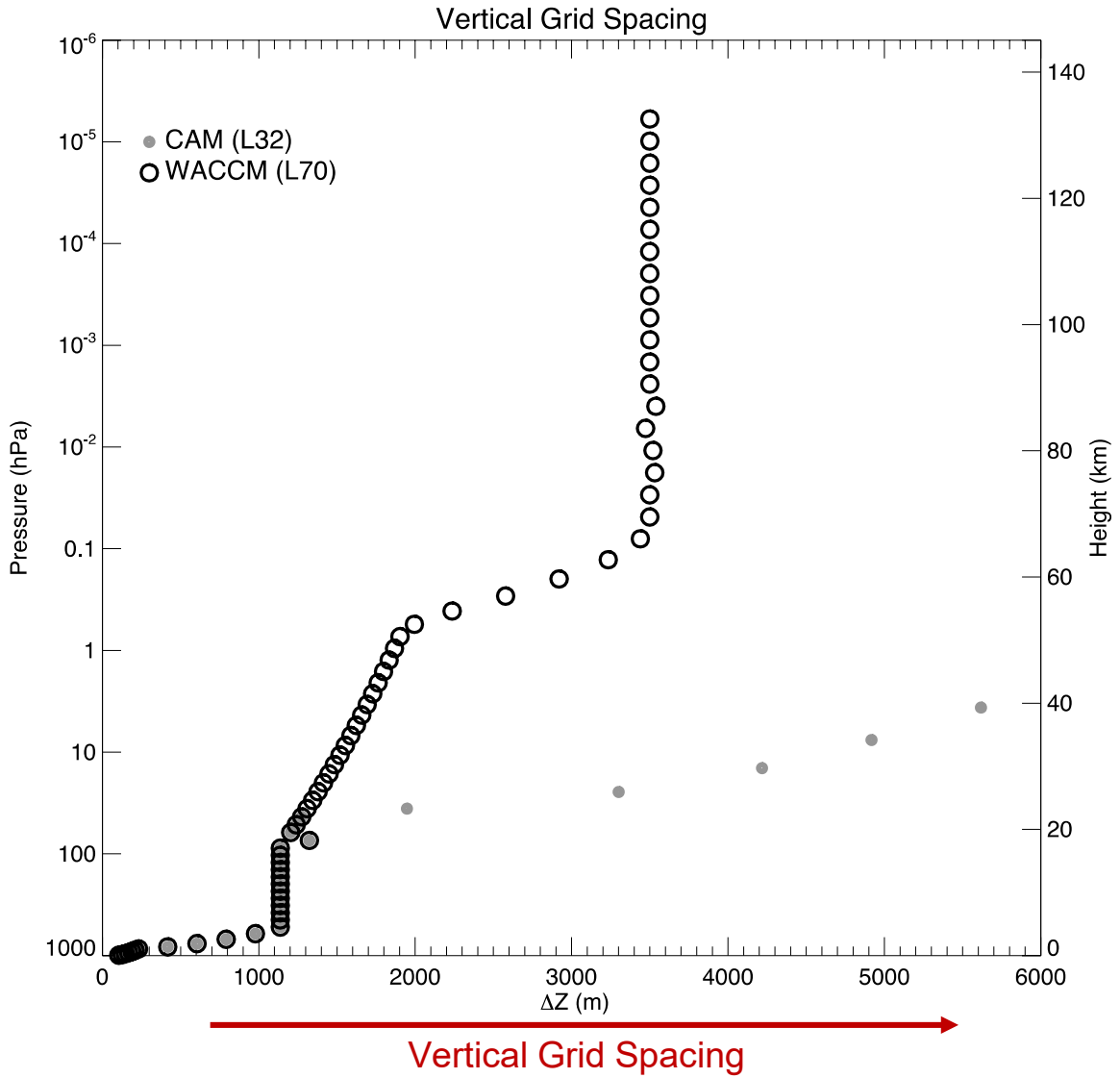

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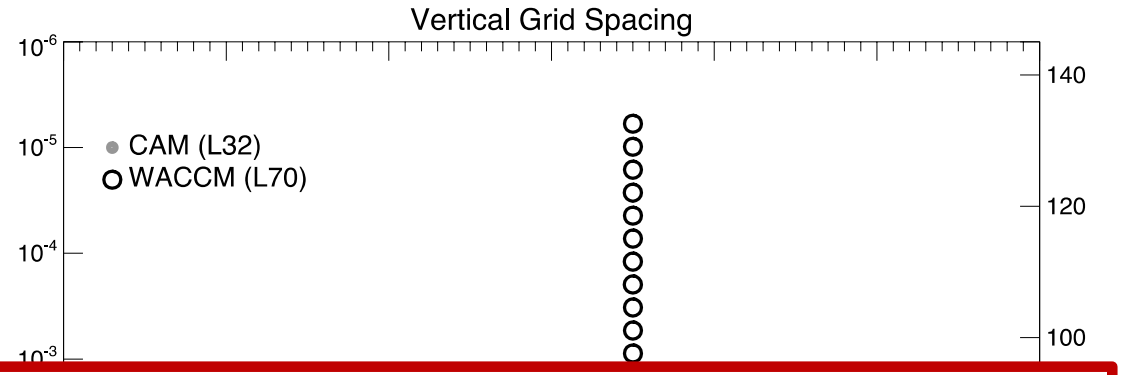

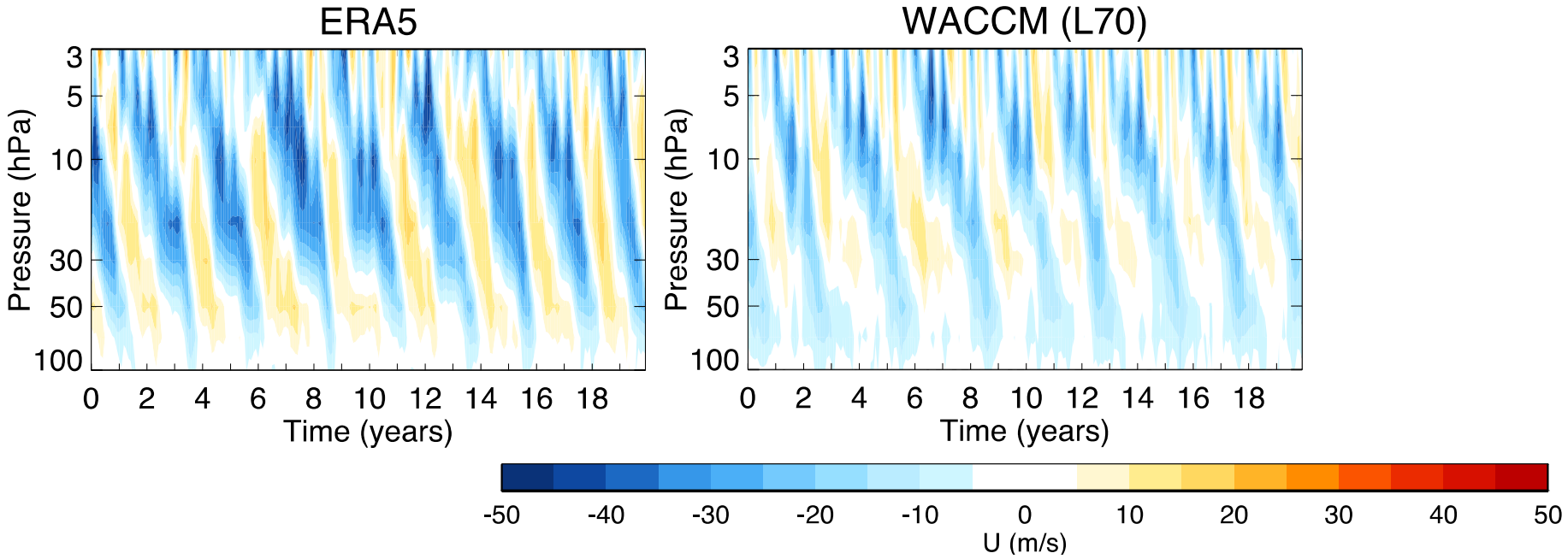

(see e.g., Richter et al (2014) for discussion of the resolution influence on the QBO)

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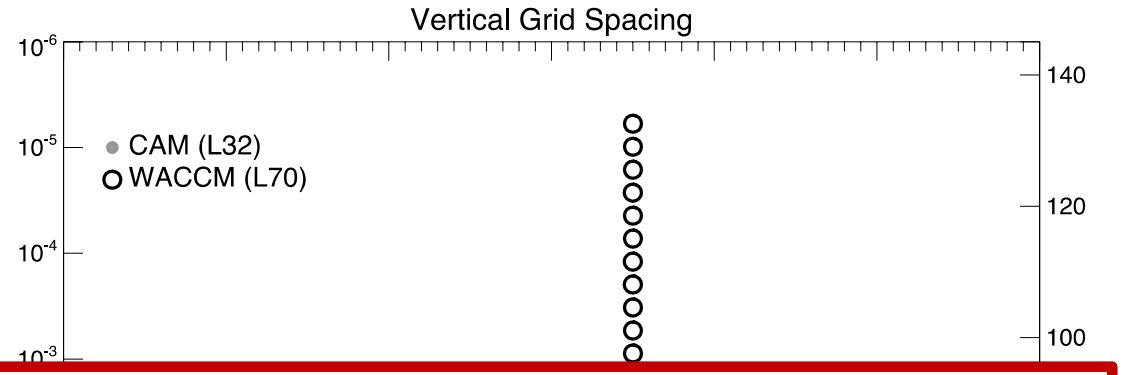

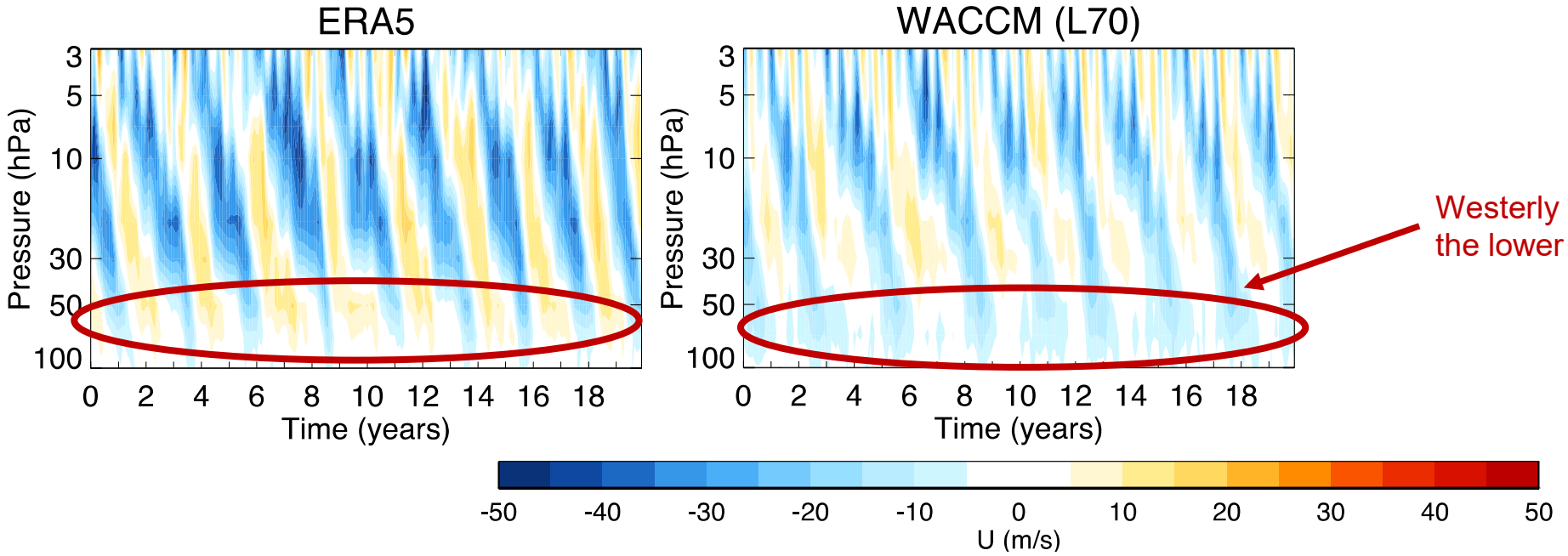

Westerly phase doesn't reach into the lower stratosphere

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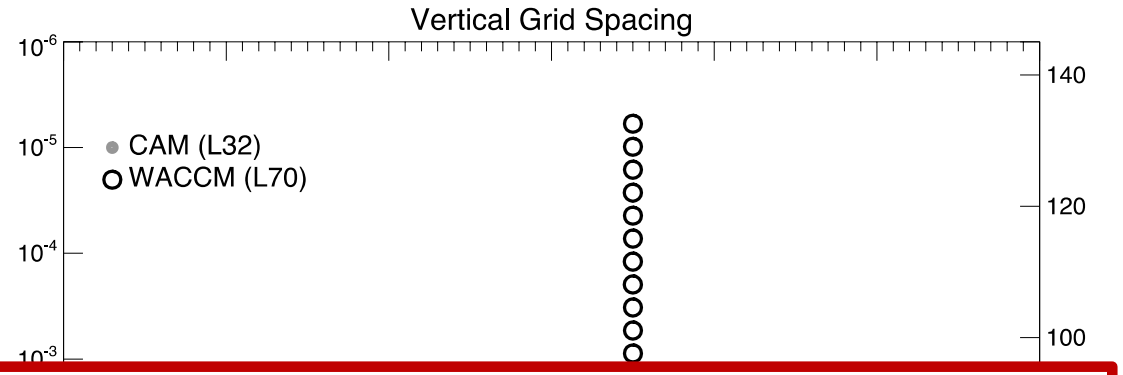

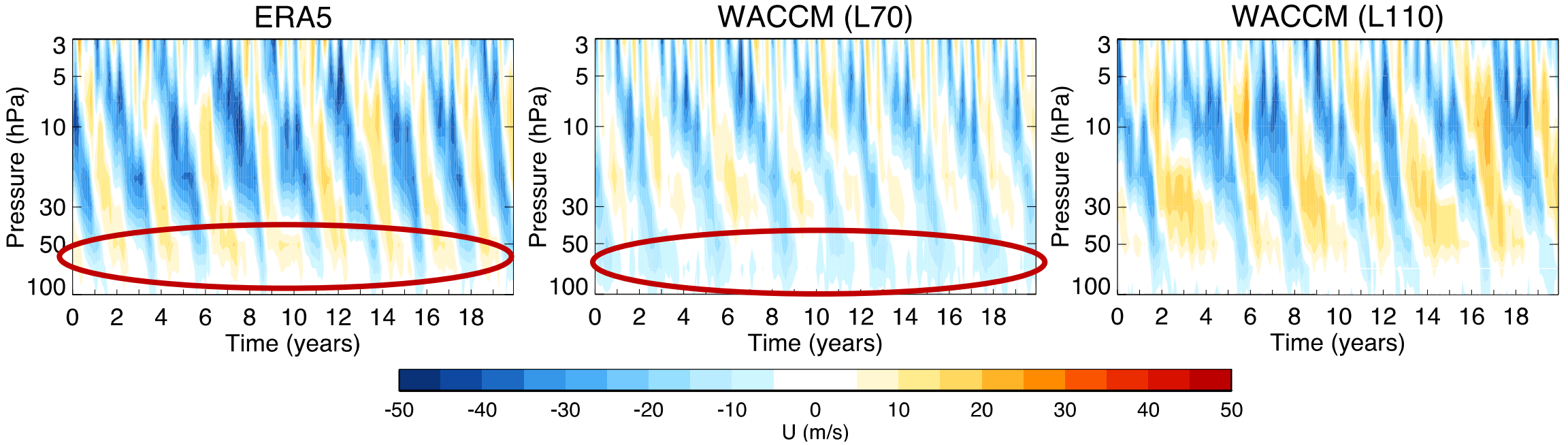

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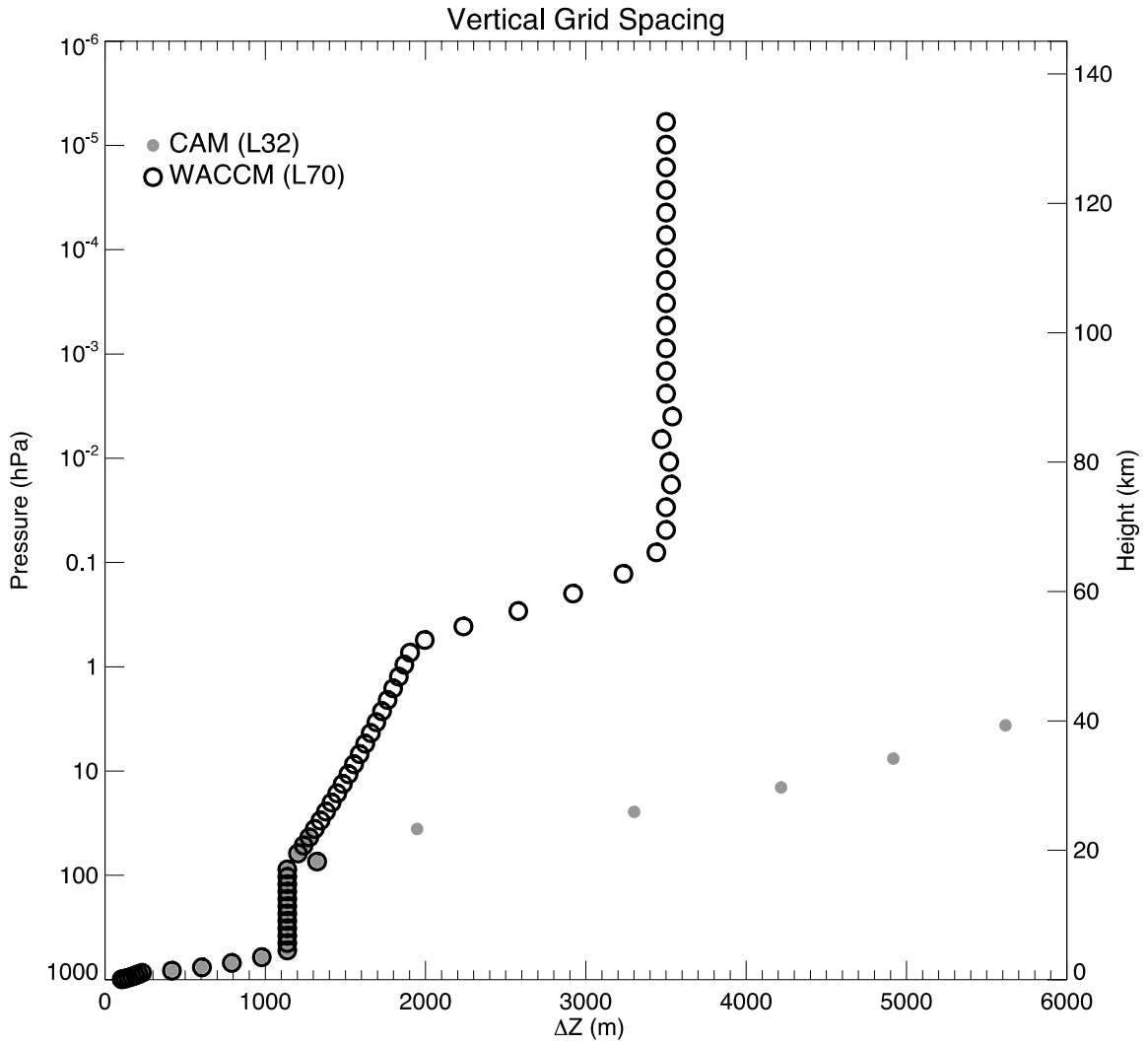
- WACCM still doesn't have a high enough vertical resolution to adequately represent the QBO
- It is well established that extra-tropical stratospheric variability and change have an important influence on the troposphere (CAM is too low to have confidence in its stratospheric representation)



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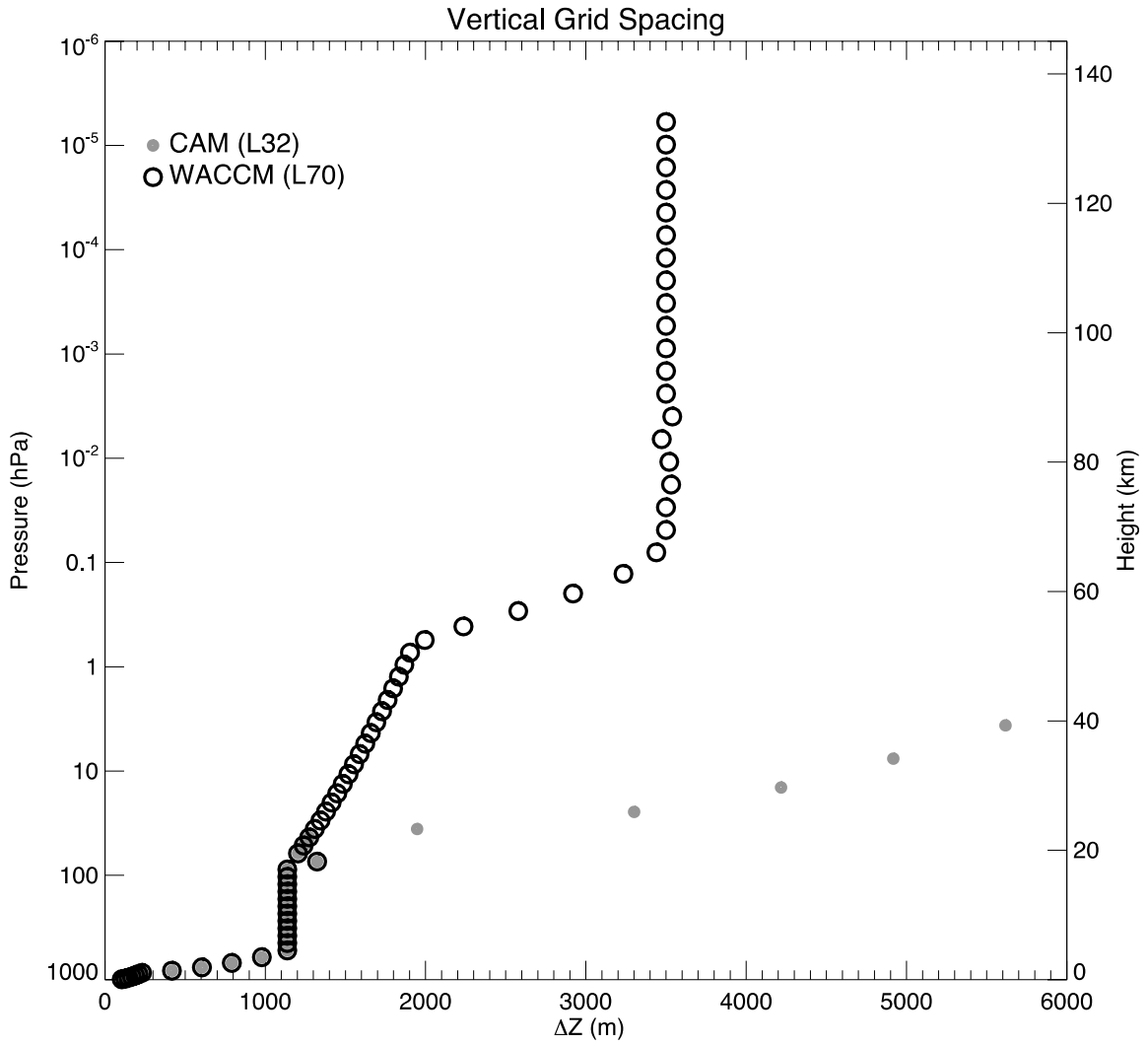

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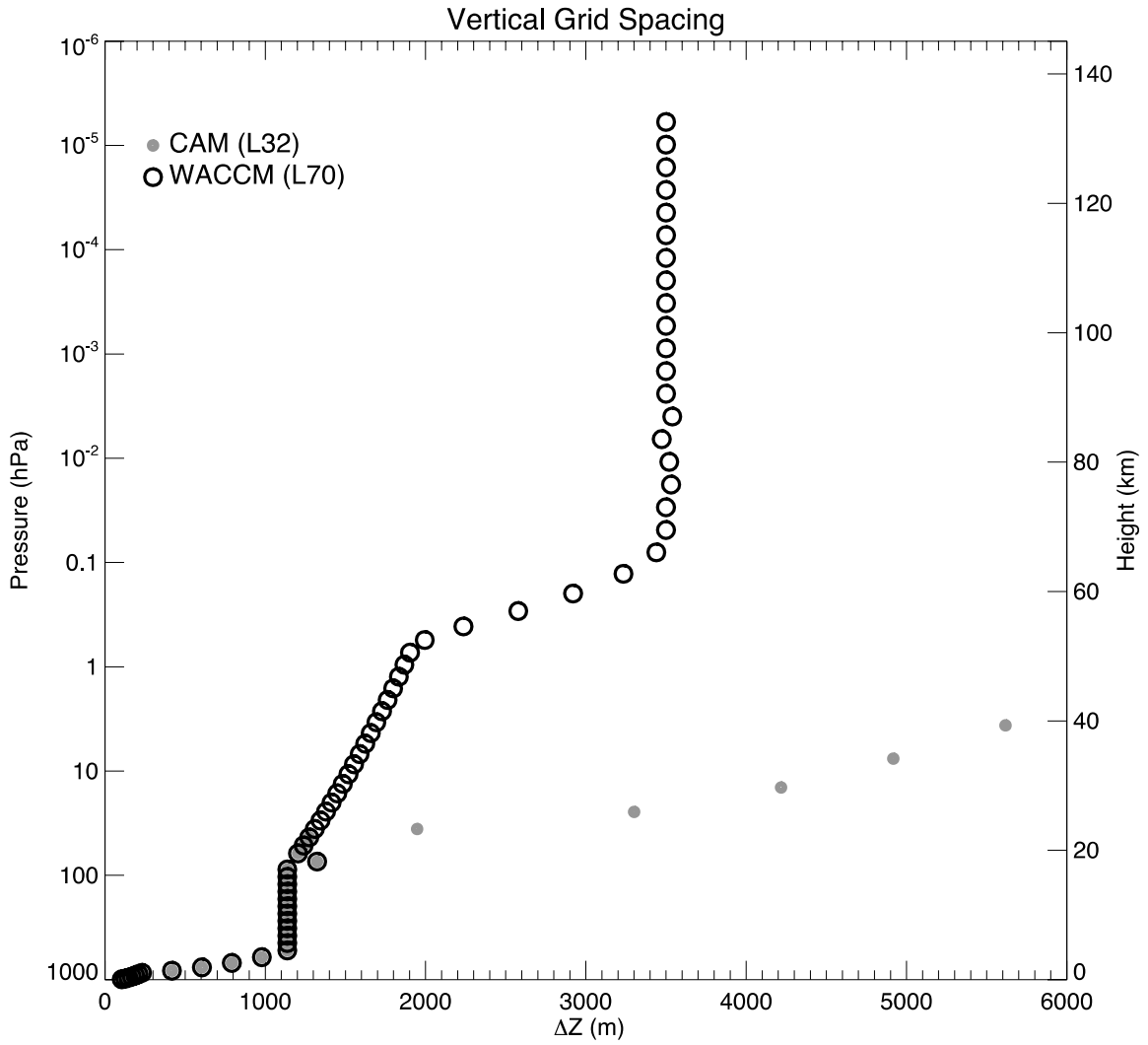
- Many reasons to increase resolution in the boundary layer and lower the lowest model level.

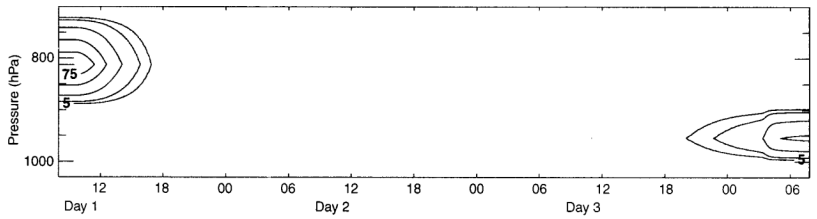


Motivation

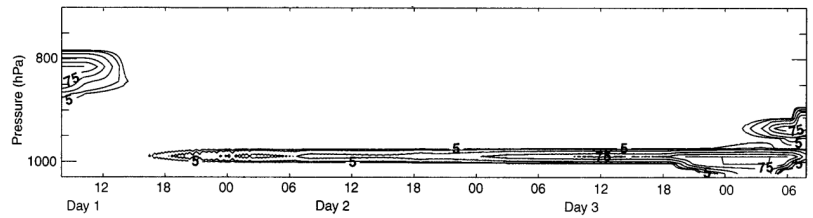
- Resolve thin cloud layers and improve cloud vertical structure

Layer cloud amount in single column model stratocumulus case (Bushell and Martin 1999)

15 level model

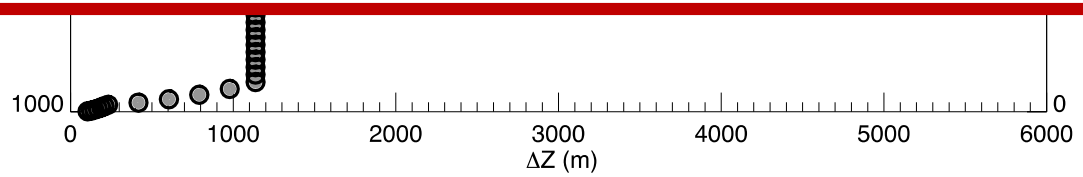


30 level model

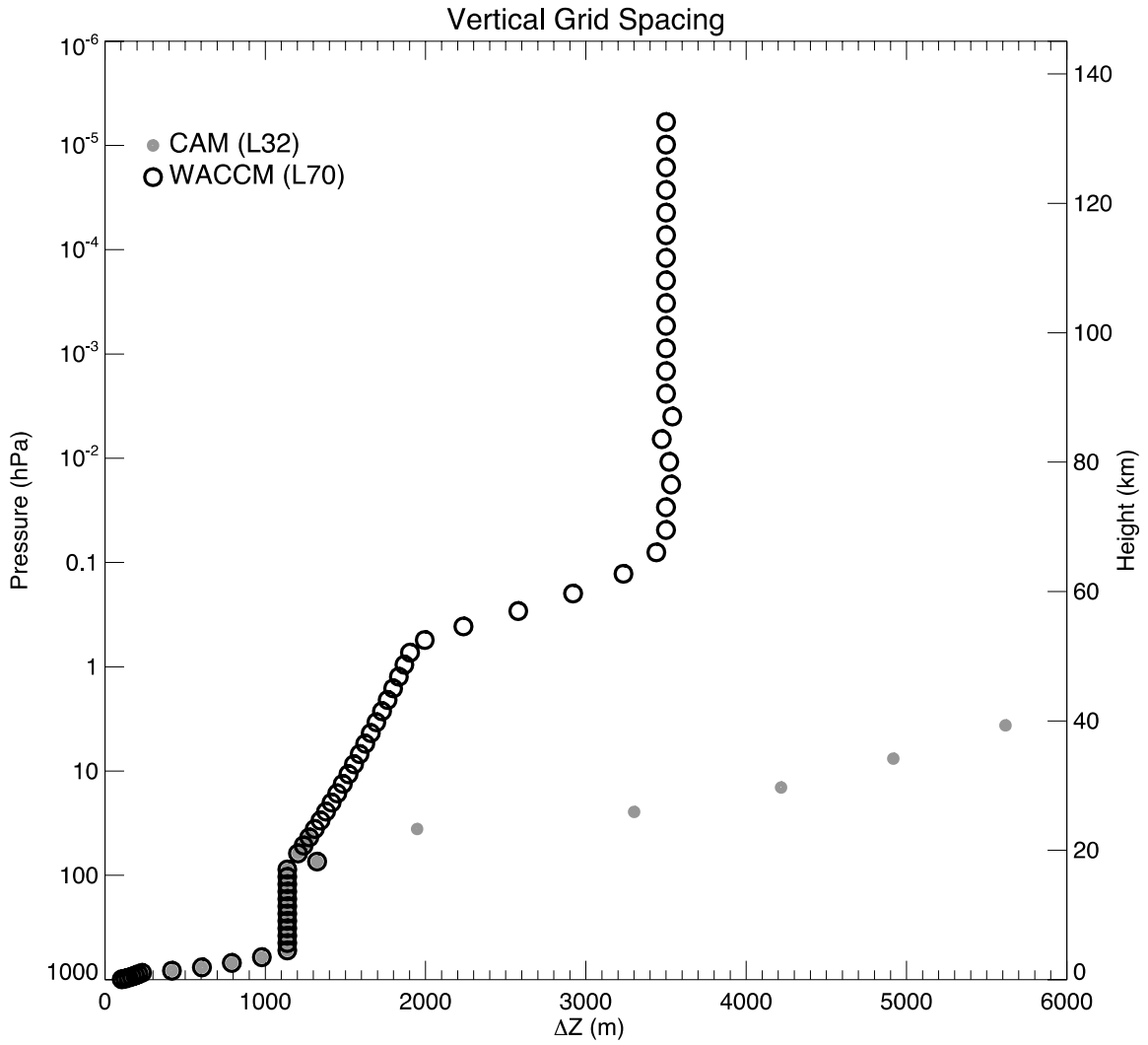


- Improved representation of water vapor and temperature profiles (Tomkins and Emanuel 2000)
- Improved representation of Arctic boundary layers (Byrkjedal et al 2008)
- Improved representation of nocturnal stable boundary layers over land →implications for the representation of surface temperature and the diurnal cycle
- Improved representation of low level winds e.g., wind turning in the boundary layer (Lindvall and Svensson 2018) → improvements in the representation of surface fluxes.
- Lowering the lowest model level into the surface layer where Monin-Obhukov theory is actually valid. Important for impacts relevant studies to have a good representation of surface winds
- Chemistry – needs an accurate representation of the boundary layer. Also, our emissions should really be emitted much lower than they are.
- Indications that CLUBB physics hasn't converged and needs about double the PBL resolution to do so (Rich Neale)

- Many reasons to increase resolution in the boundary layer and lower the lowest model level.



Desired features



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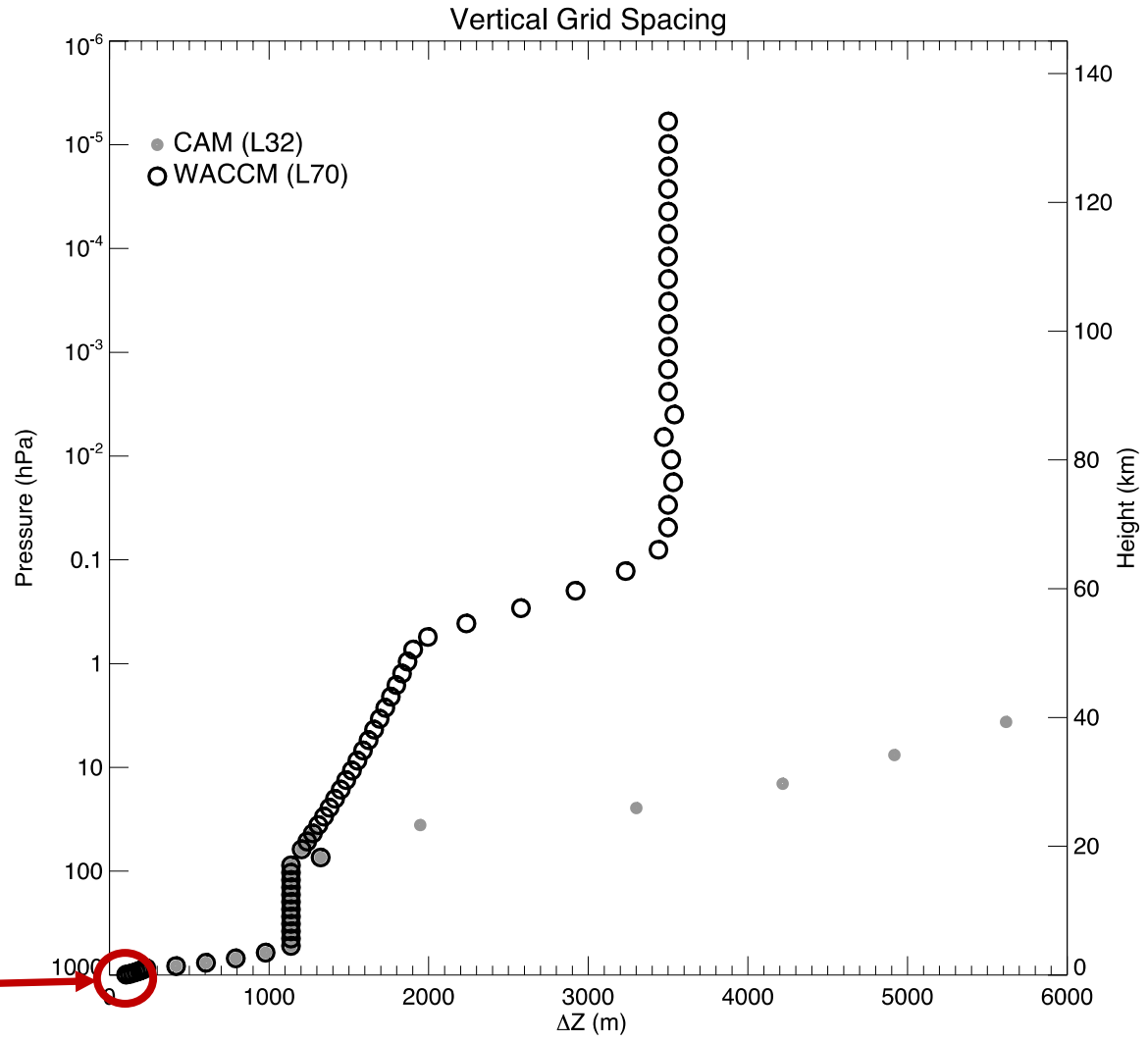

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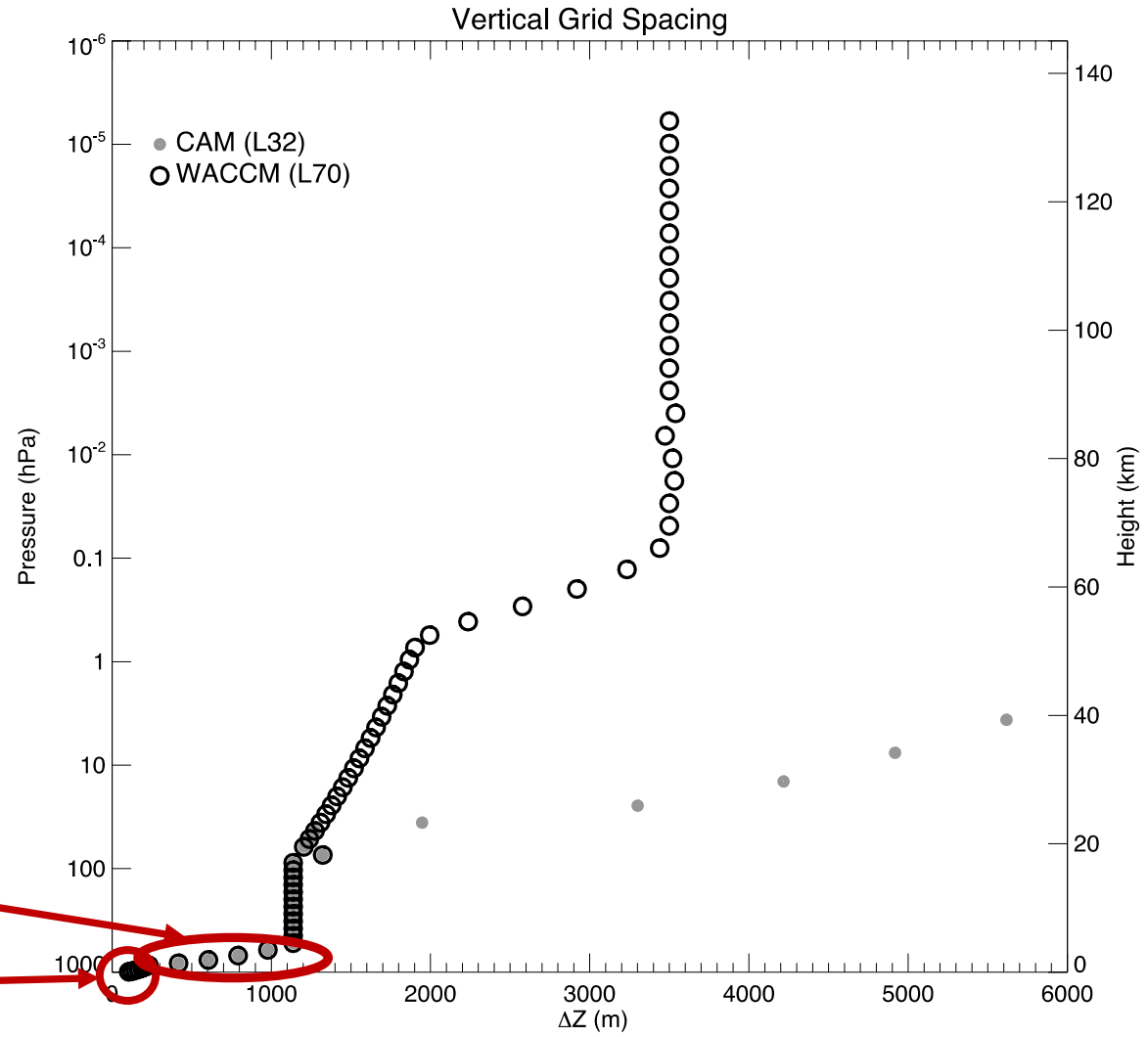

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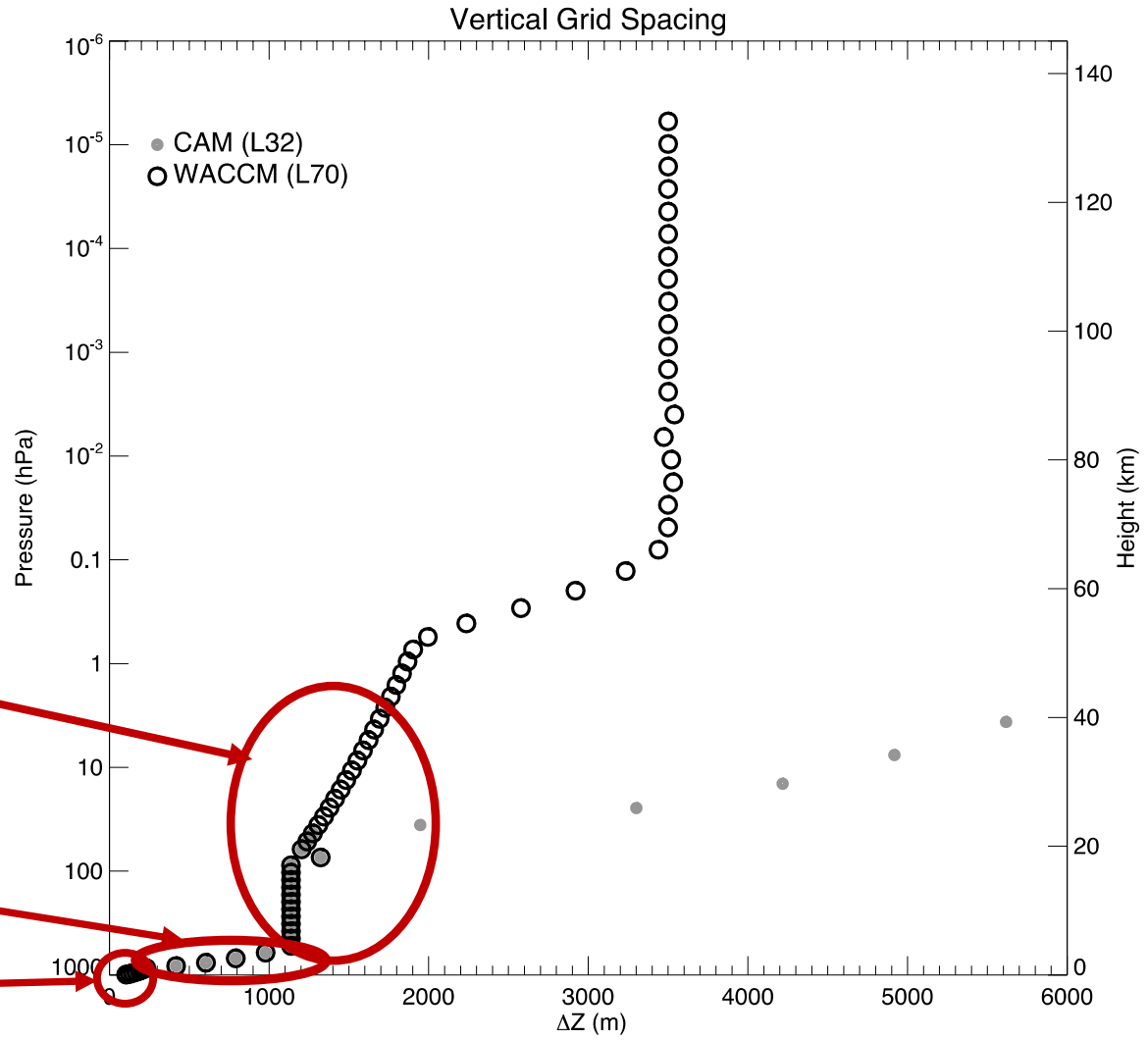

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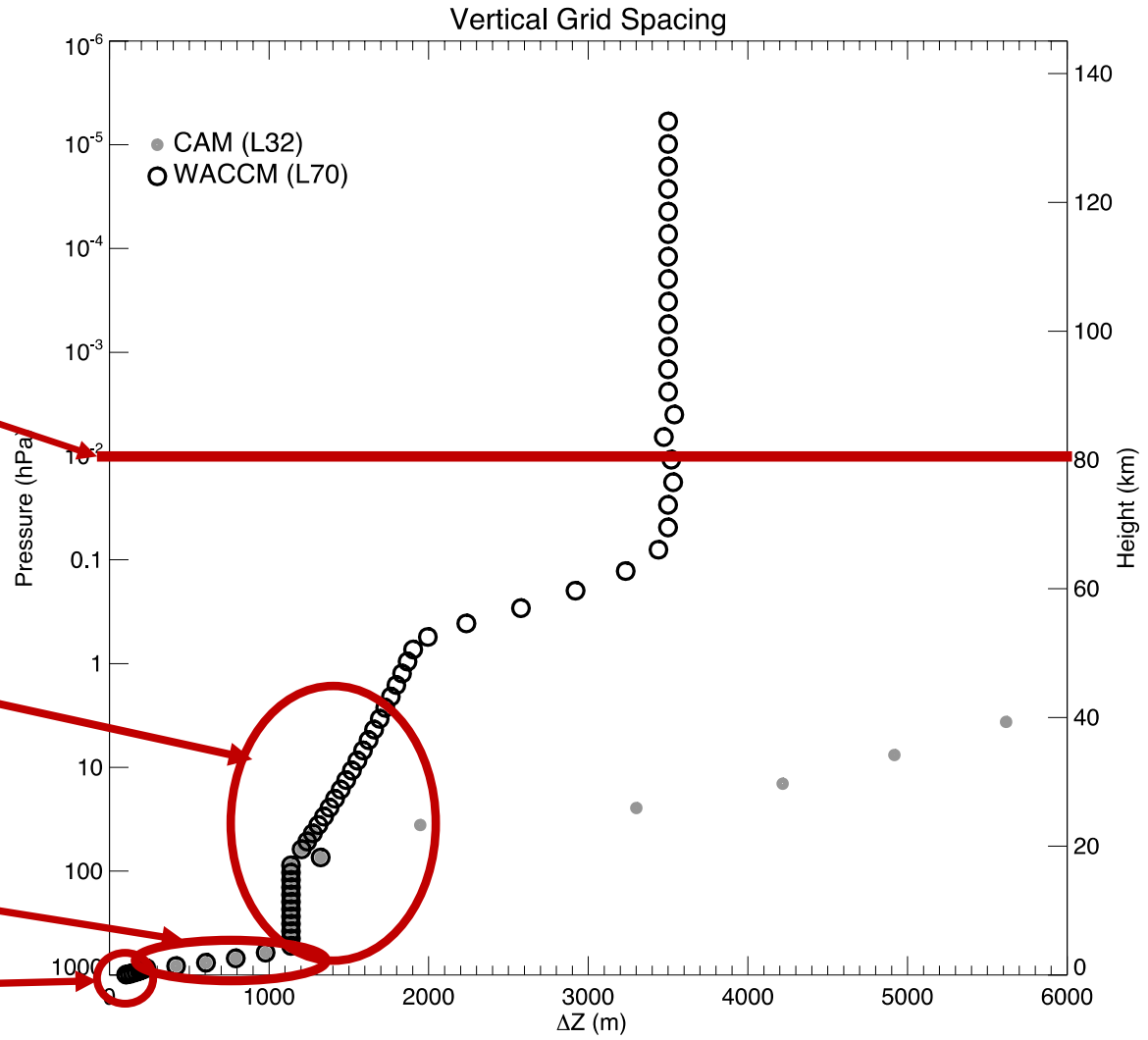

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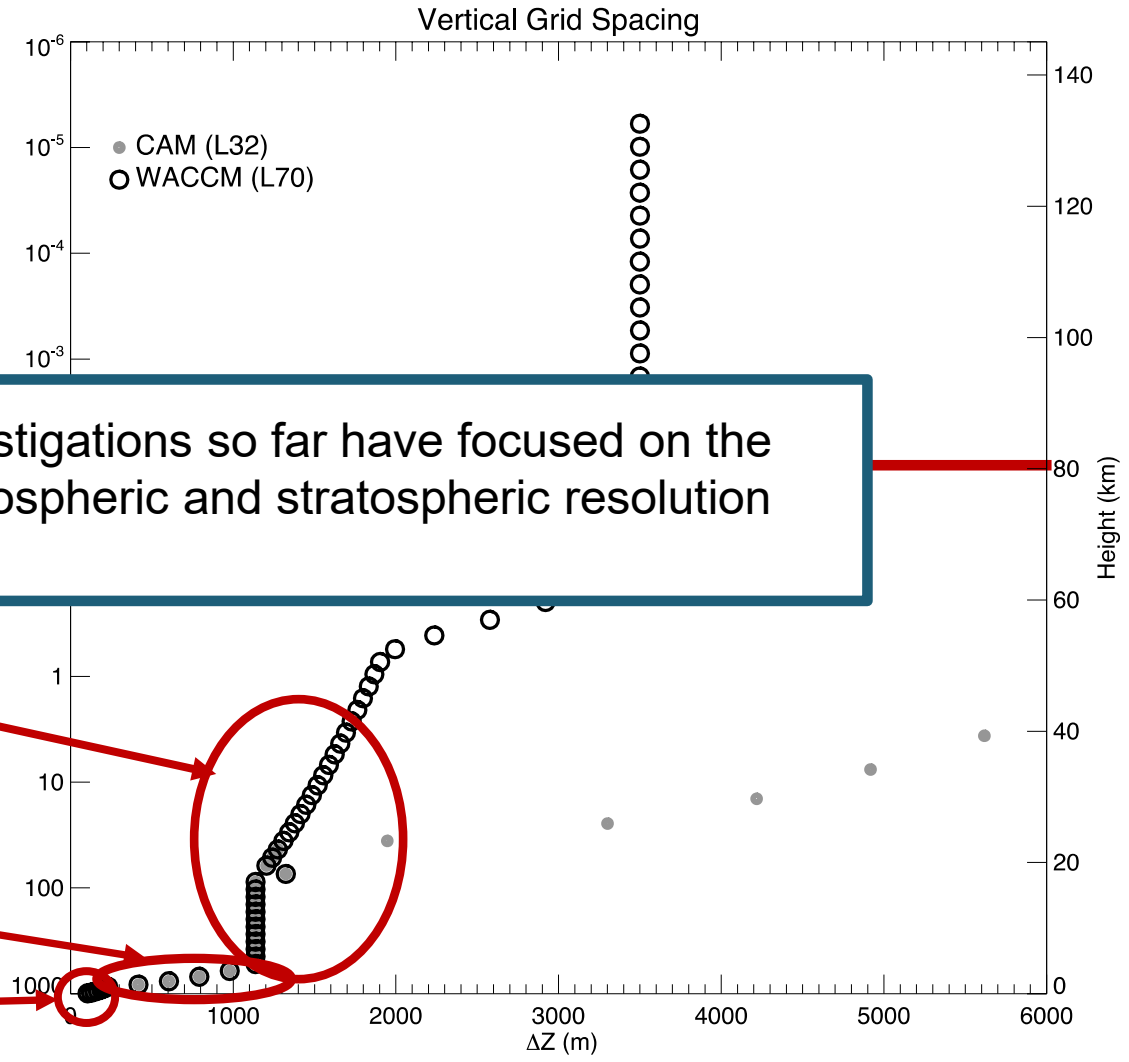

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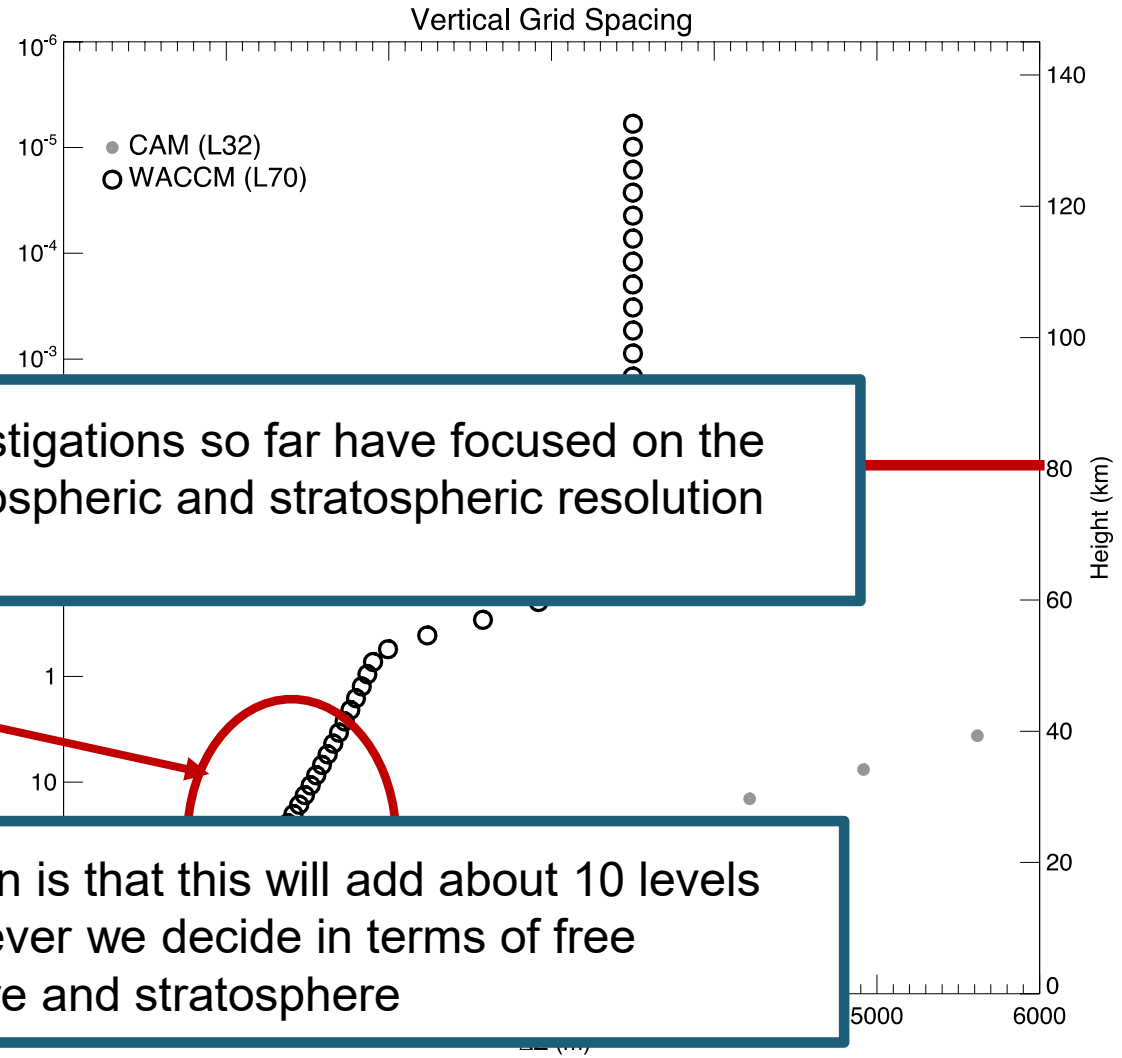
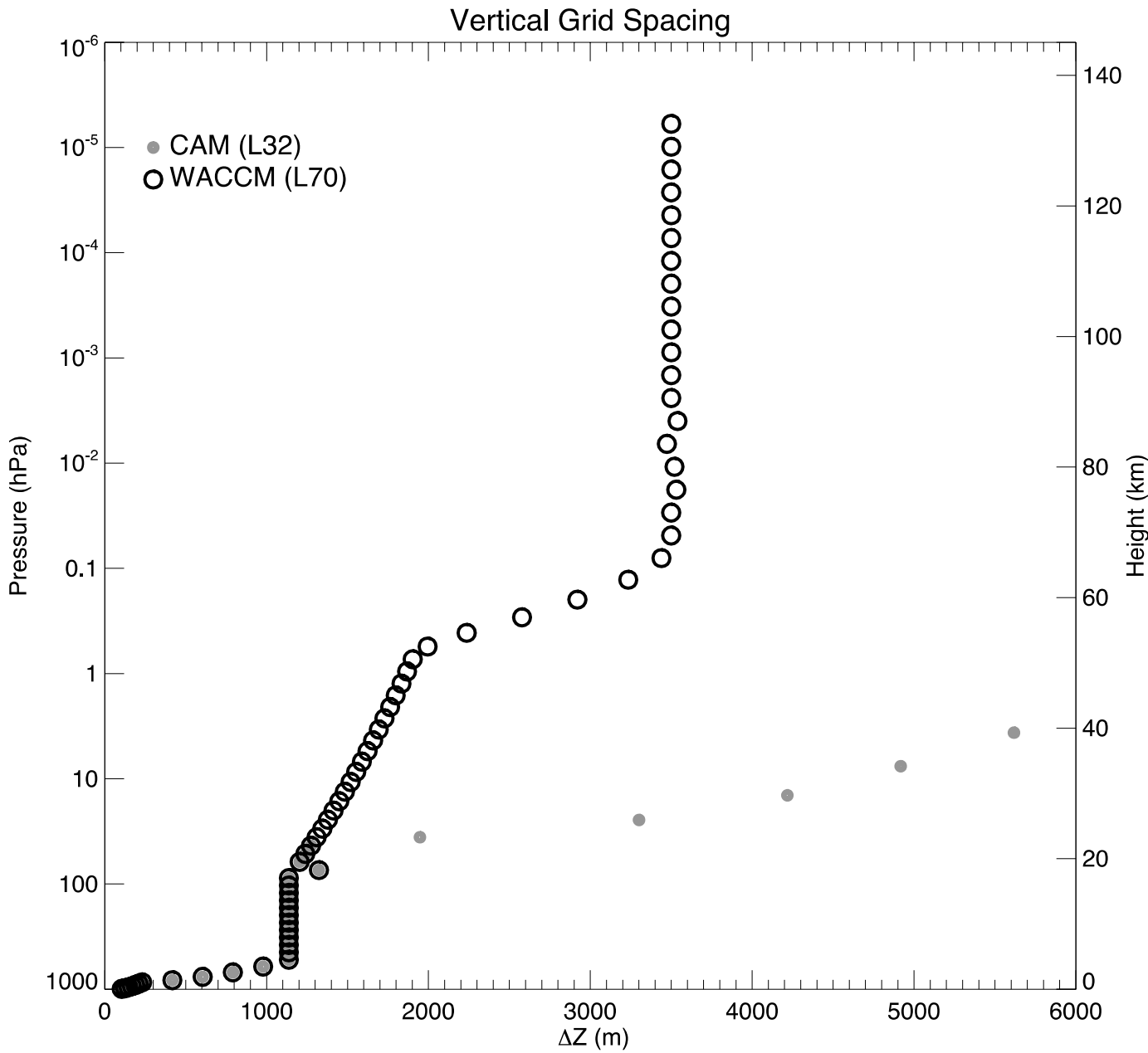
Expectation is that this will add about 10 levels onto whatever we decide in terms of free troposphere and stratosphere



Investigations into the influence of dz in the free troposphere and lower stratosphere

dz investigations



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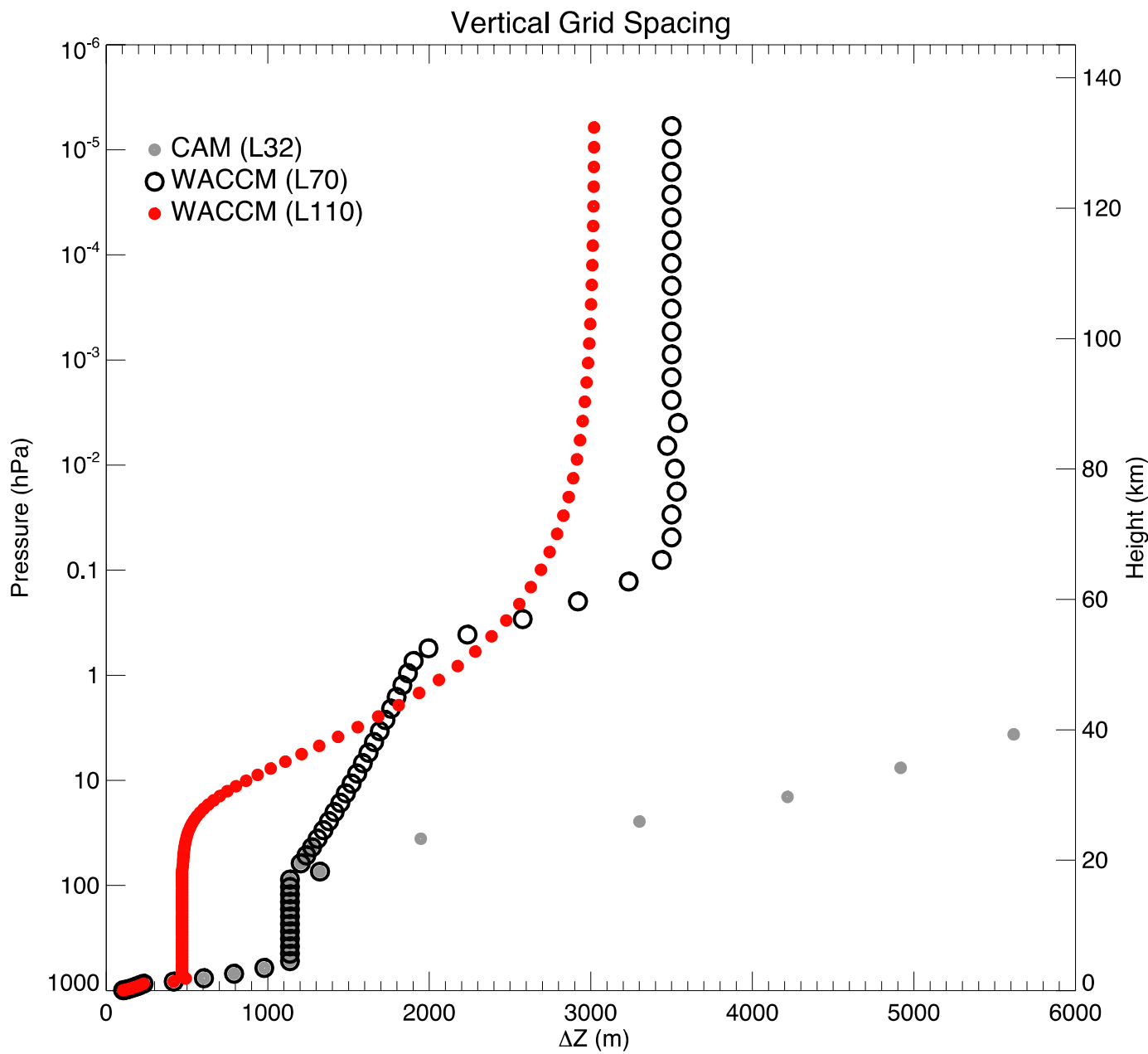

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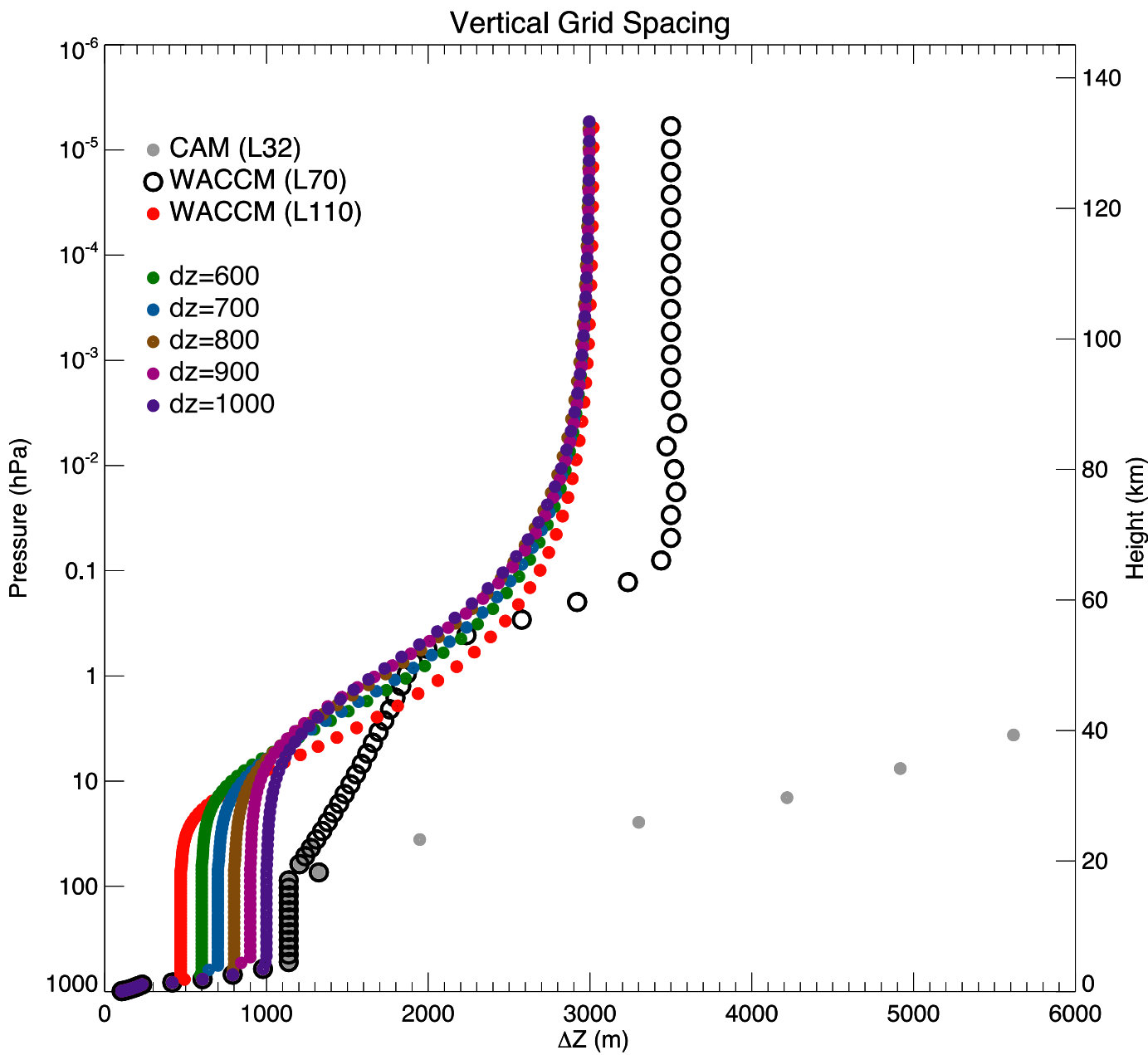
- All runs are AMIP, specified chemistry and from 1986-2006.



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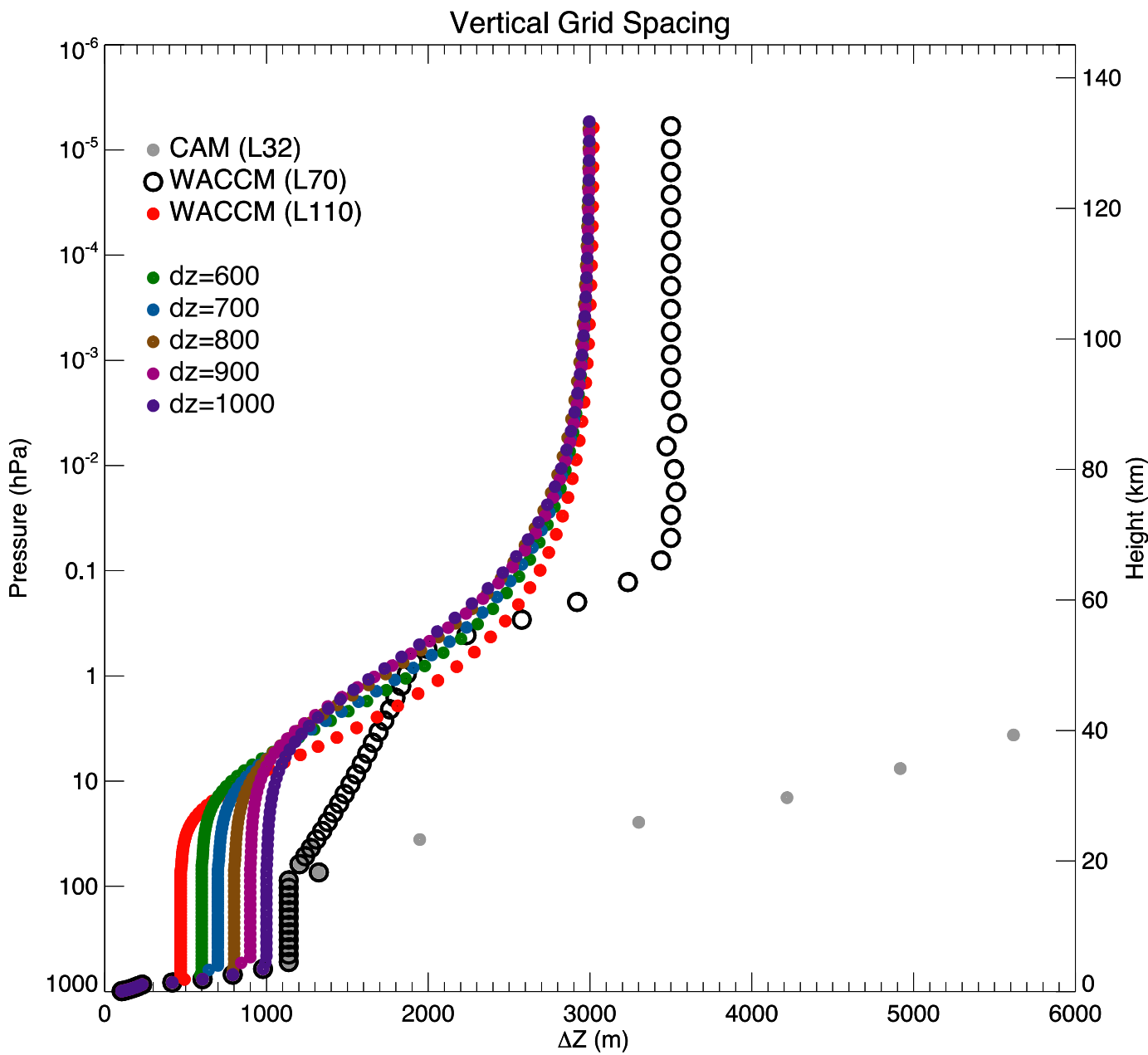
Many aspects of the climate of the extra-tropical troposphere and stratosphere did not show a strong dependence on dz. Here, we'll focus on what does show a dependence.



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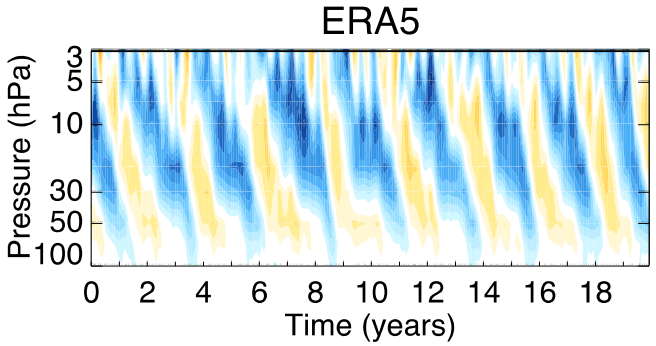

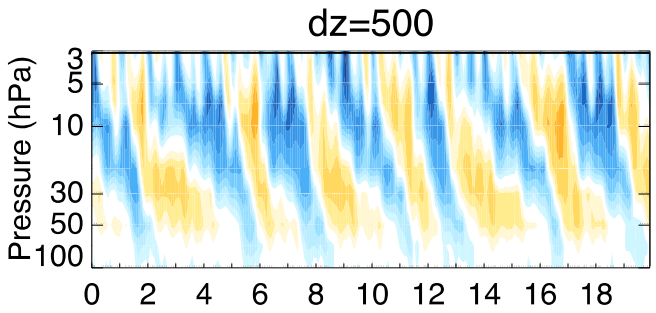

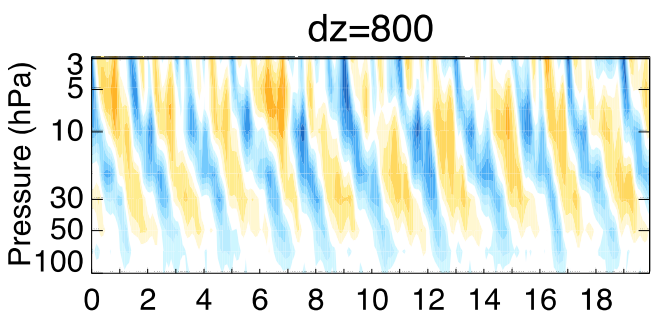

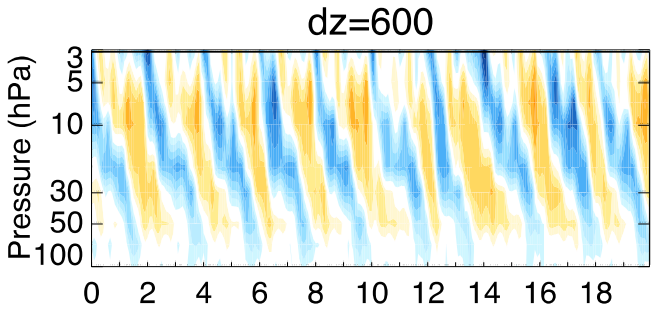

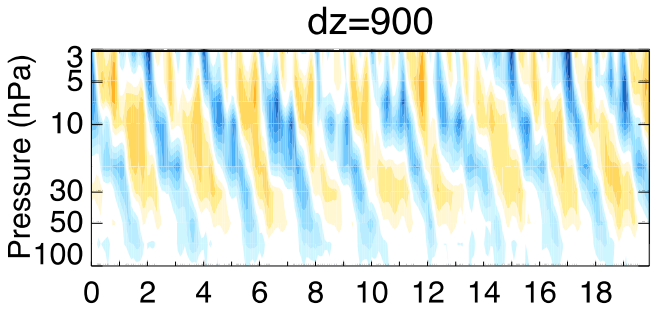

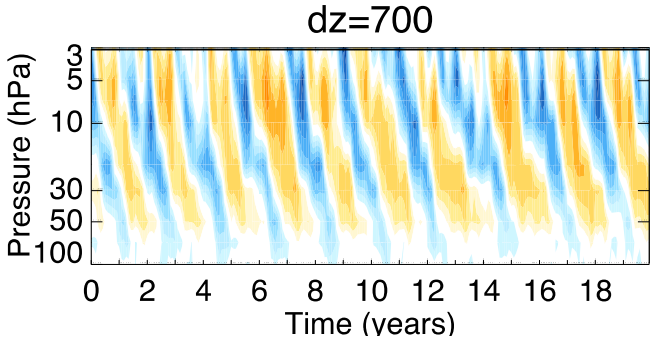

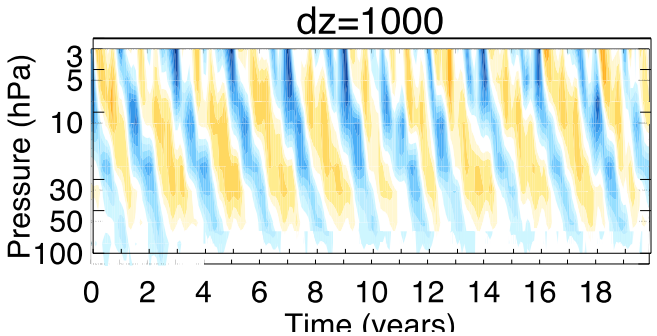

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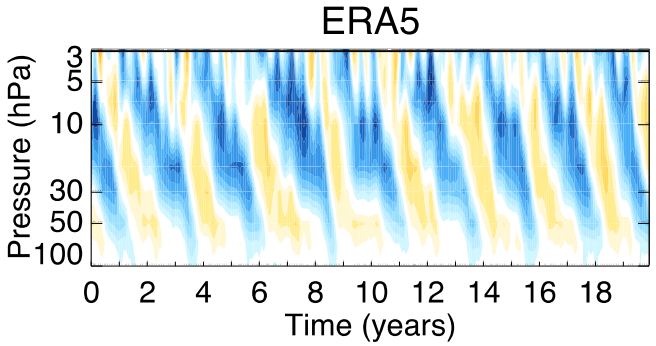

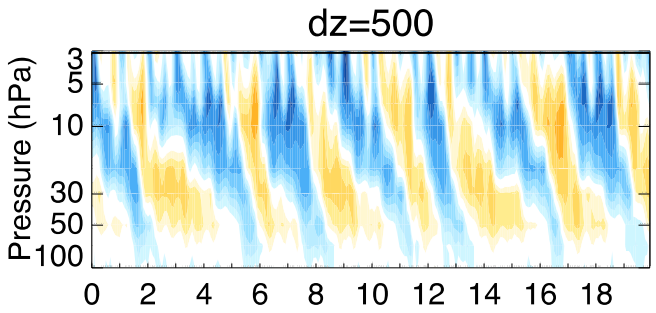

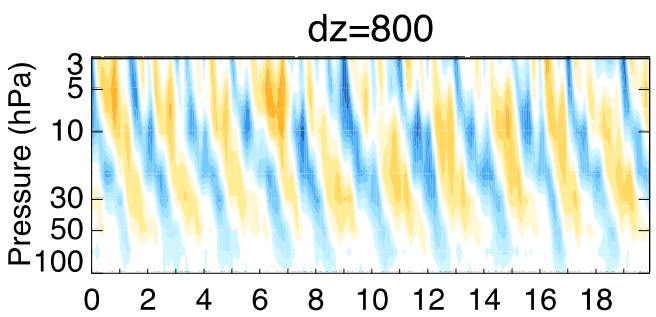

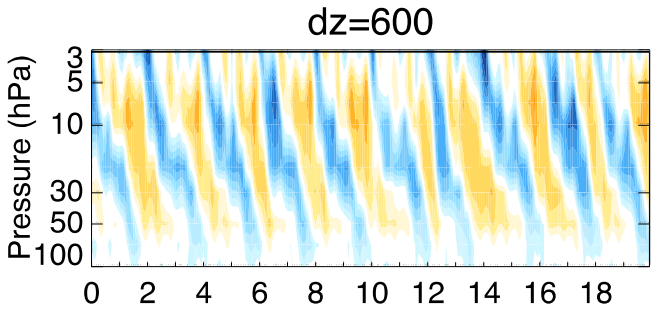

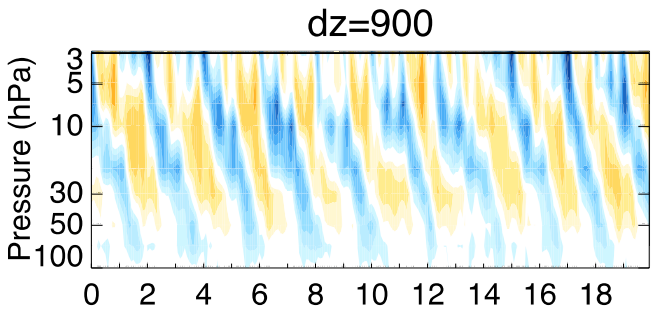

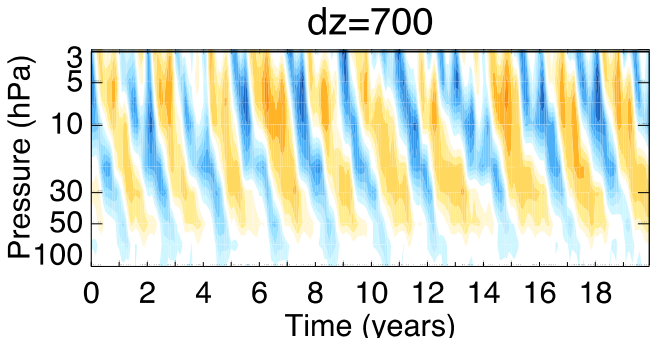

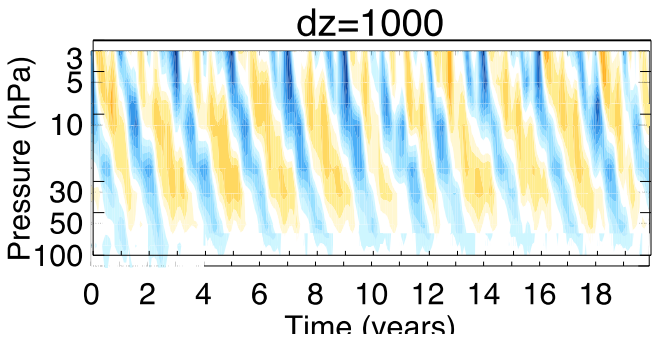

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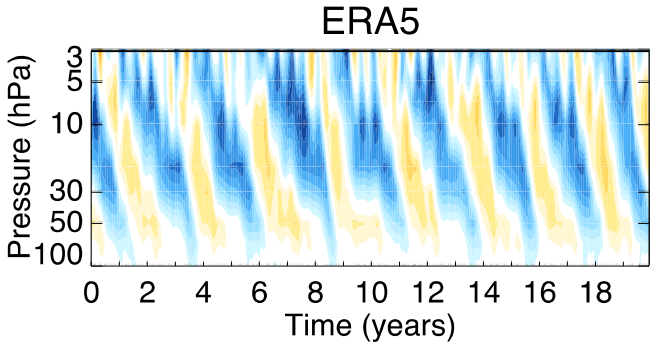

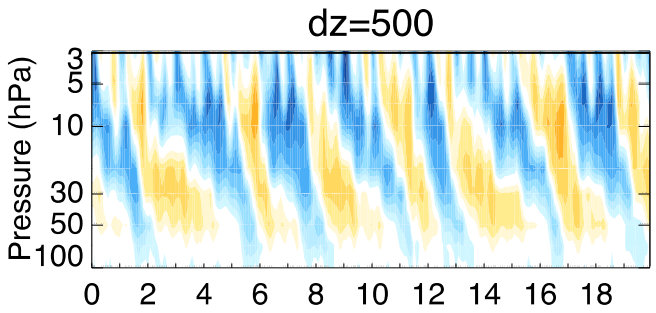

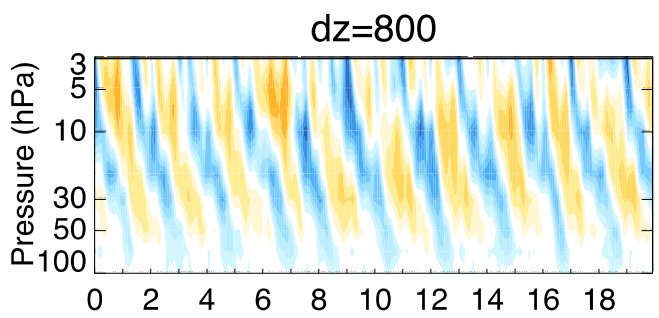

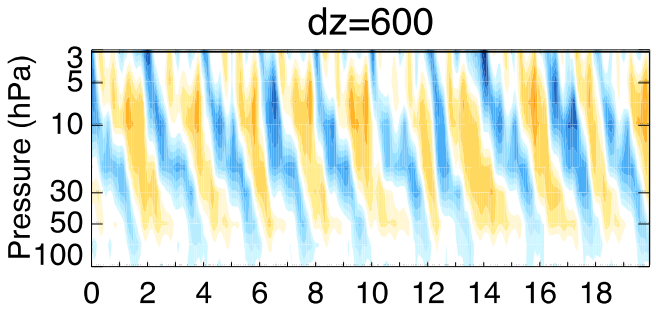

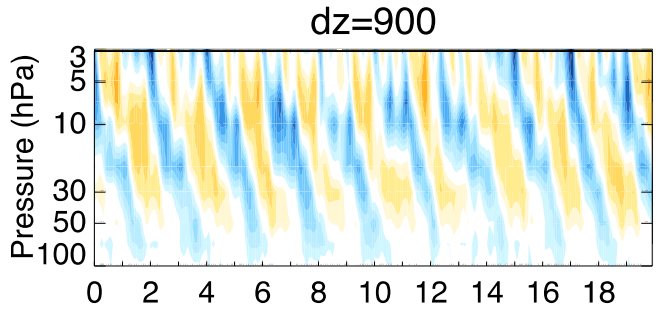

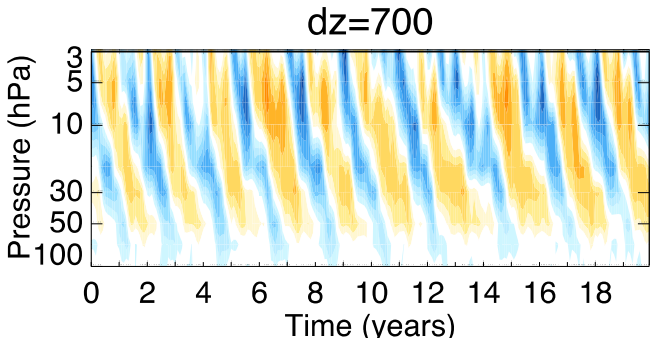

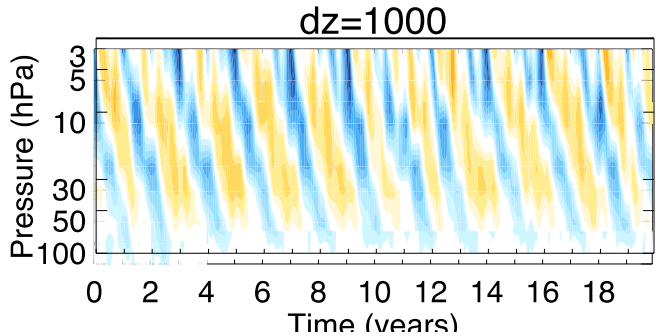

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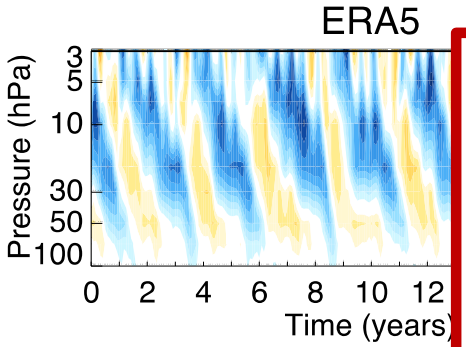
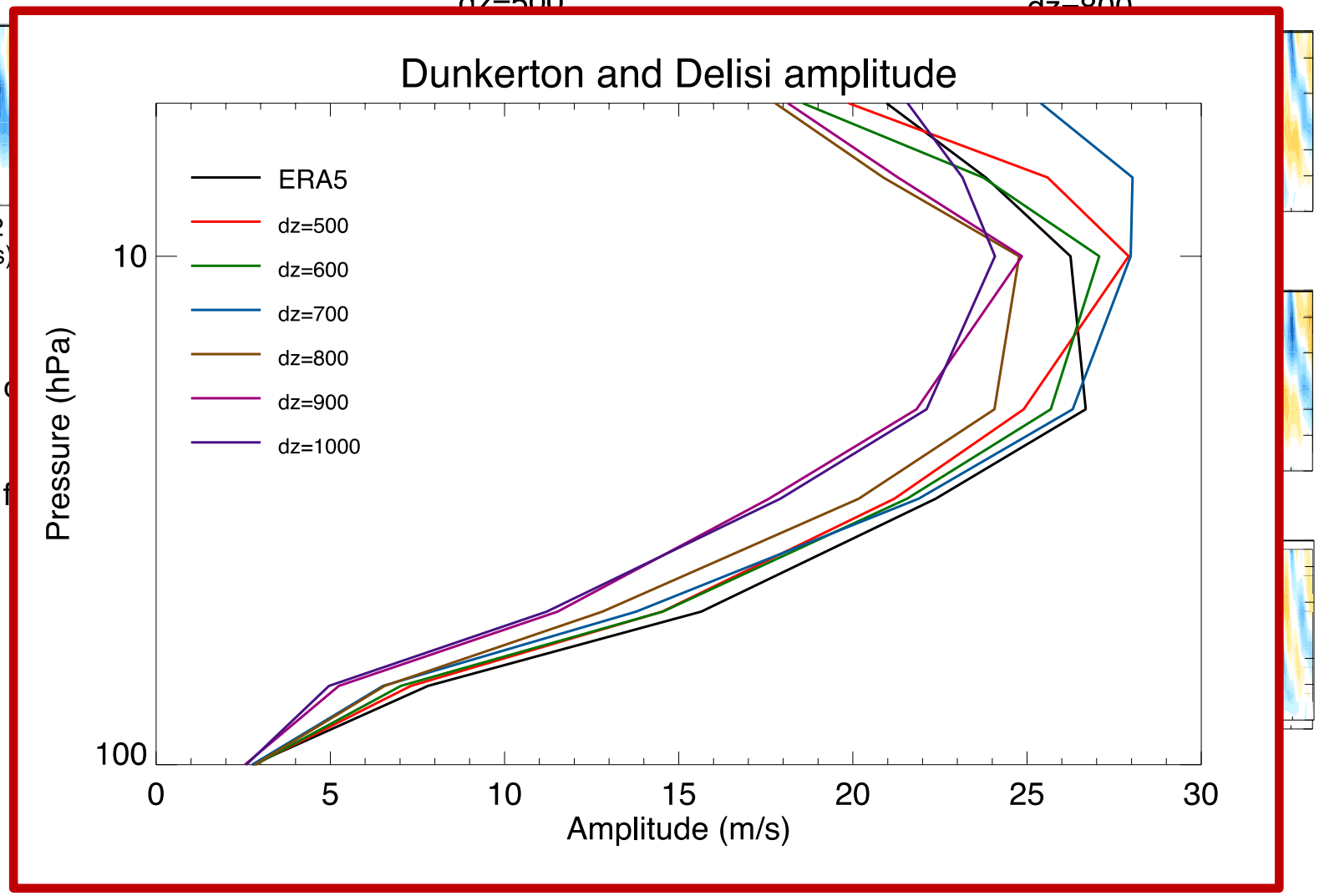
- Indications that the westerly phase doesn't reach as far down with lower resolution

The representation of the QBO



- All configurations have a QBO of some form
- Some sensitivity of the period to resolution. But this c tuned with gravity wave drag changes
- Indications that the westerly phase doesn't reach as f with lower resolution



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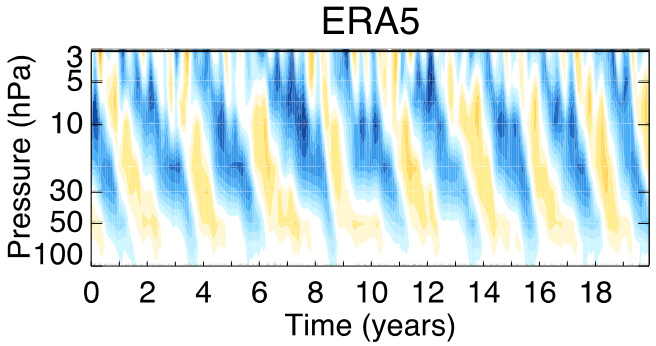
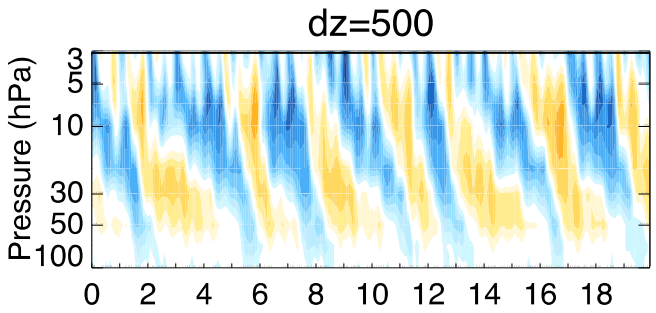
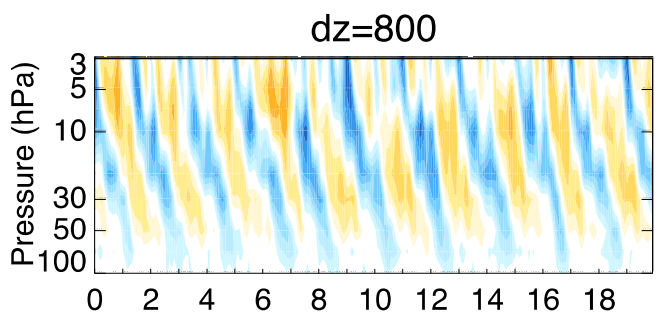
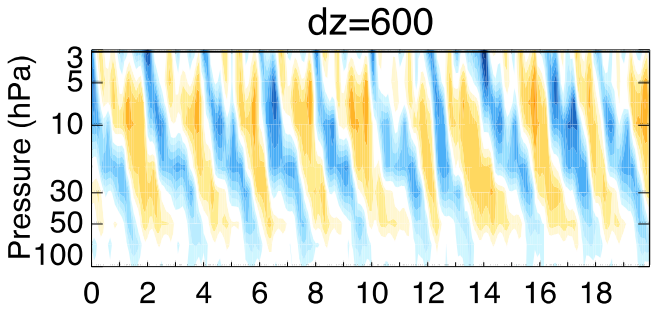
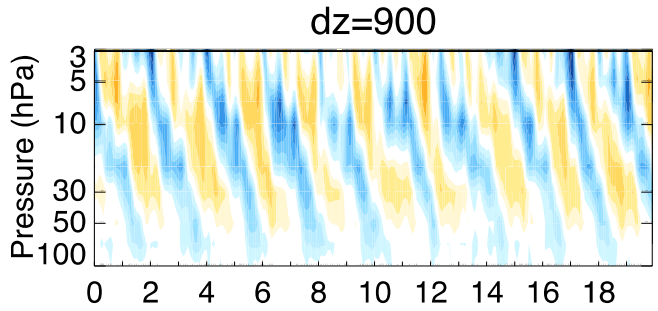
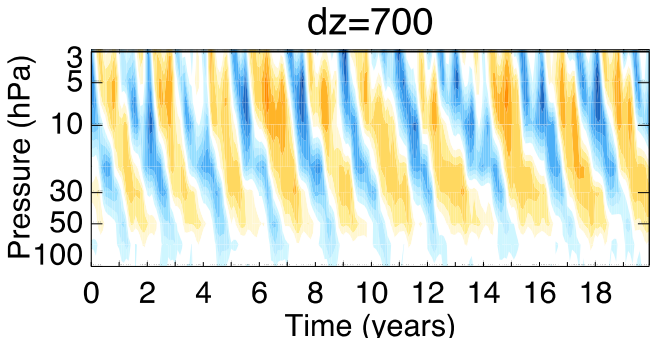


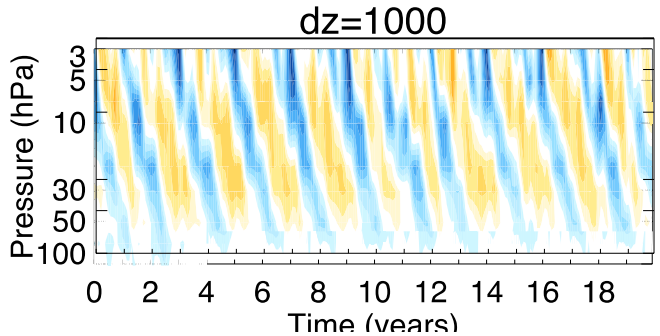






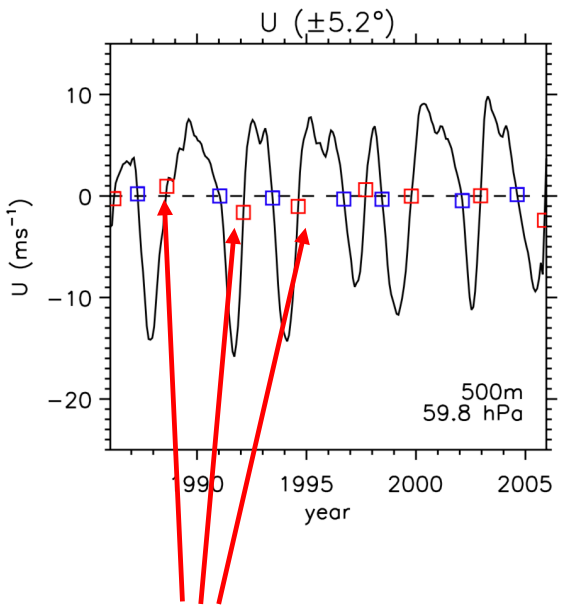






- All configurations have a QBO of some form
- Some sensitivity of the period to resolution. But this can be tuned with gravity wave drag changes
- Indications that the westerly phase doesn't reach as far down with lower resolution
- Less prevalence of the easterly phase in the lower resolution runs, which is likely related to the westerly phase in the lower stratosphere not lasting long enough.

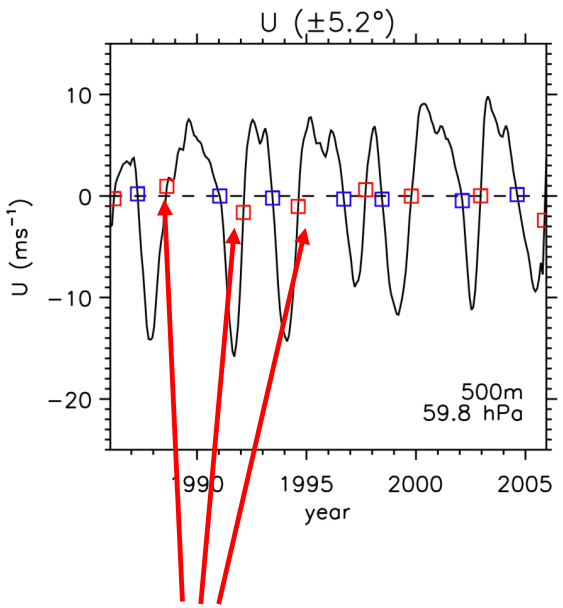
Differences in the wave driving of the descending westerly phase



Pick out the months when the 5S-5N zonal mean zonal wind at 60hPa transitions from easterly to westerly and composite U and the wave driving.

Figure Credit: Rolando Garcia

Differences in the wave driving of the descending westerly phase



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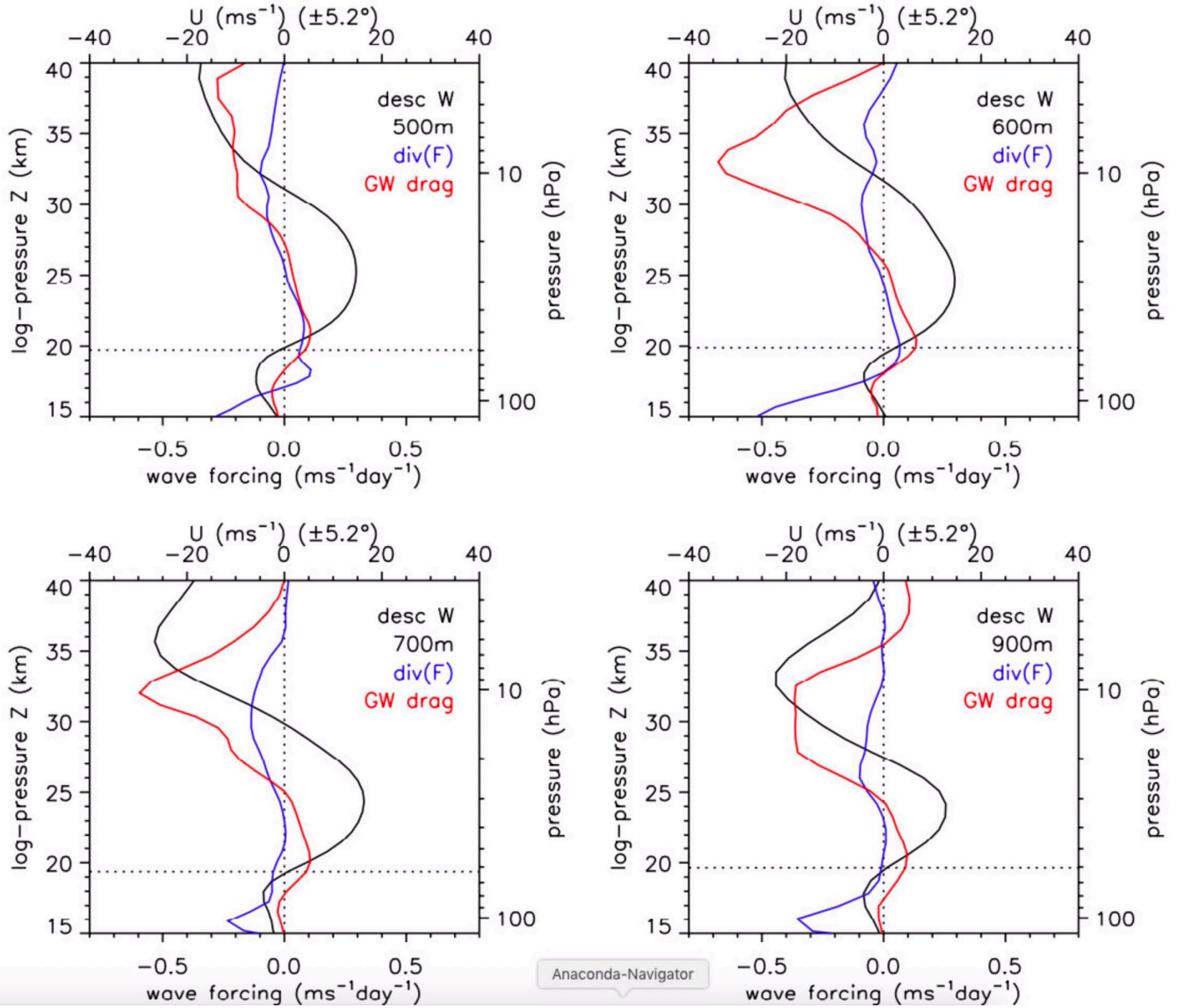
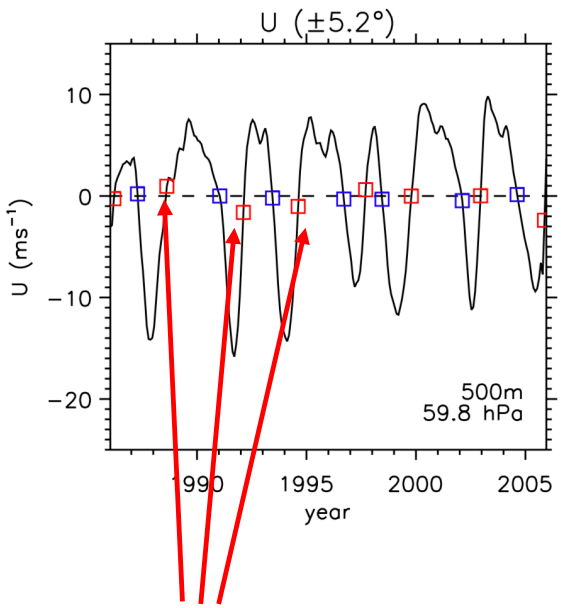


Figure Credit: Rolando Garcia

Differences in the wave driving of the descending westerly phase



Pick out the months when the 5S-5N zonal mean zonal wind at 60hPa transitions from easterly to westerly and composite U and the wave driving.

With dz=500 there is a role for resolved waves in driving the decent of the westerly phase into the lower stratosphere

Resolved wave driving of the descending westerly phase is not apparent in lower resolutions

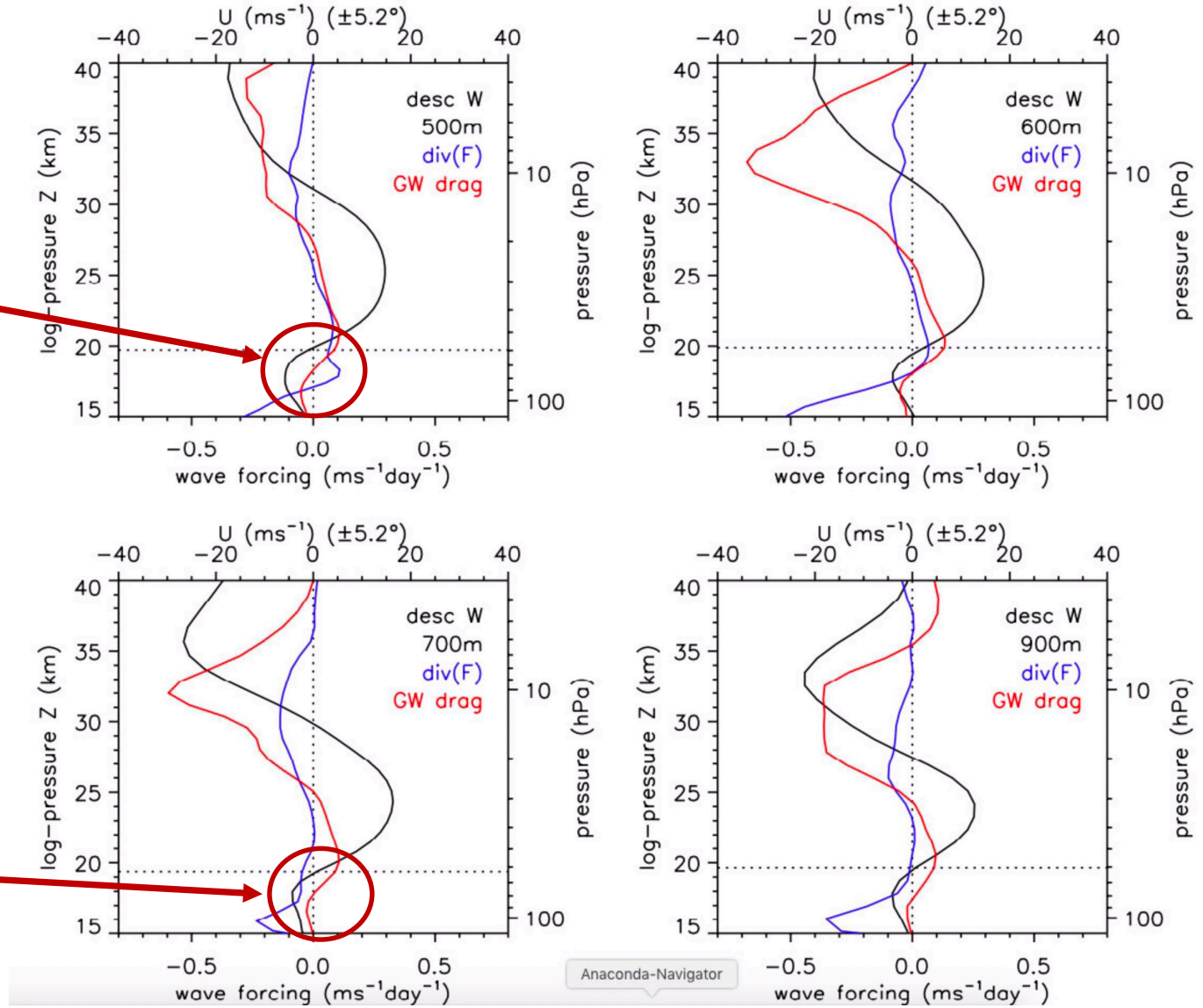
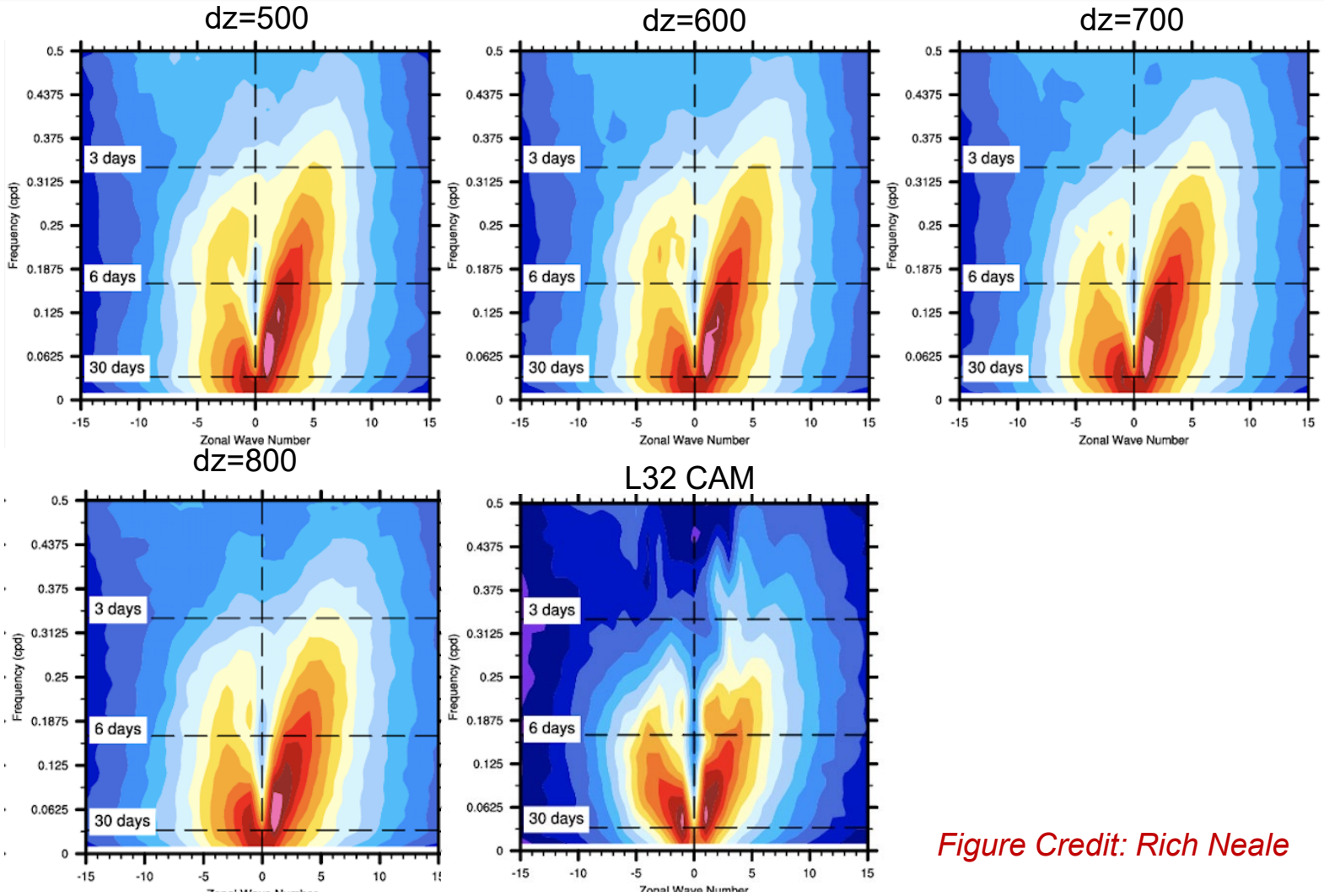


Figure Credit: Rolando Garcia

Differences in lower stratospheric wave activity

Wavenumber – frequency spectra of 50hPa U, Symmetric, +/-5deg lat



But no apparent dependence of lower stratospheric Kelvin wave activity on dz

Figure Credit: Rich Neale

Differences in lower stratospheric wave activity

Wavenumber – frequency spectra of 50hPa U, Antisymmetric, +/-5deg lat

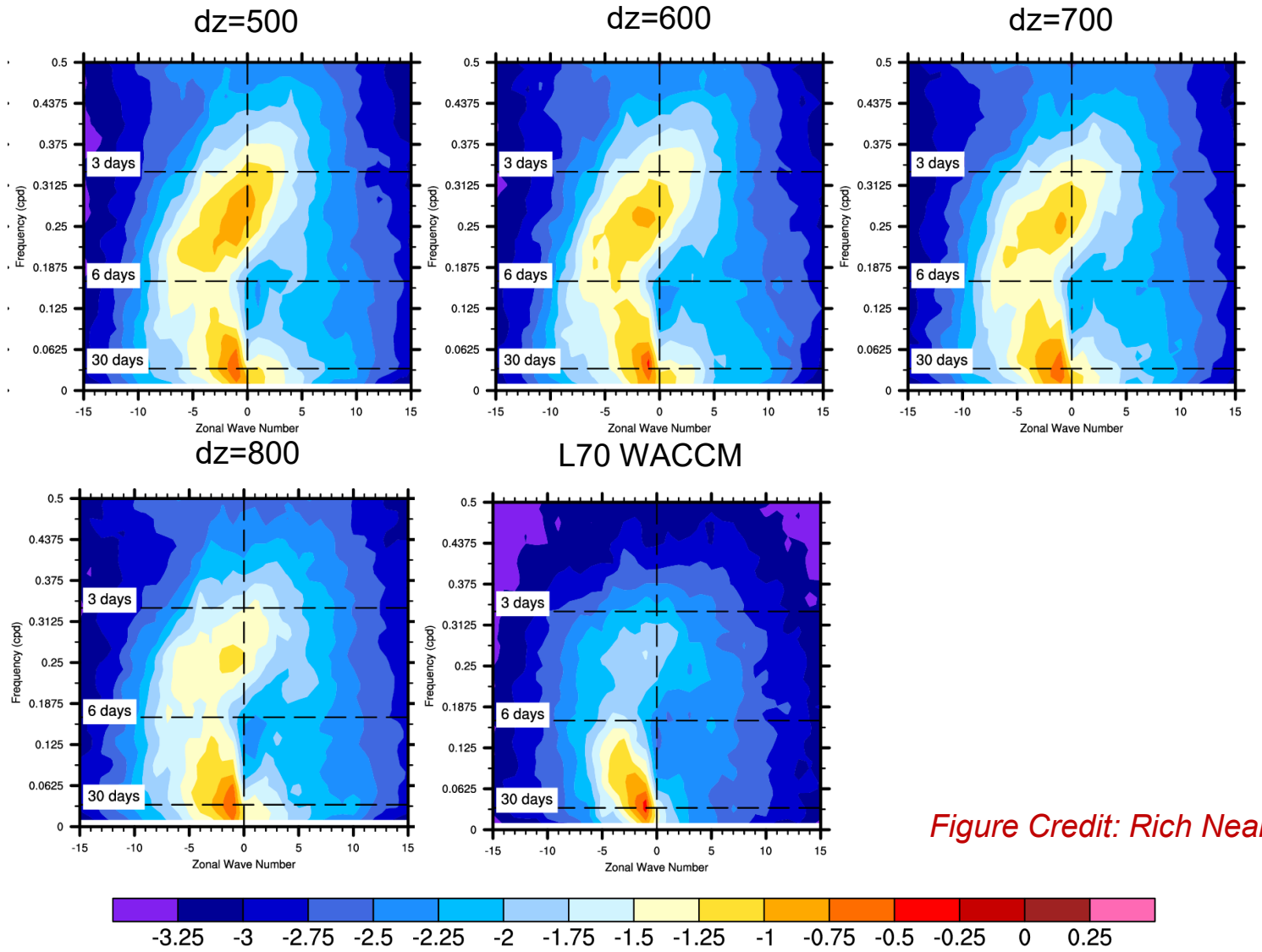


Figure Credit: Rich Neale

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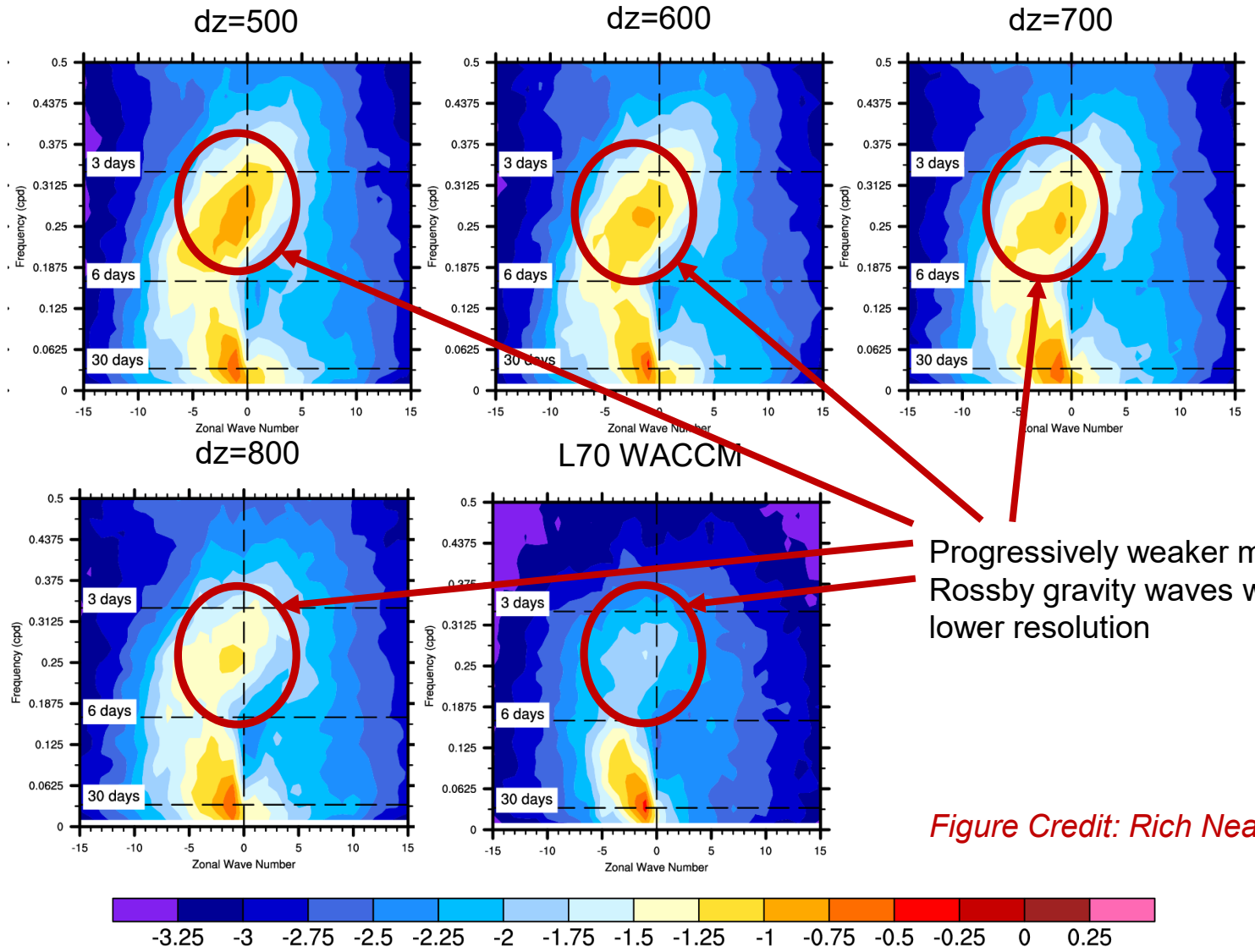


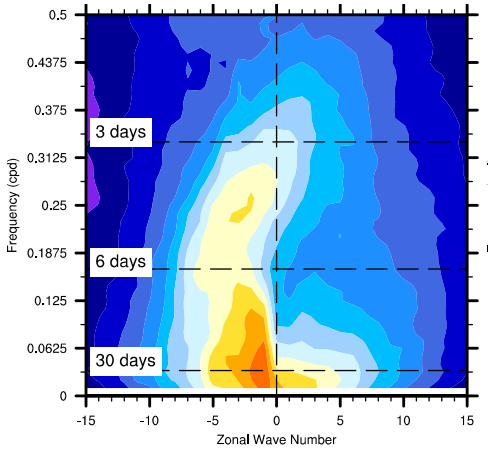
Progressively weaker mixed-Rossby gravity waves with lower resolution

Figure Credit: Rich Neale

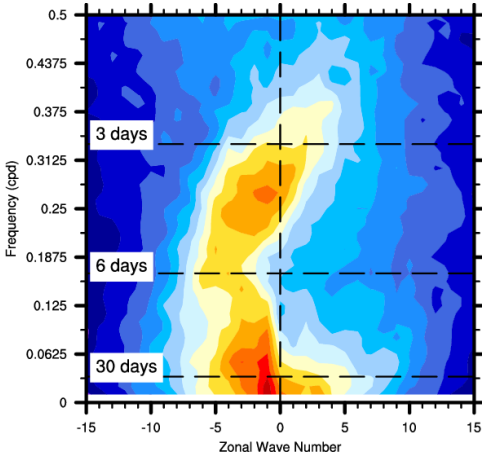
Differences in lower stratospheric wave activity

Wavenumber – frequency spectra of 50hPa U, Antisymmetric, +/-5deg lat

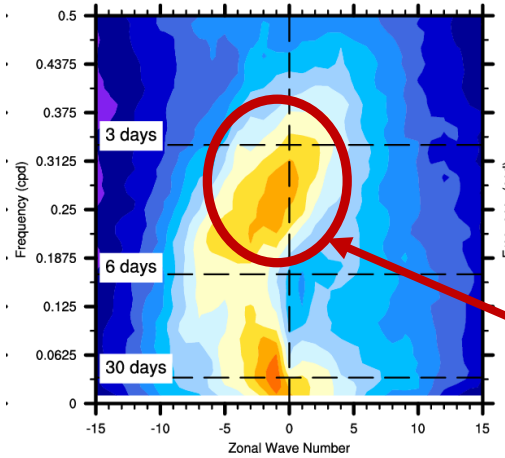
MERRA2, dz~1100



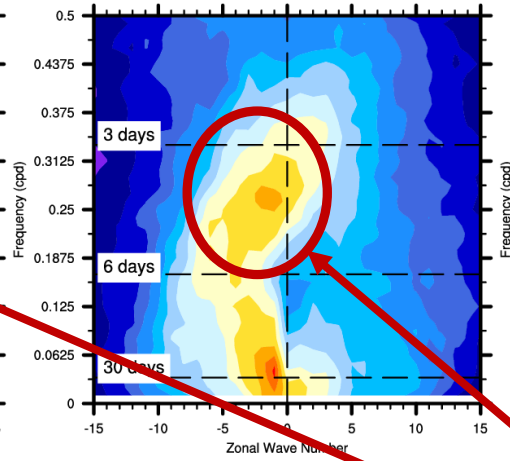
ERA5, dz~300-500



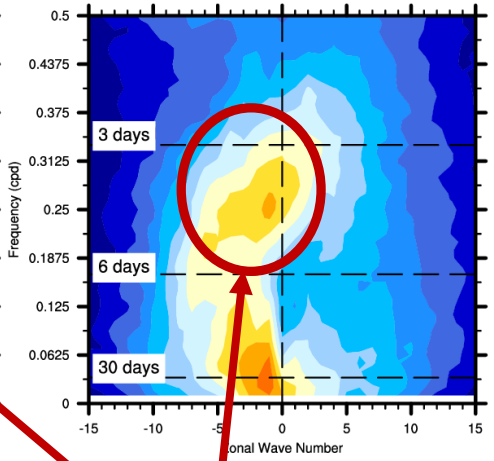
dz=500



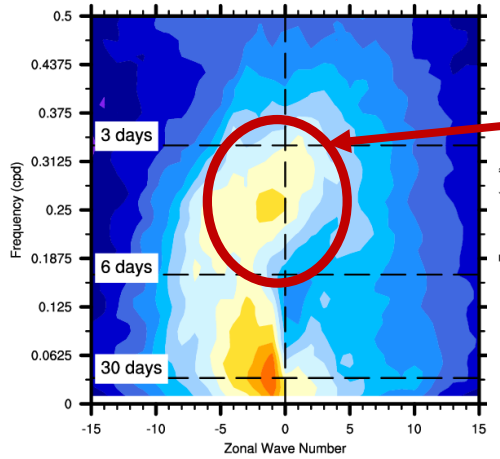
dz=600



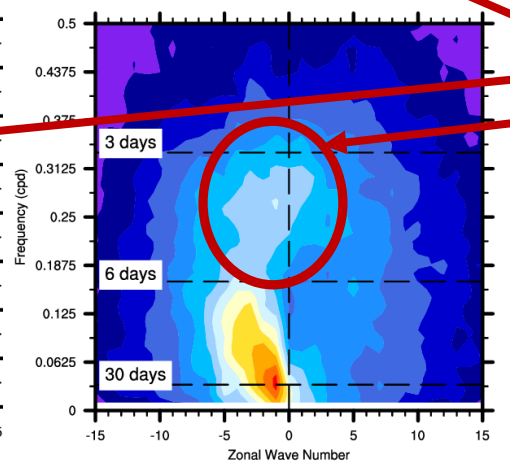
dz=700



dz=800

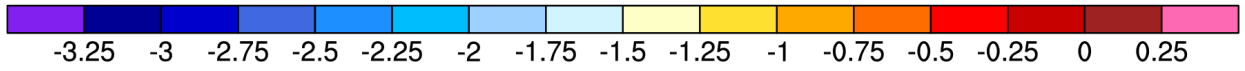


L70 WACCM



Progressively weaker mixed-Rossby gravity waves with lower resolution

Figure Credit: Rich Neale

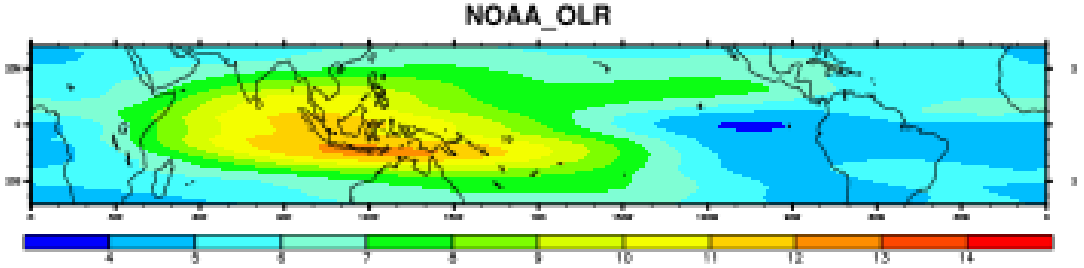


Differences in the MJO, OLR variability

MJO filtered standard deviation of OLR

Difference from obs

OBS



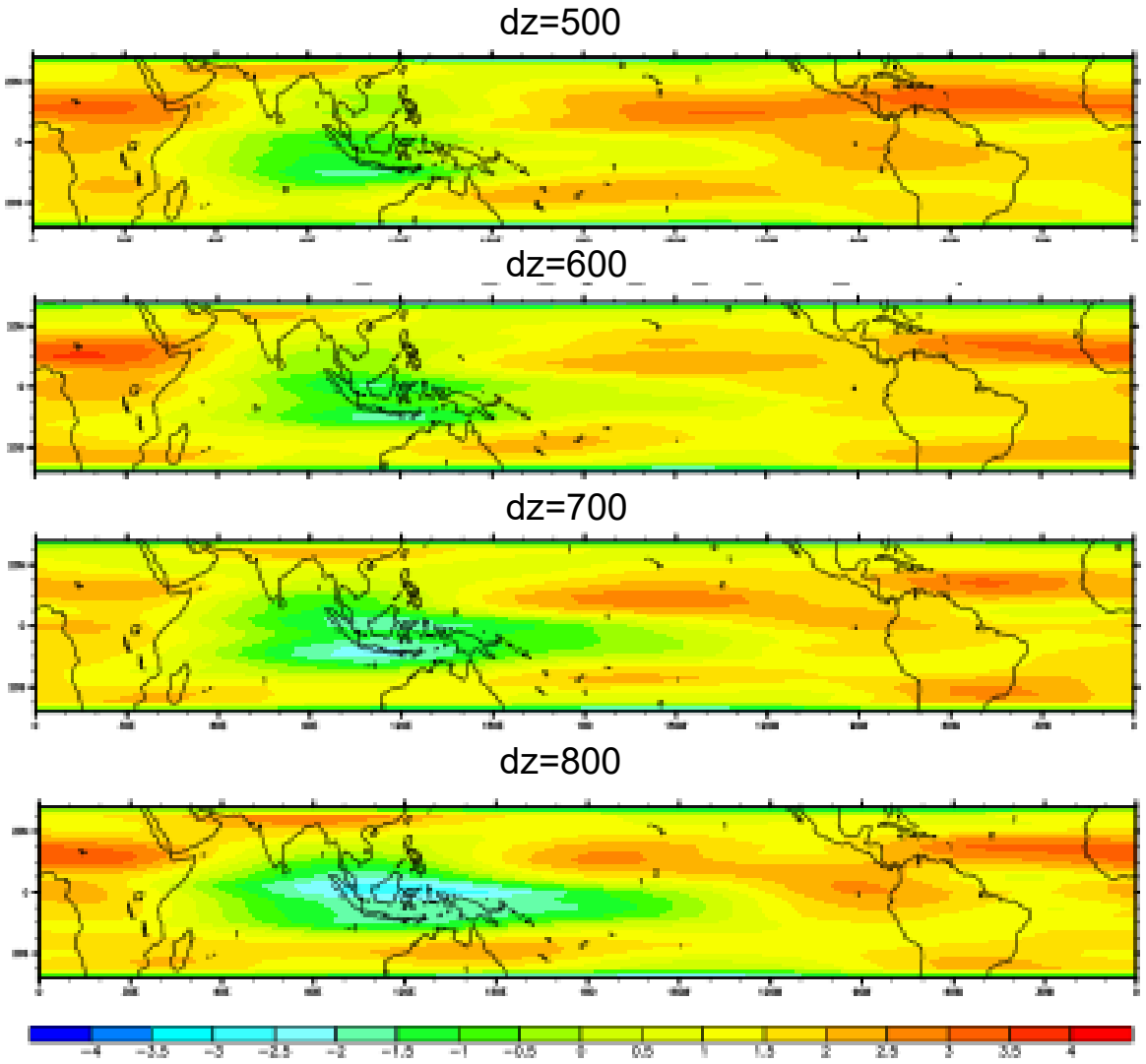
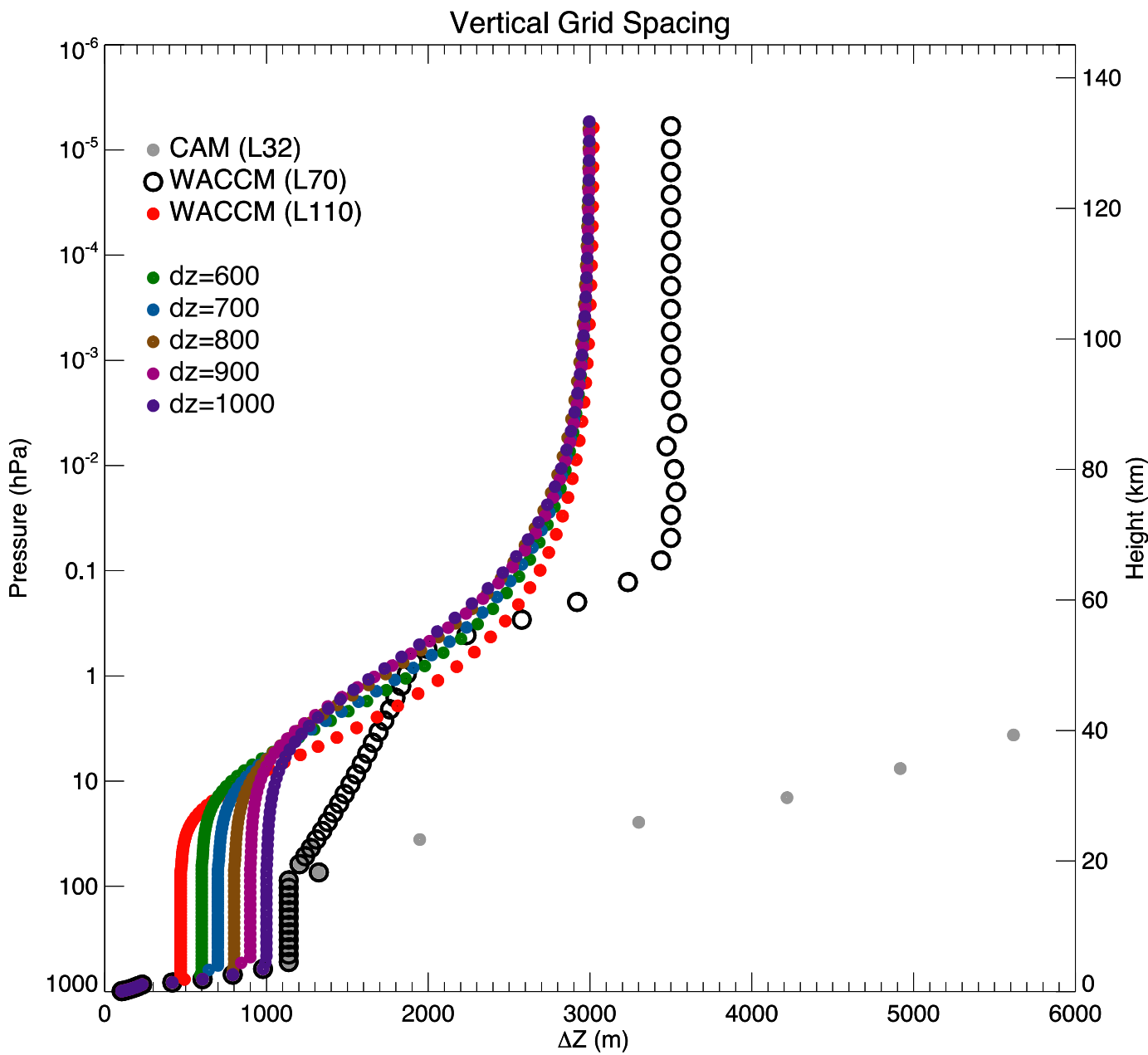


Figure Credit: Julie Caron

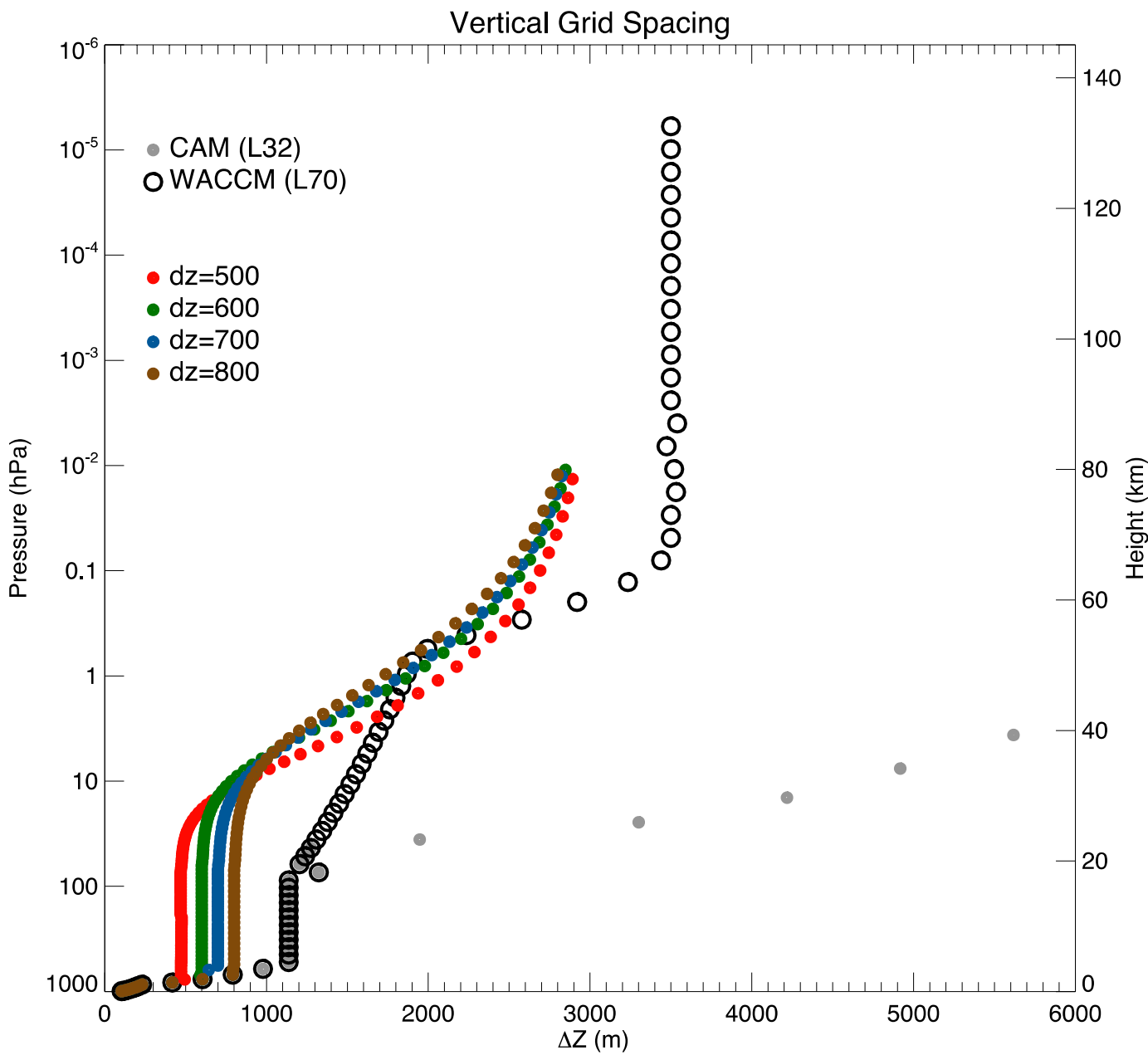
Investigations into chopping off the model top

chopping investigations



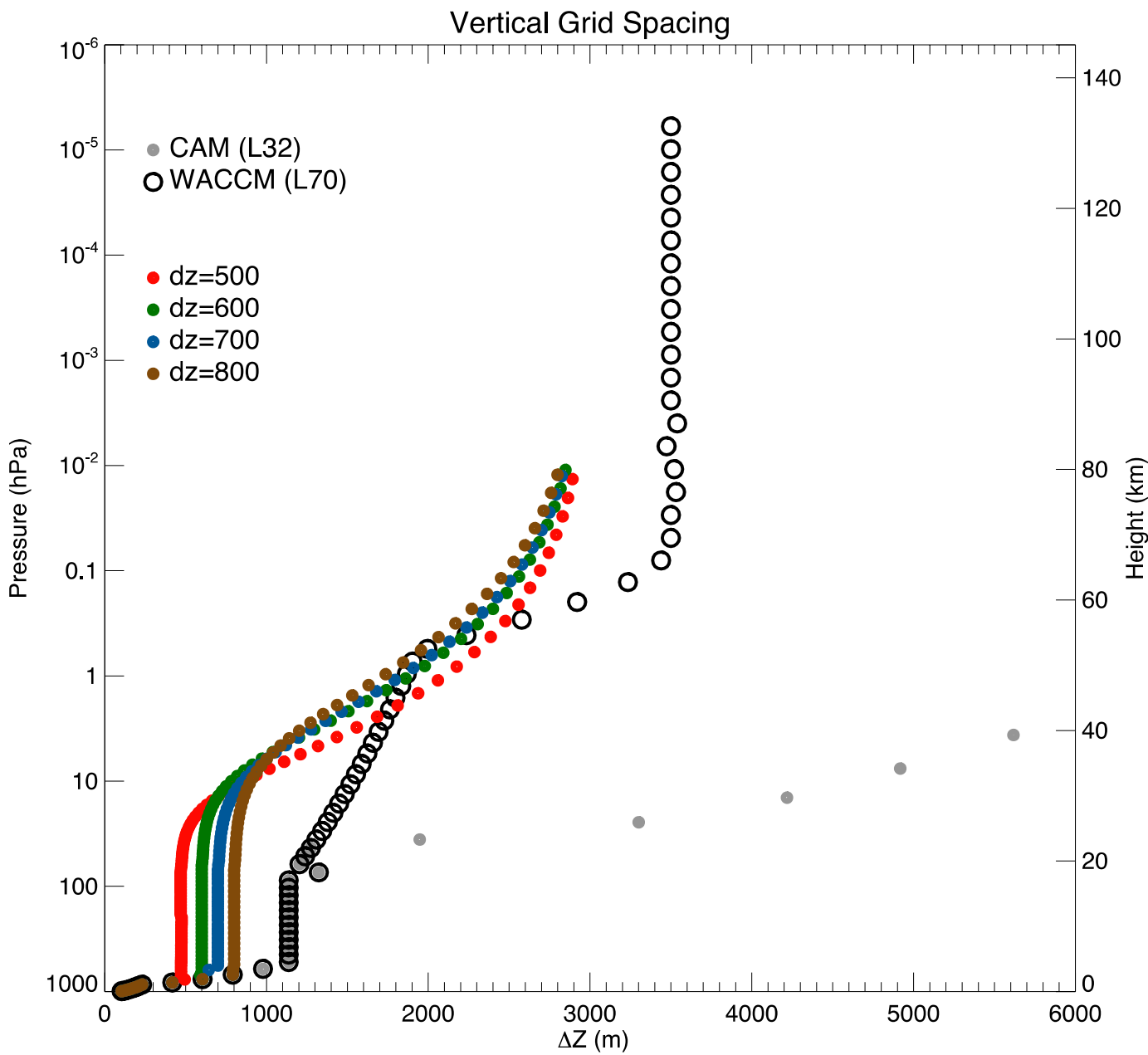
chopping investigations

- Ran four of the cases with the lid chopped off at 80km.



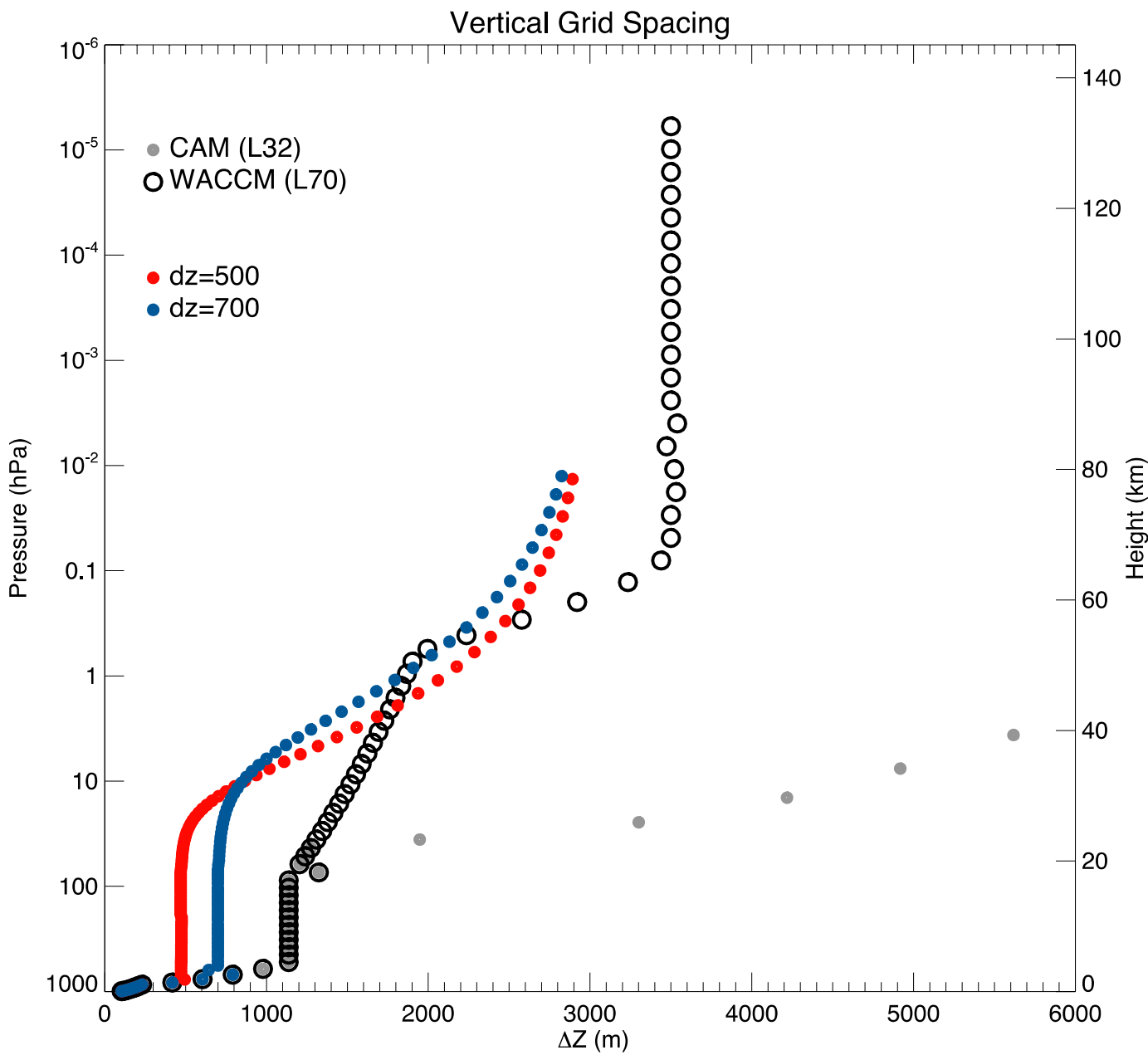
chopping investigations

- Ran four of the cases with the lid chopped off at 80km.
- QBO representation, tropical waves and MJO not substantially impacted by lowering the model top (*Rolando, Yaga, Rich, Julie*)
- Many things not impacted by chopping off the model lid, or changing dz
  - Tropical lower stratospheric upwelling (*Nick*)
  - Zonal mean climatologies: zonal wind, E-P flux divergence (*Brian, Isla*)
  - Tropospheric stationary waves (*Isla*)
  - Daily stratospheric zonal mean zonal wind variability (*Isla*)

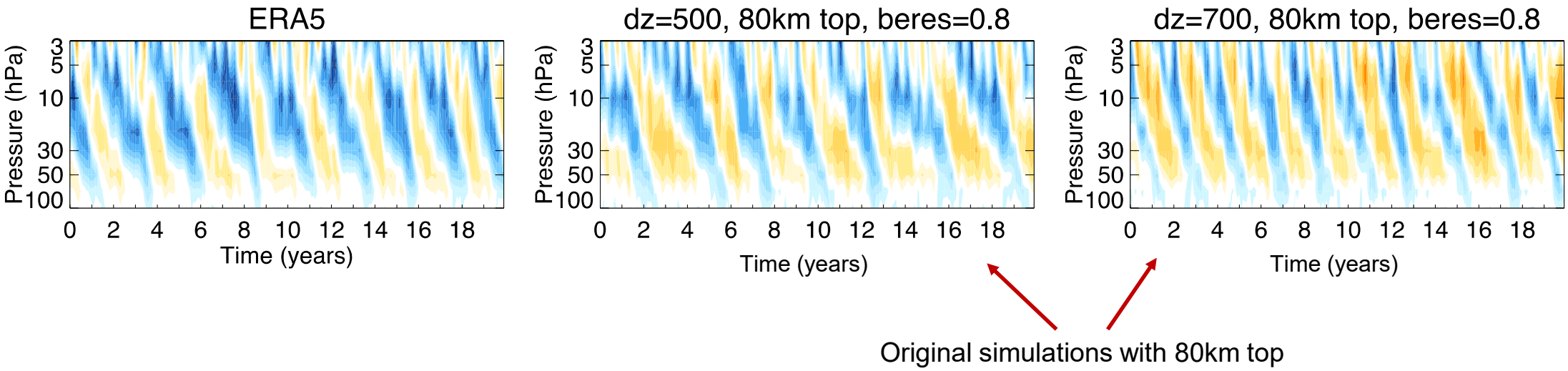


chopping investigations

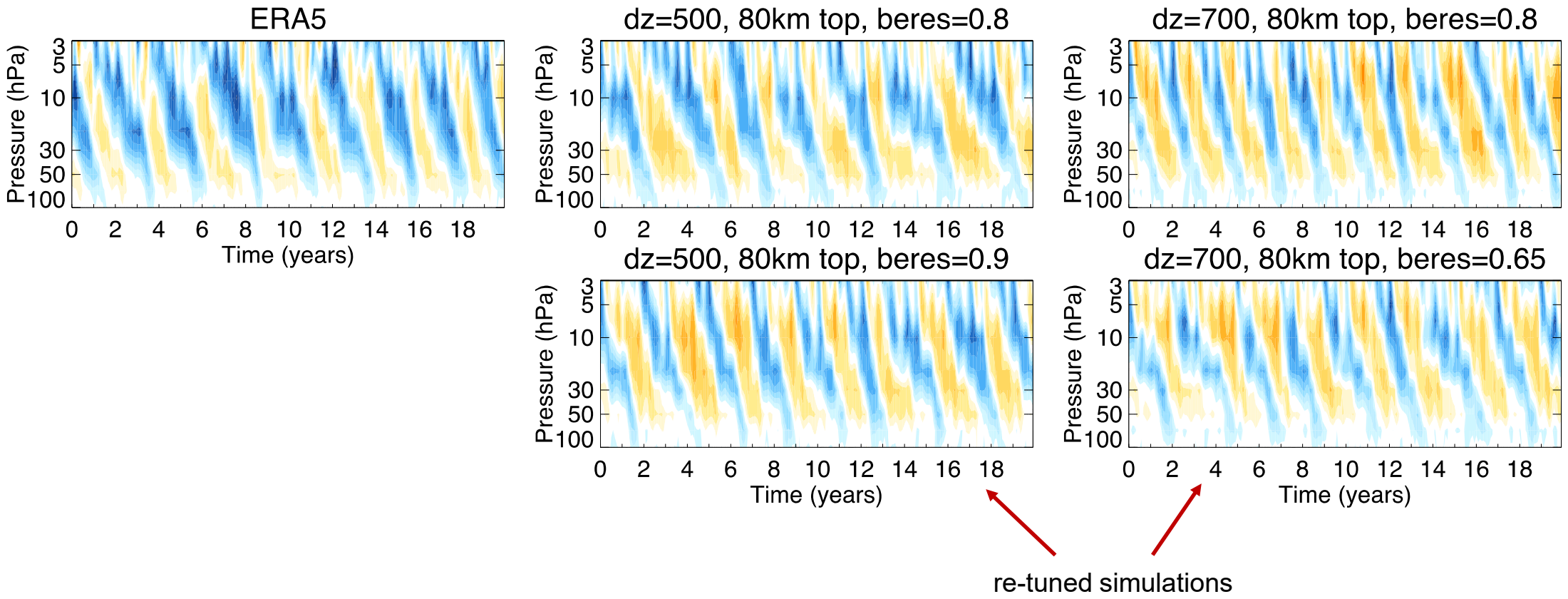
- Focussed on dz=500 and dz=700 with some gravity wave drag tuning to improve the QBO period.



QBO in re-tuned dz=500 and dz=700 runs



QBO in re-tuned dz=500 and dz=700 runs



Wave driving of the QBO

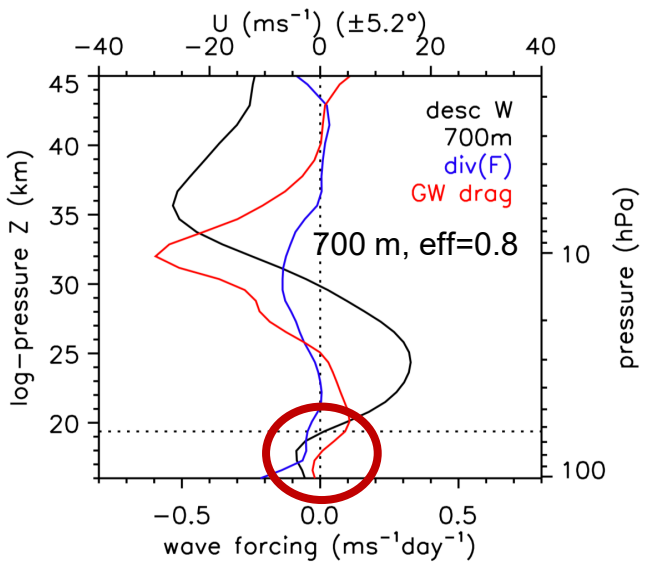
More resolved wave driving of the descending westerly phase of the QBO in each dz=500 case

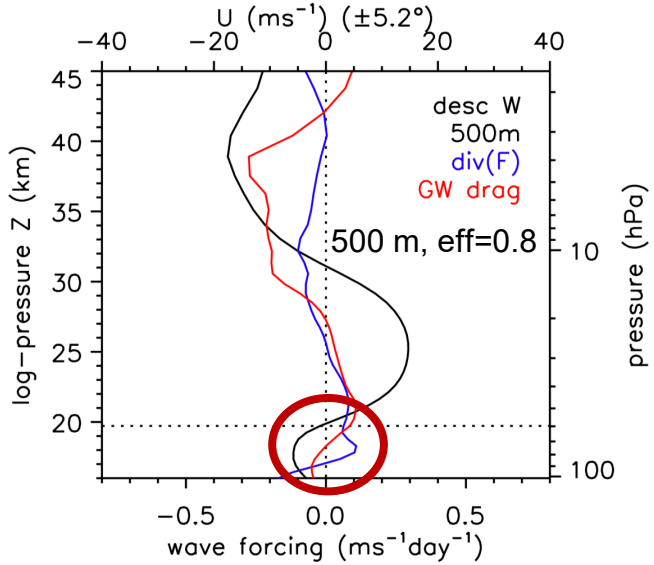
dz=700

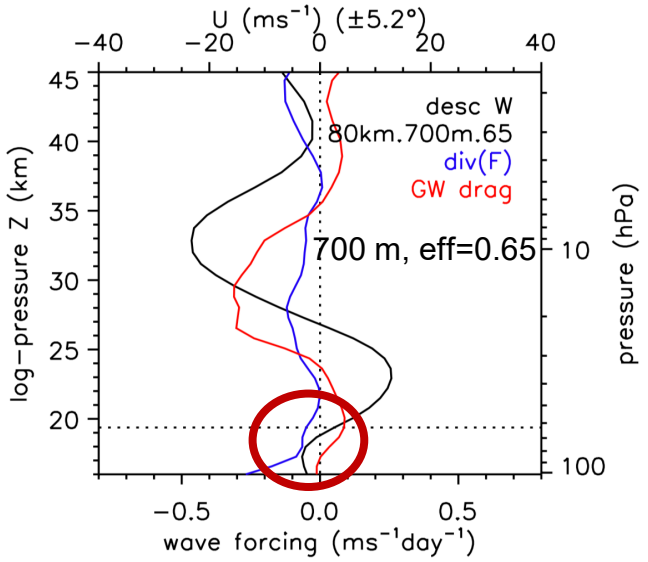
dz=500

original tuning →

new tuning →







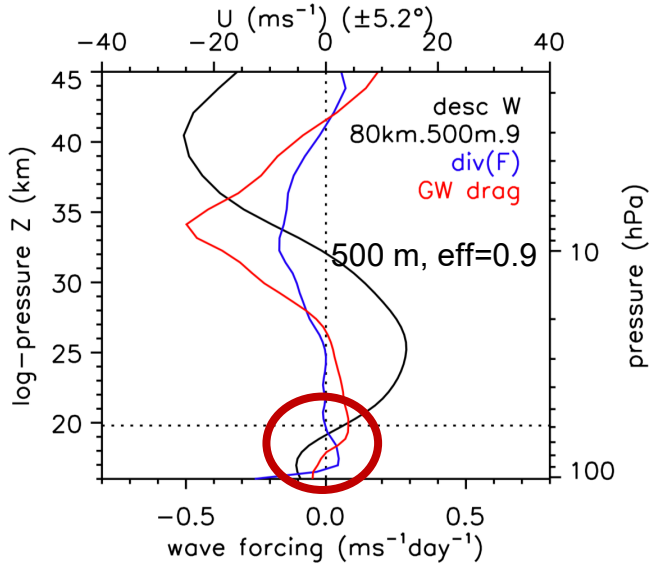


Figure credit: Rolando Garcia

Amplitude of the QBO

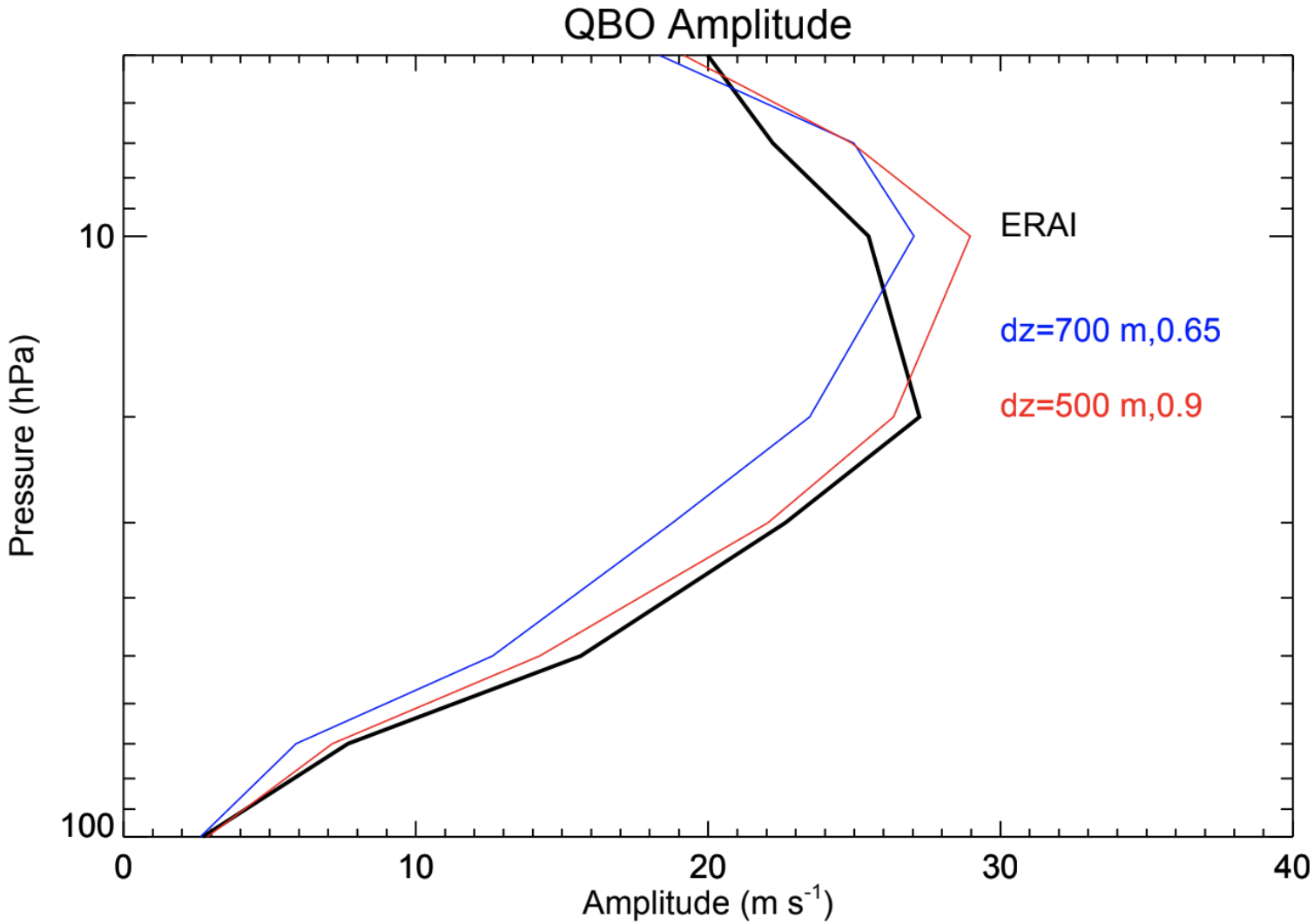
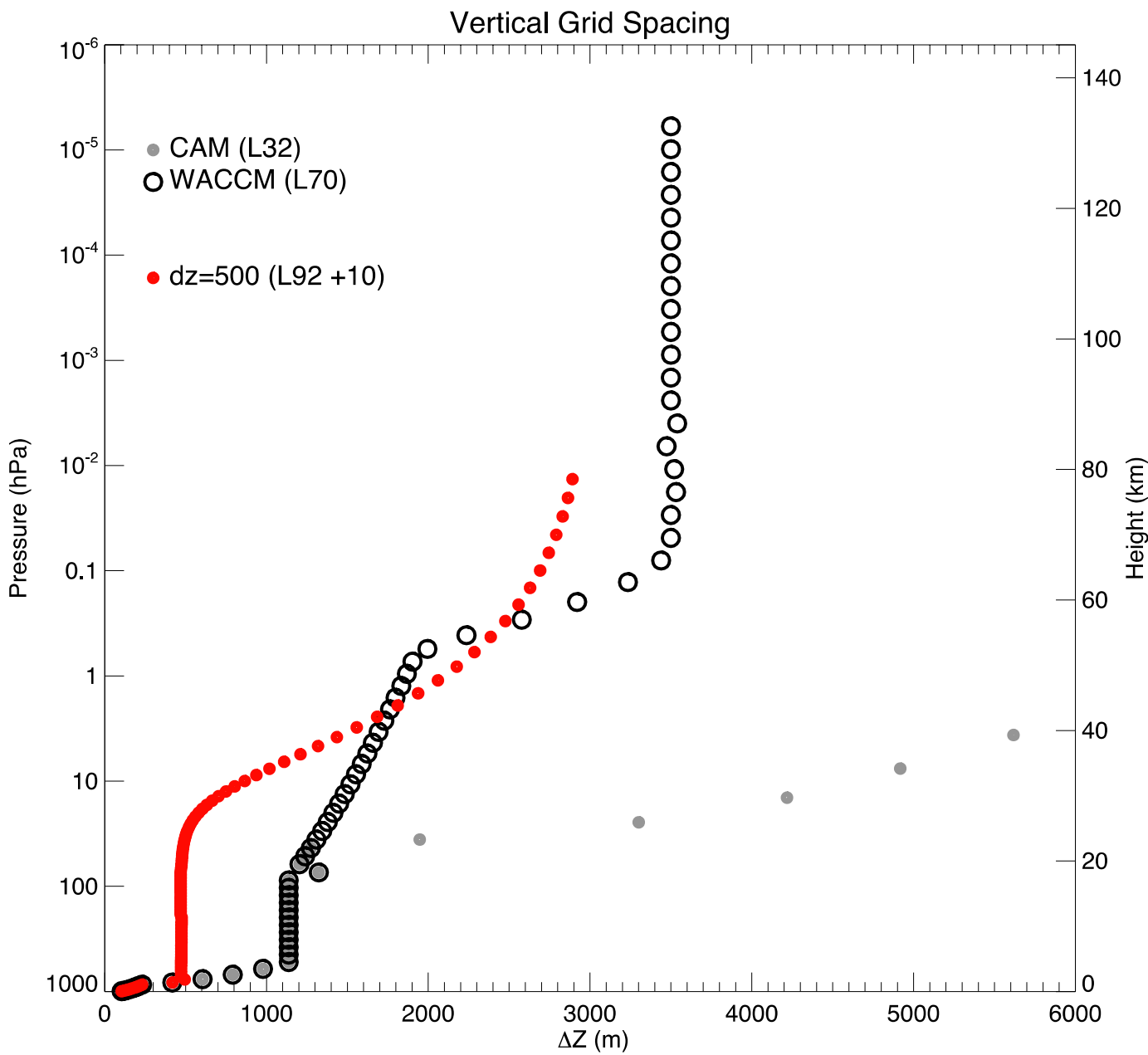


Figure credit: Yaga Richter

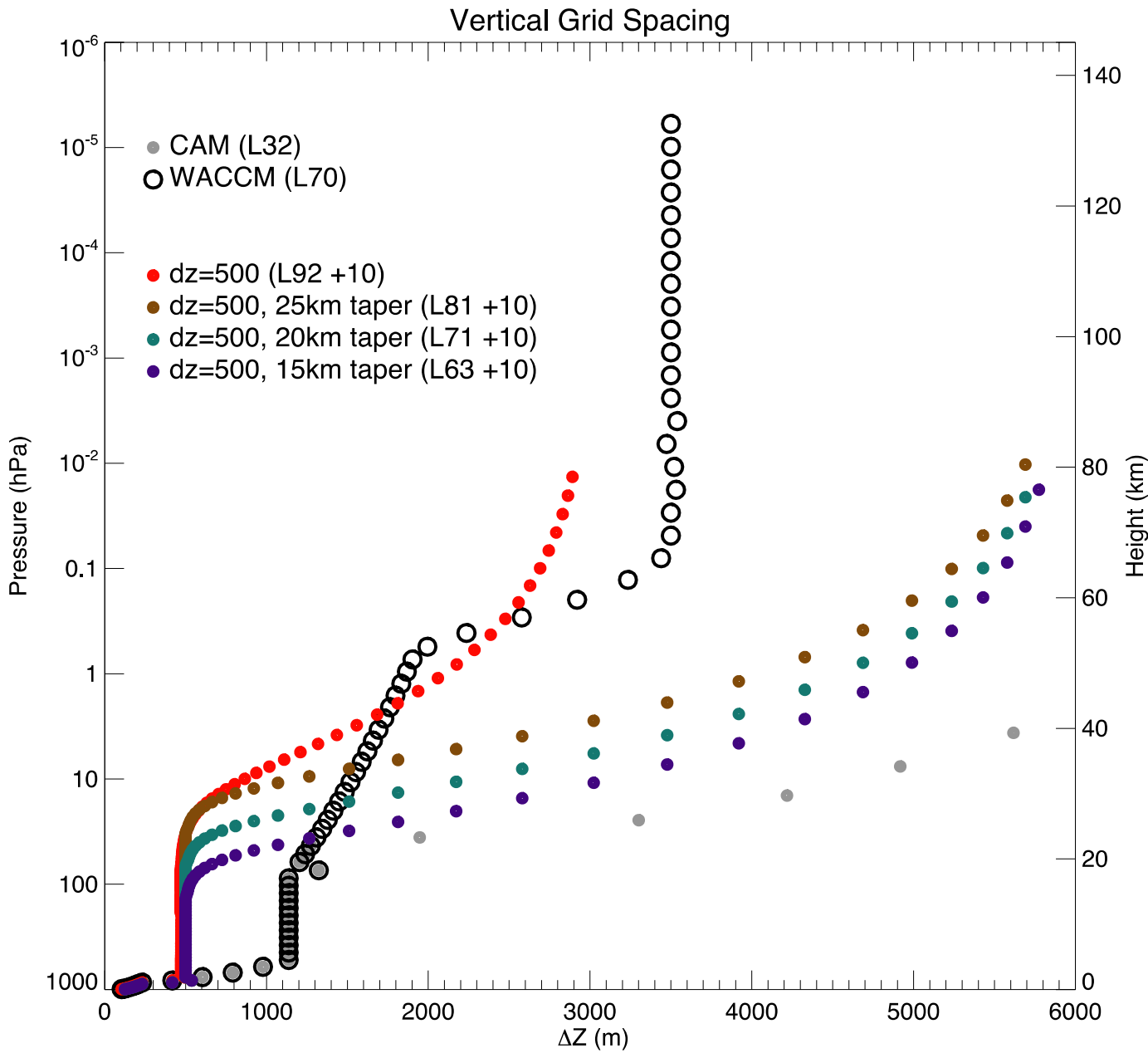
Suppose we want to have dz=500, how many levels will that be? Can we limit it?

Tapering tests

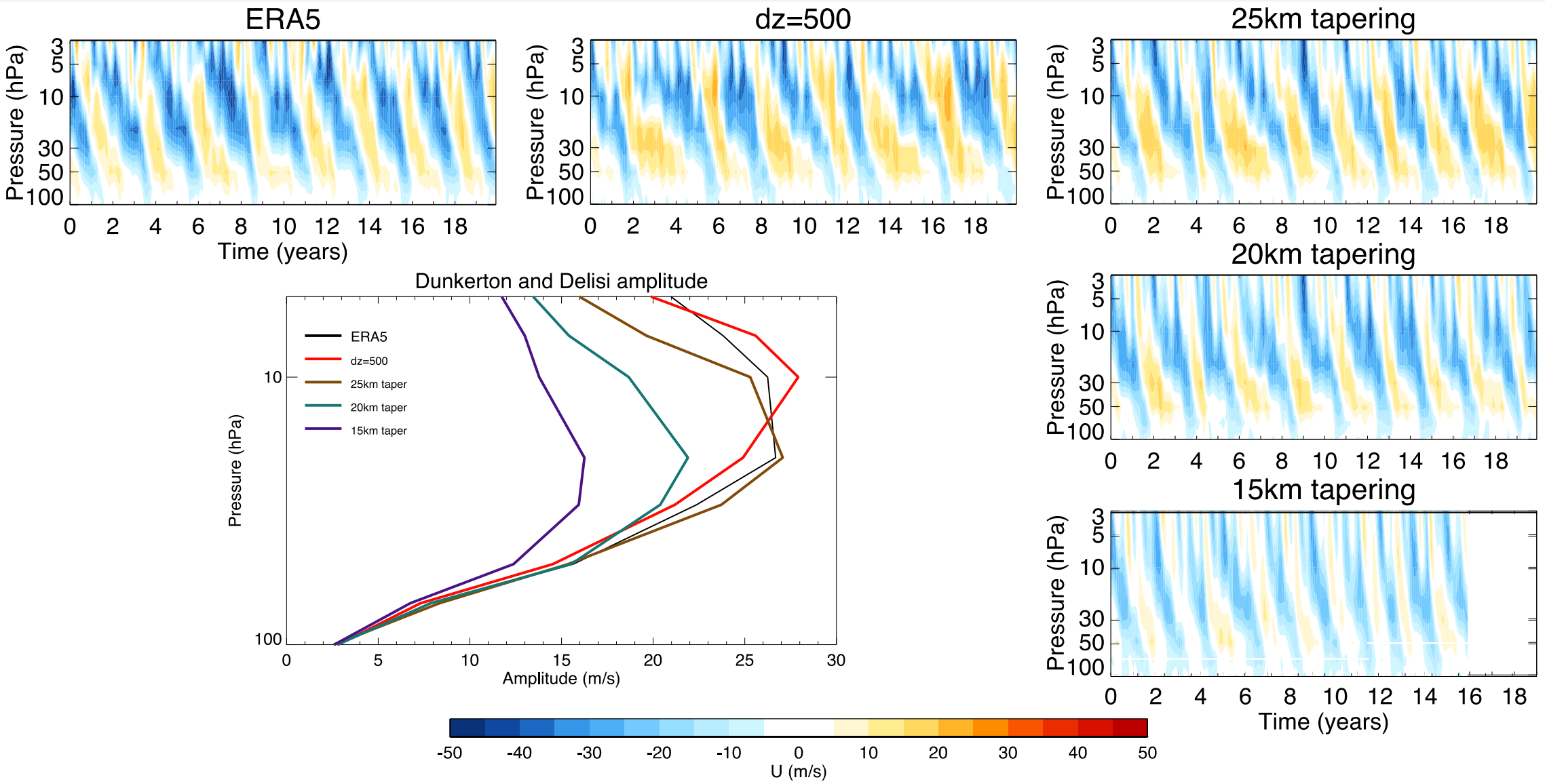


Tapering tests

- Ran three tests with additional tapering out to about 6000m at the model top
  - Taper starting at 25km
  - Taper starting at 20km
  - Taper starting at 15km



The QBO in the tapering tests



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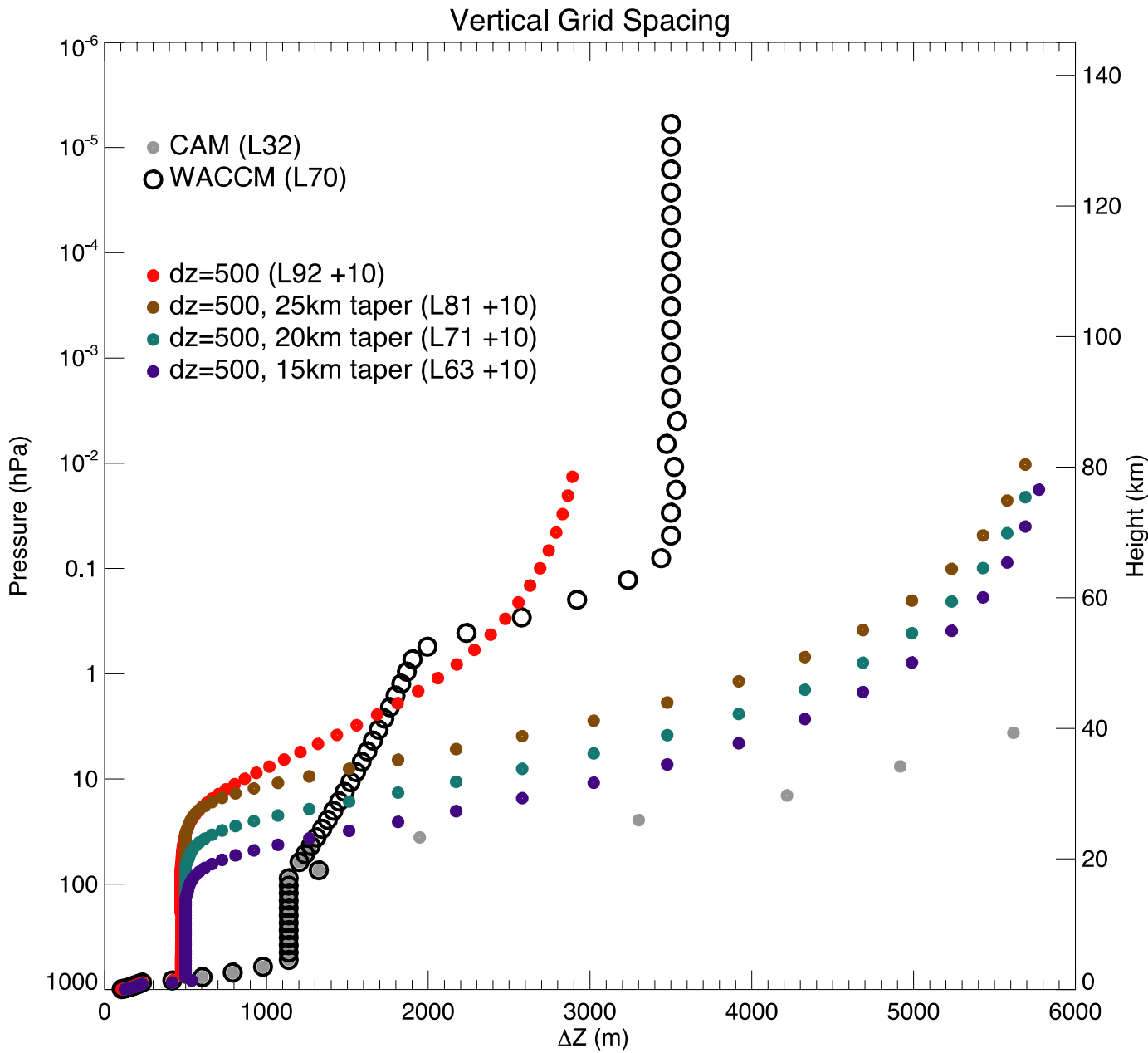

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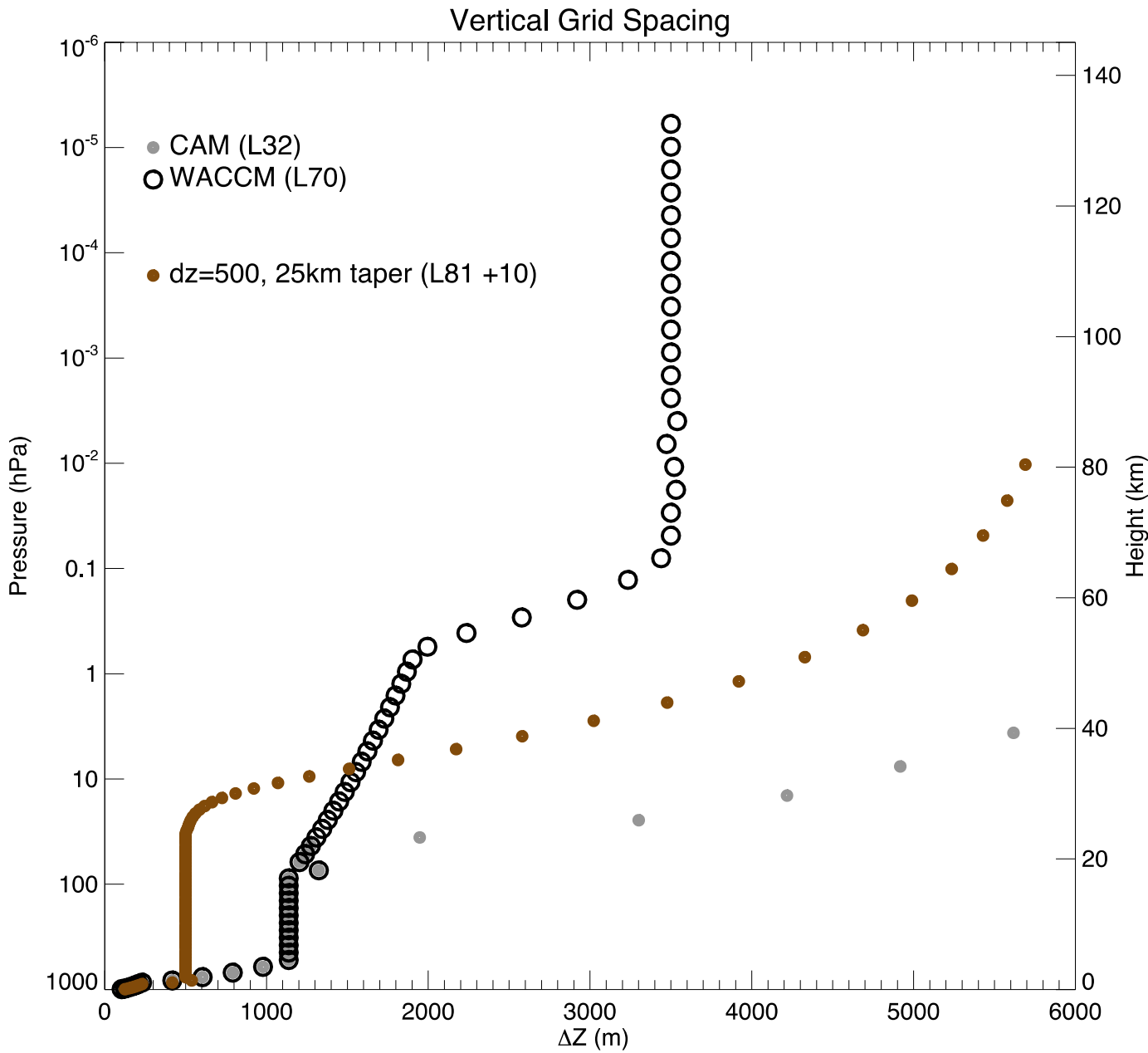
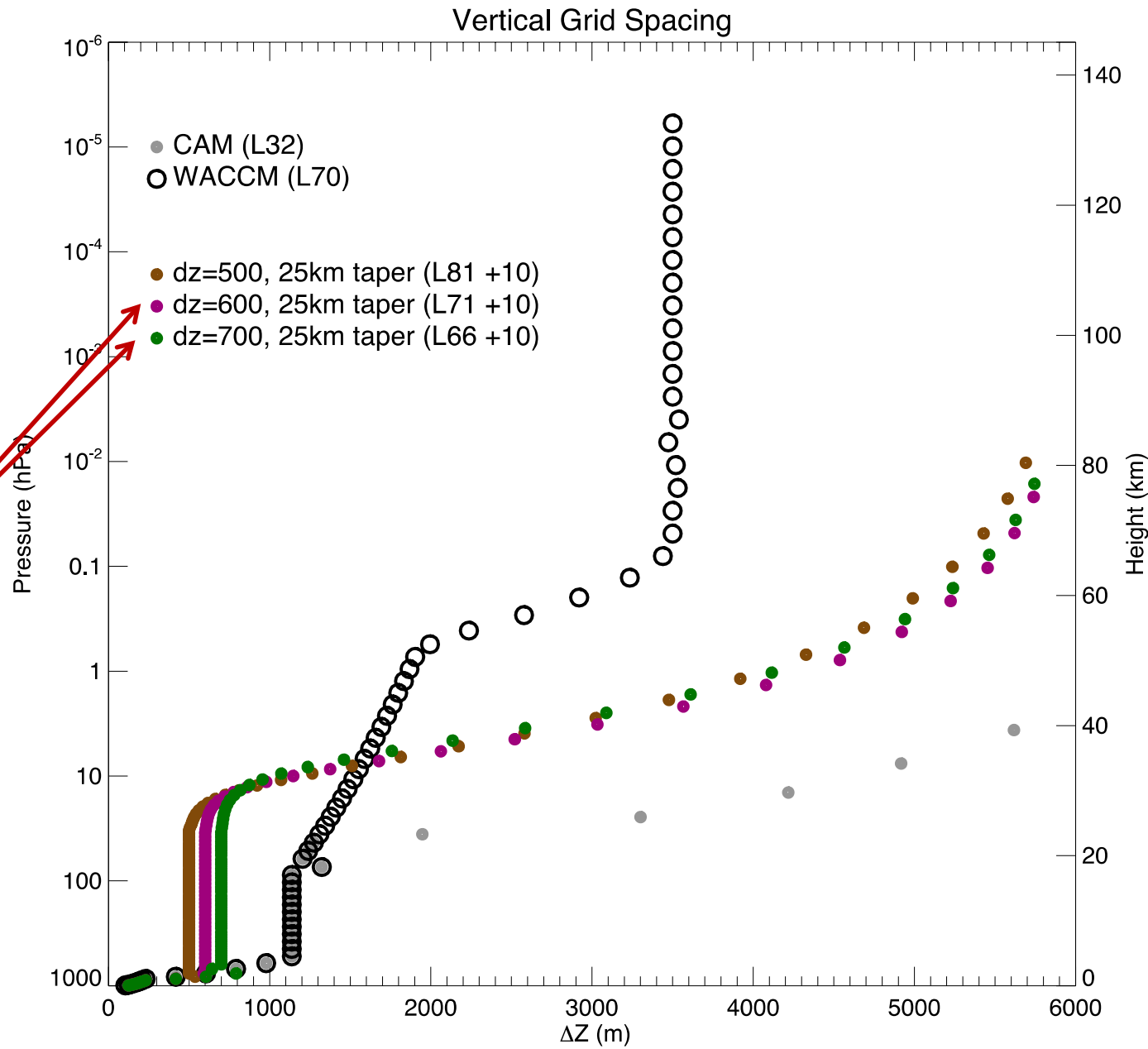


Tapering tests

- Ran three tests with additional tapering out to about 6000m at the model top
  - Taper starting at 25km
  - Taper starting at 20km
  - Taper starting at 15km

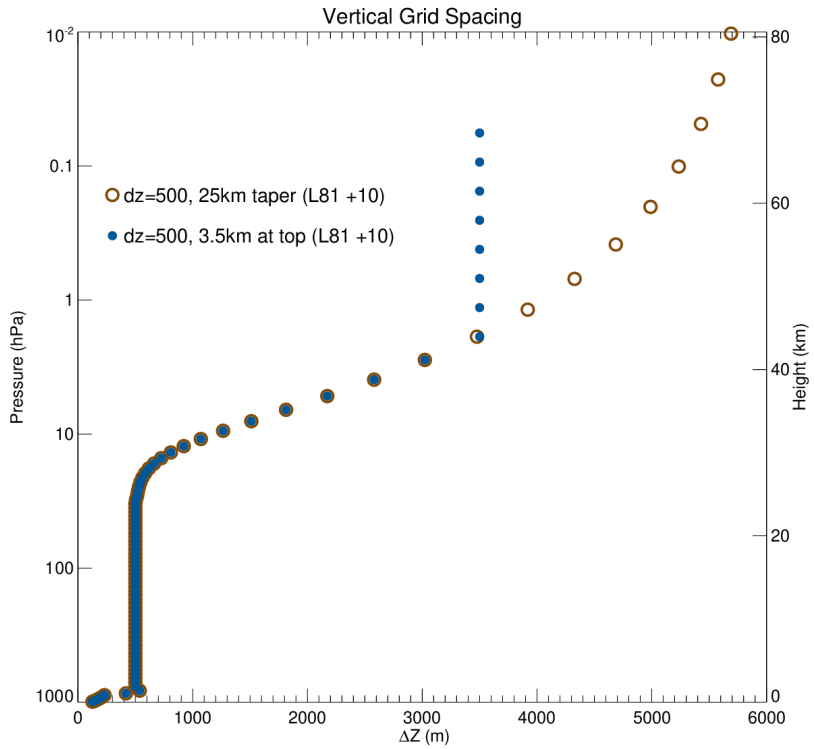
Cost could be reduced with dz=600 or even more with dz=700, but then we'd likely be compromising on the QBO

The dz=600 may still be an option though and will should be kept under consideration with the next generation dynamical core (likely SE).

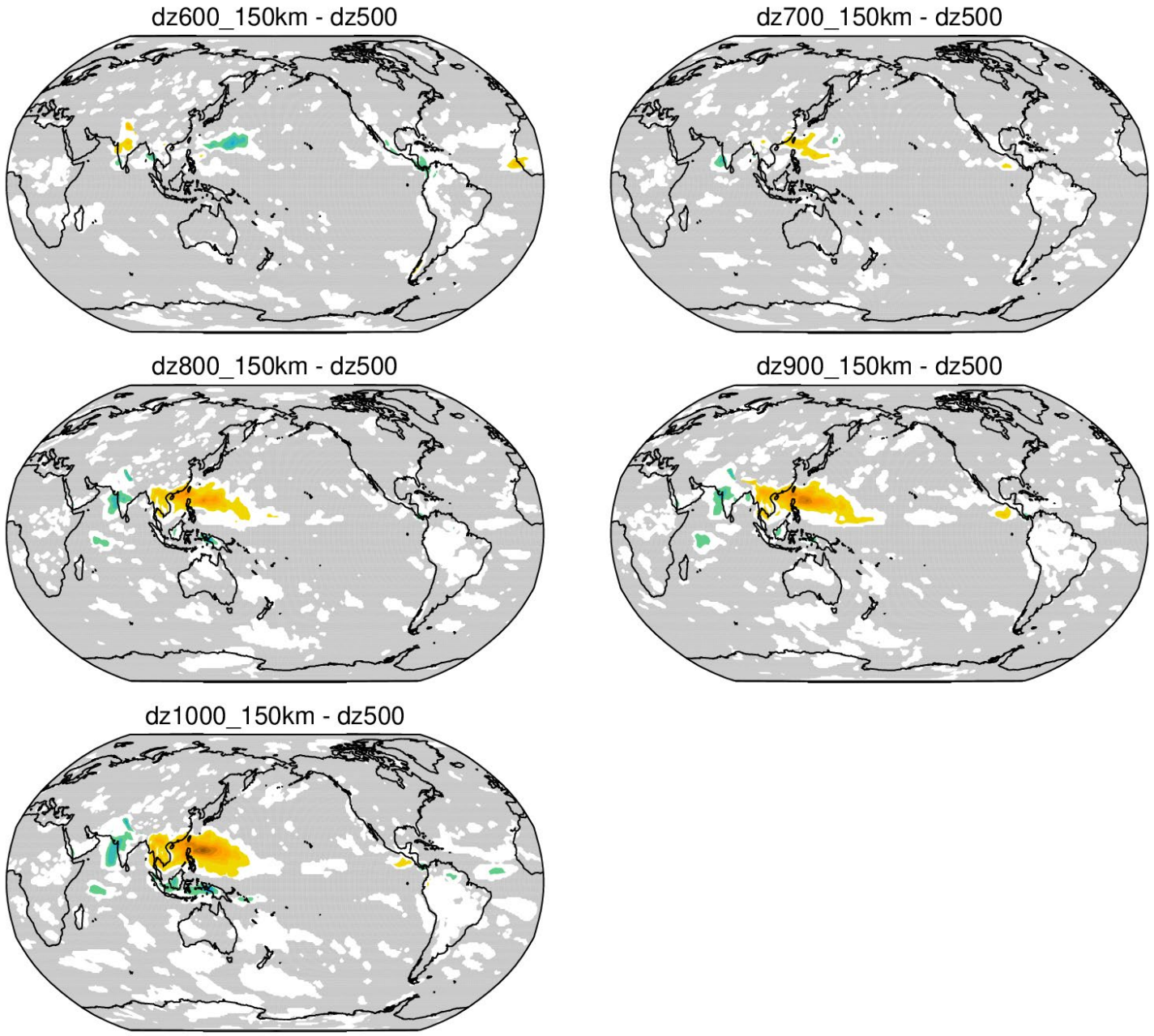


Conclusions

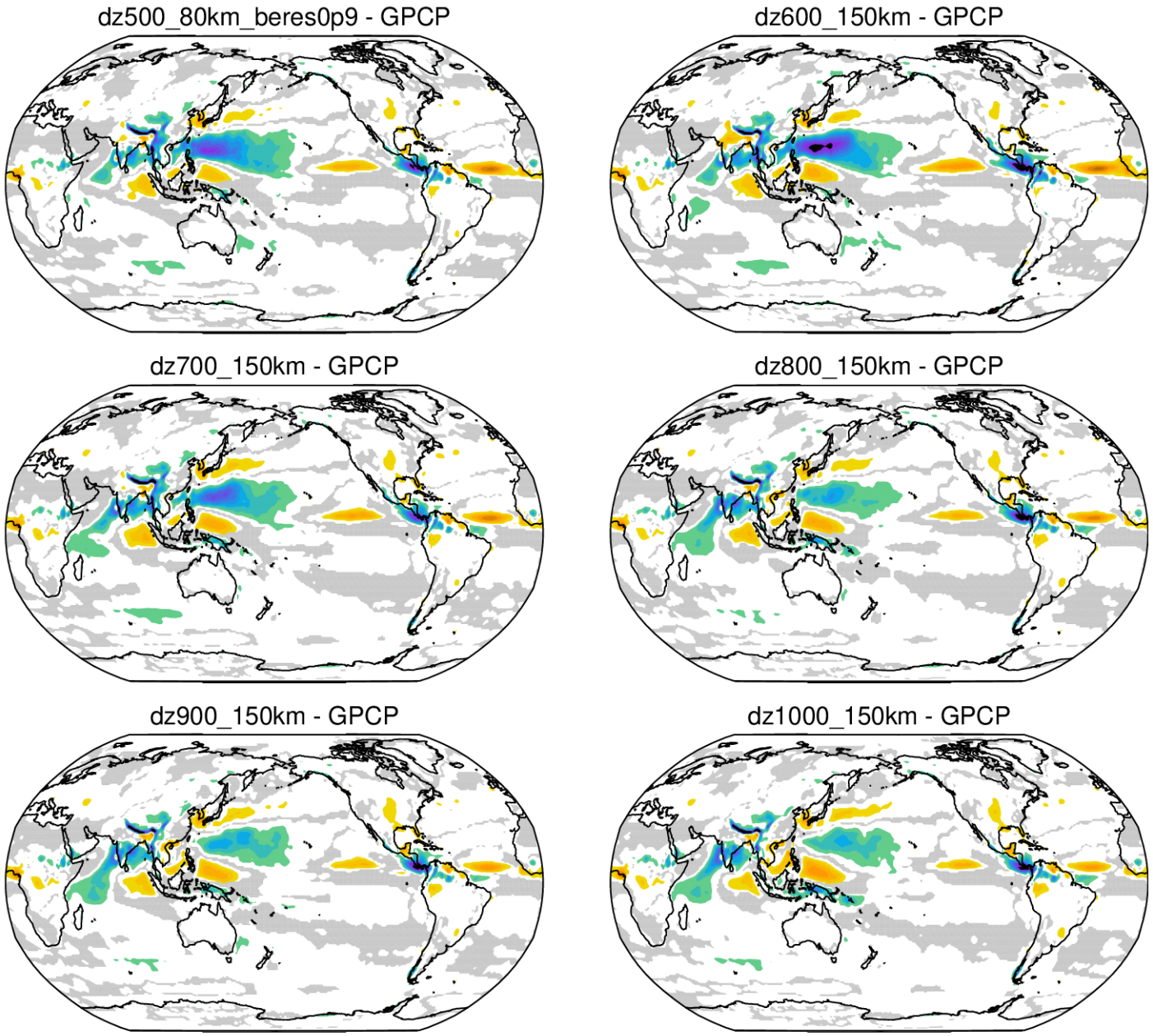
- Lots of tests have been performed
- We can place the model top at 80km with substantial tapering off of the model levels starting around 25km without having drastic influences on the tropospheric and stratospheric climate (at least by the measures examined so far)
- Likely we will try to leave the maximum dz at 3.5km and lower the model top slightly for ease of building WACCM on top (currently being tested)
- To capture the finer details of the QBO, dz=500 is optimal. This captures resolved wave driving of the descent of the westerly phase and gives a good QBO amplitude once the period has been refined.
- dz=500 with tapering starting at 25km leaves us with a 91 level model after boundary layer upgrades.
- We'd like to test both dz=500 and dz=600 in the likely next generation SE dycore before drawing firm conclusions.
- Work is beginning on boundary layer options and low top options.



Extra Slides



Precip differences from dz=500 case (JJA)



Precip differences from GPCP (JJA)

Zonal mean zonal wind at 70hPa

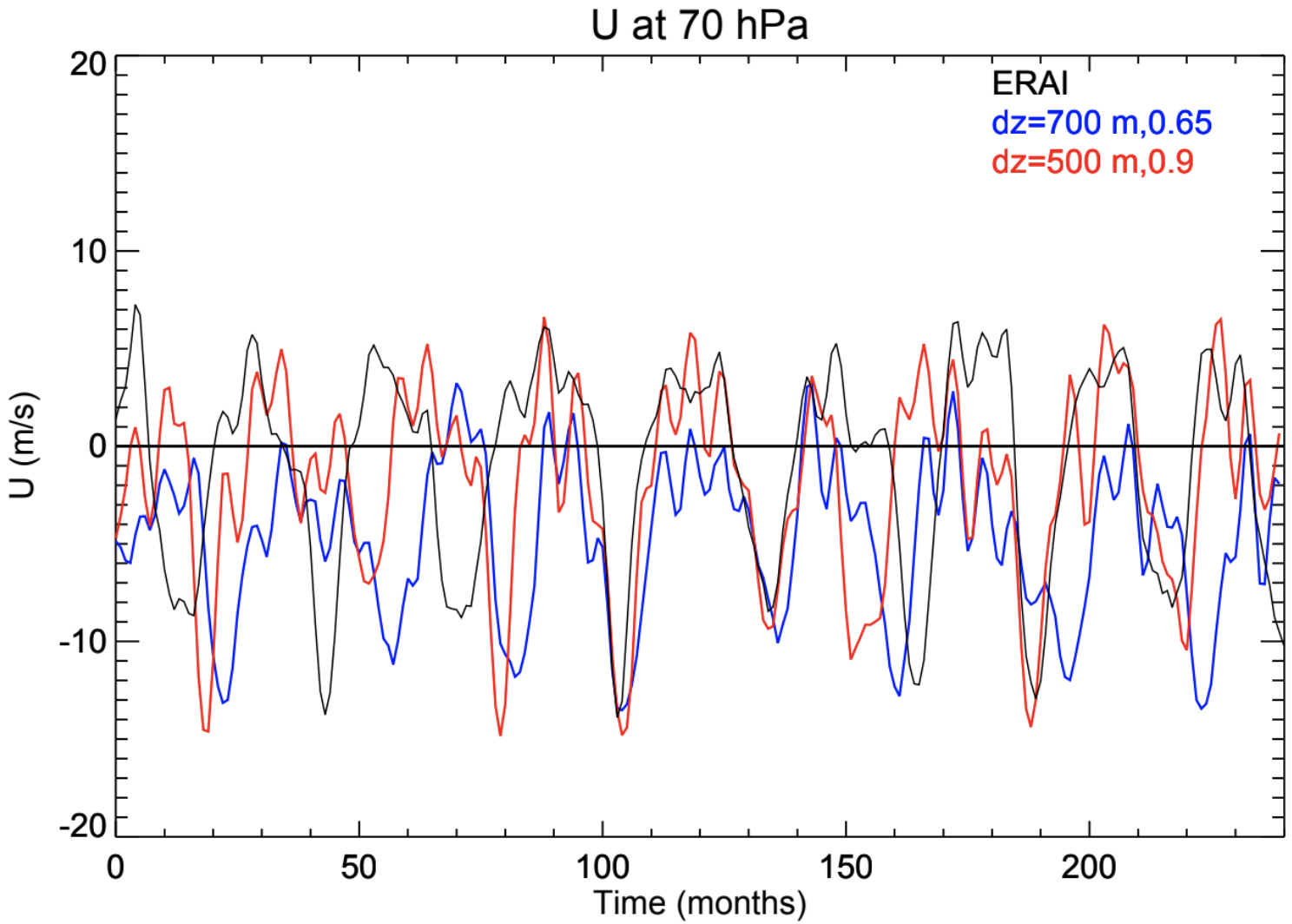
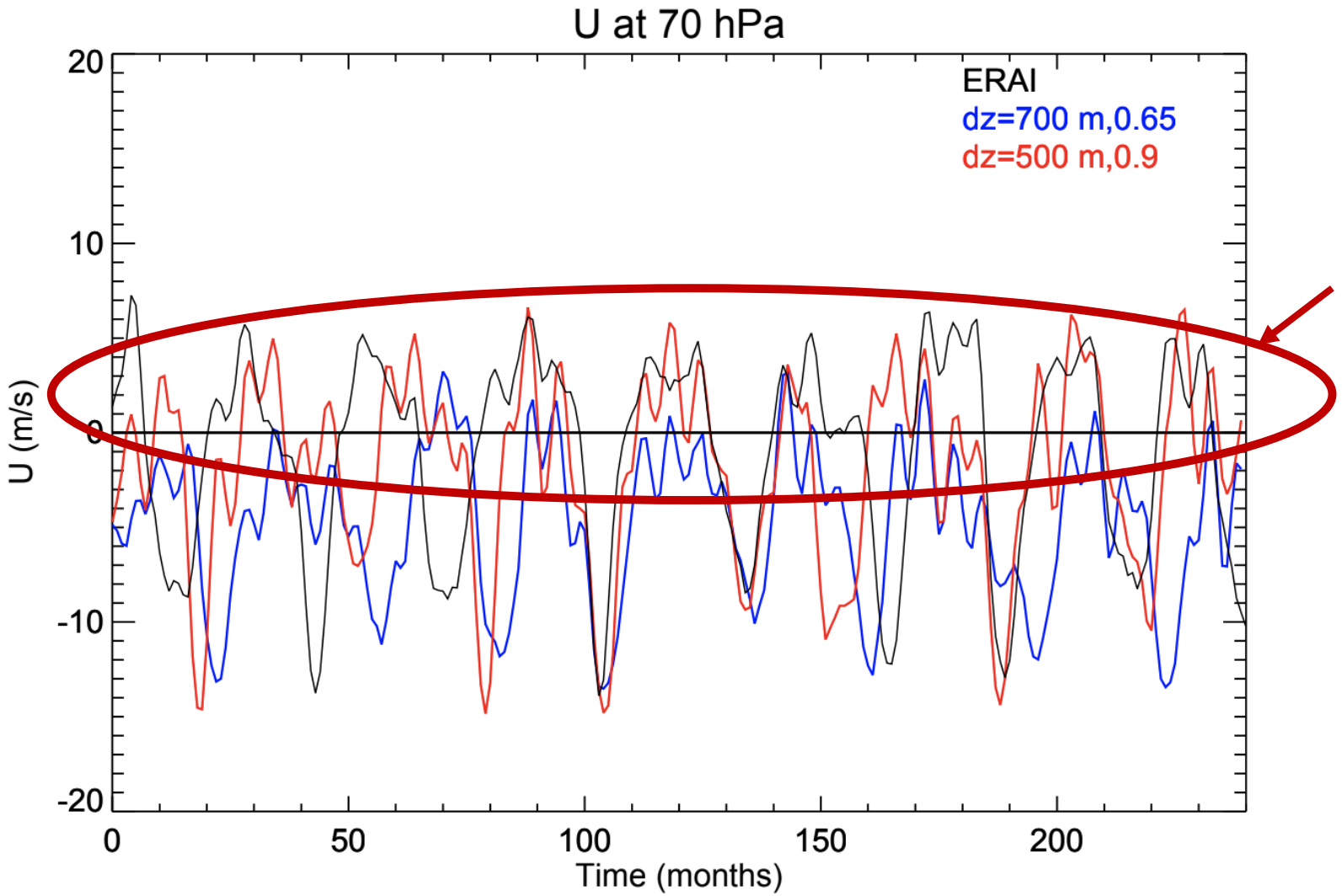


Figure credit: Yaga Richter

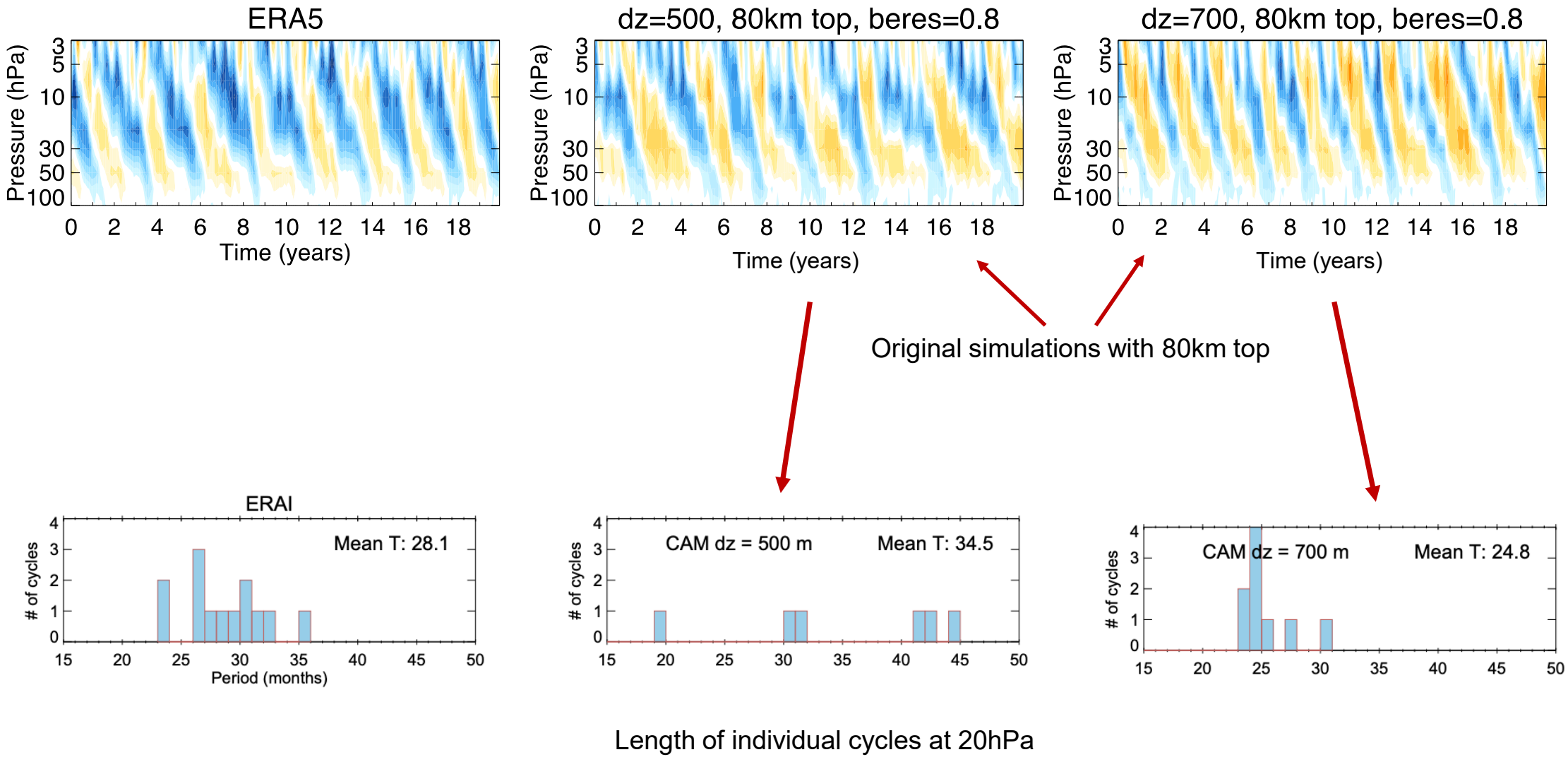
Zonal mean zonal wind at 70hPa



Westerly winds don't reach down to 70hPa as much in the dz=700 run.

Figure credit: Yaga Richter

QBO in re-tuned dz=500 and dz=700 runs



Length of individual cycles at 20hPa

Figure credit: Yaga Richter

QBO in re-tuned dz=500 and dz=700 runs

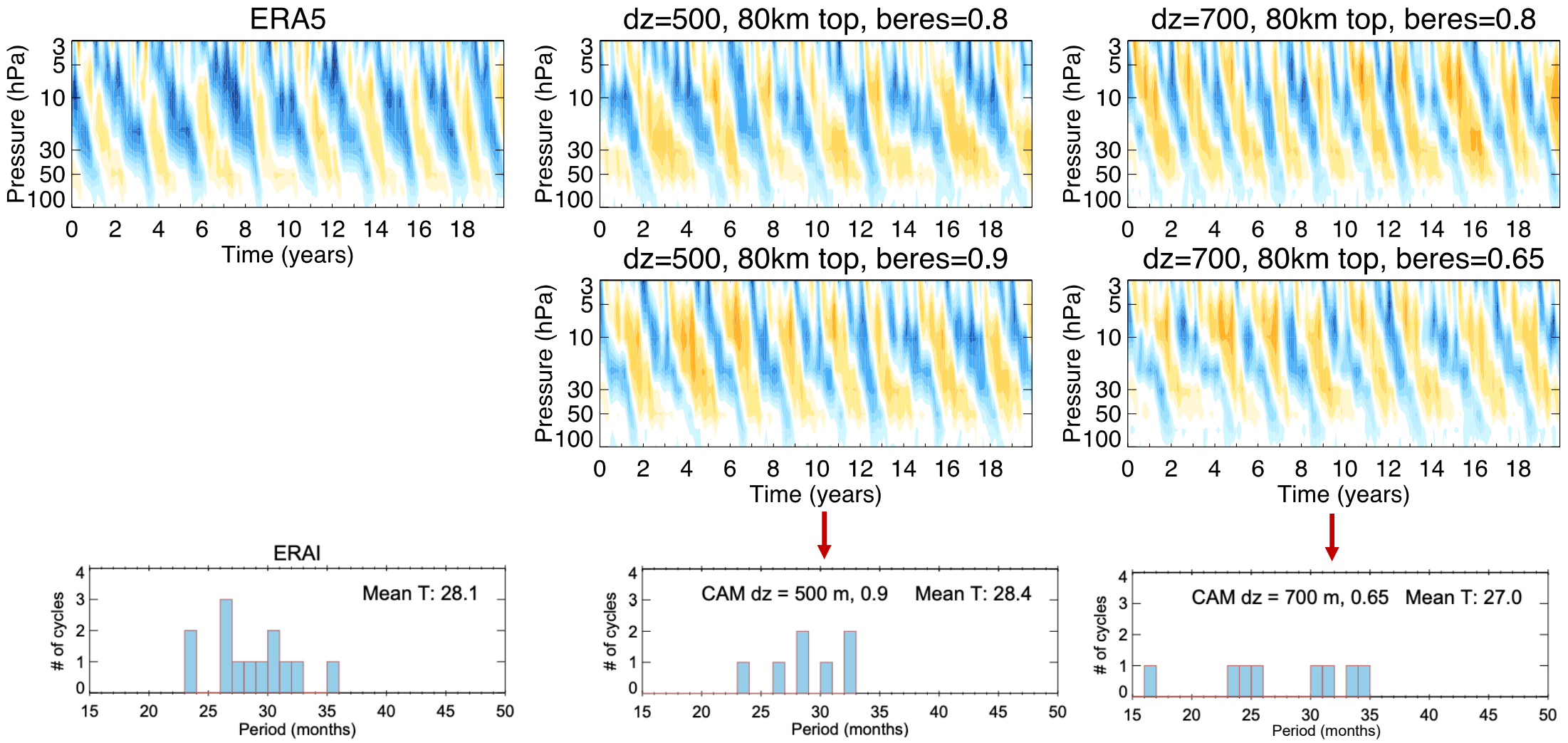


Figure credit: Yaga Richter

Length of individual cycles at 20hPa

Differences in wave driving

At each level, average the resolved wave driving over months when it's positive (solid) and months when it's negative (dashed)

Less positive resolved wave driving in the lower stratosphere

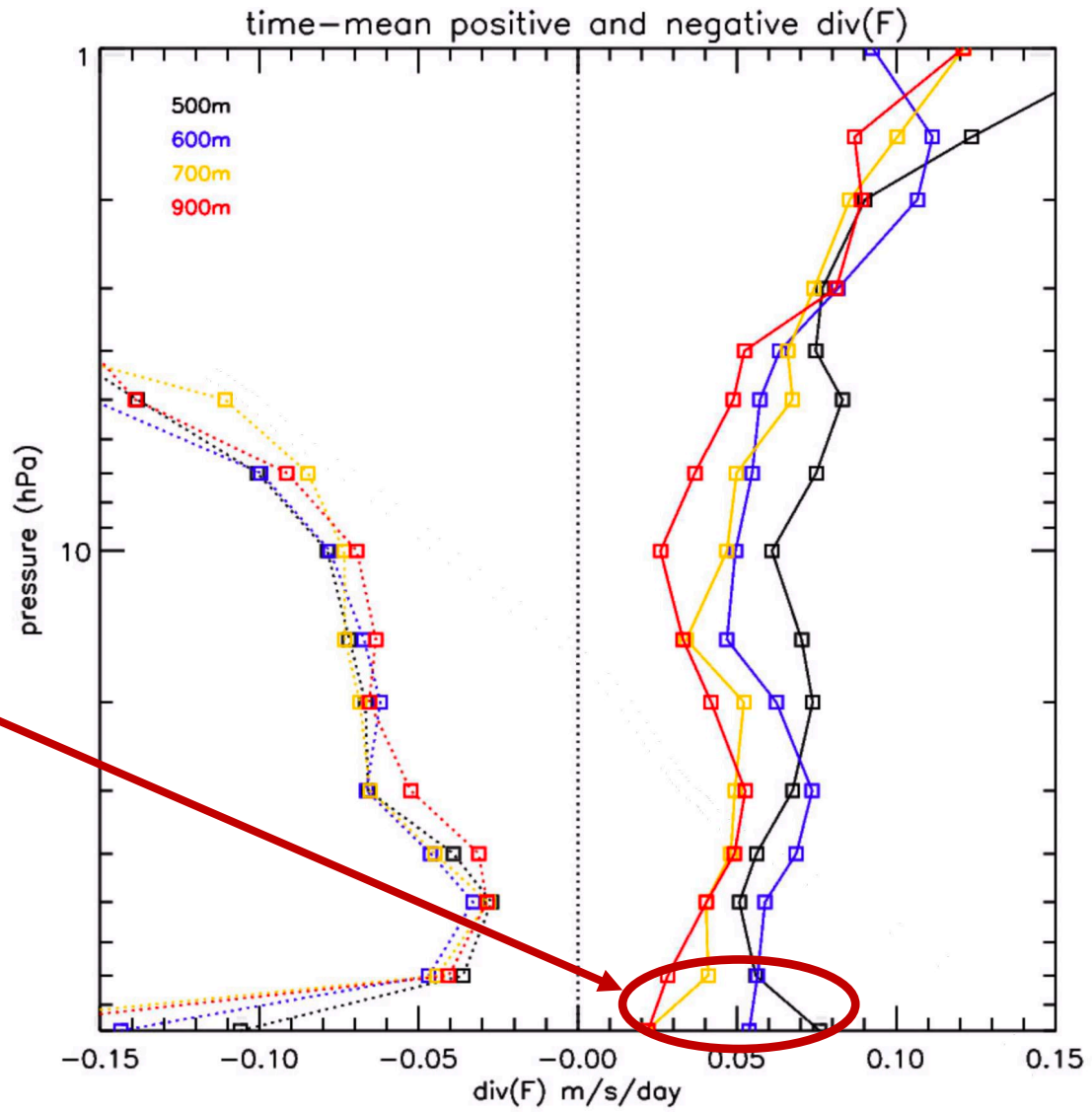


Figure Credit: Rolando Garcia

Time mean positive and negative E -P flux

At each level, average the resolved wave driving over months when it's positive (solid) and months when it's negative (dashed)

Consistently more westerly resolved wave drag in the lower stratosphere

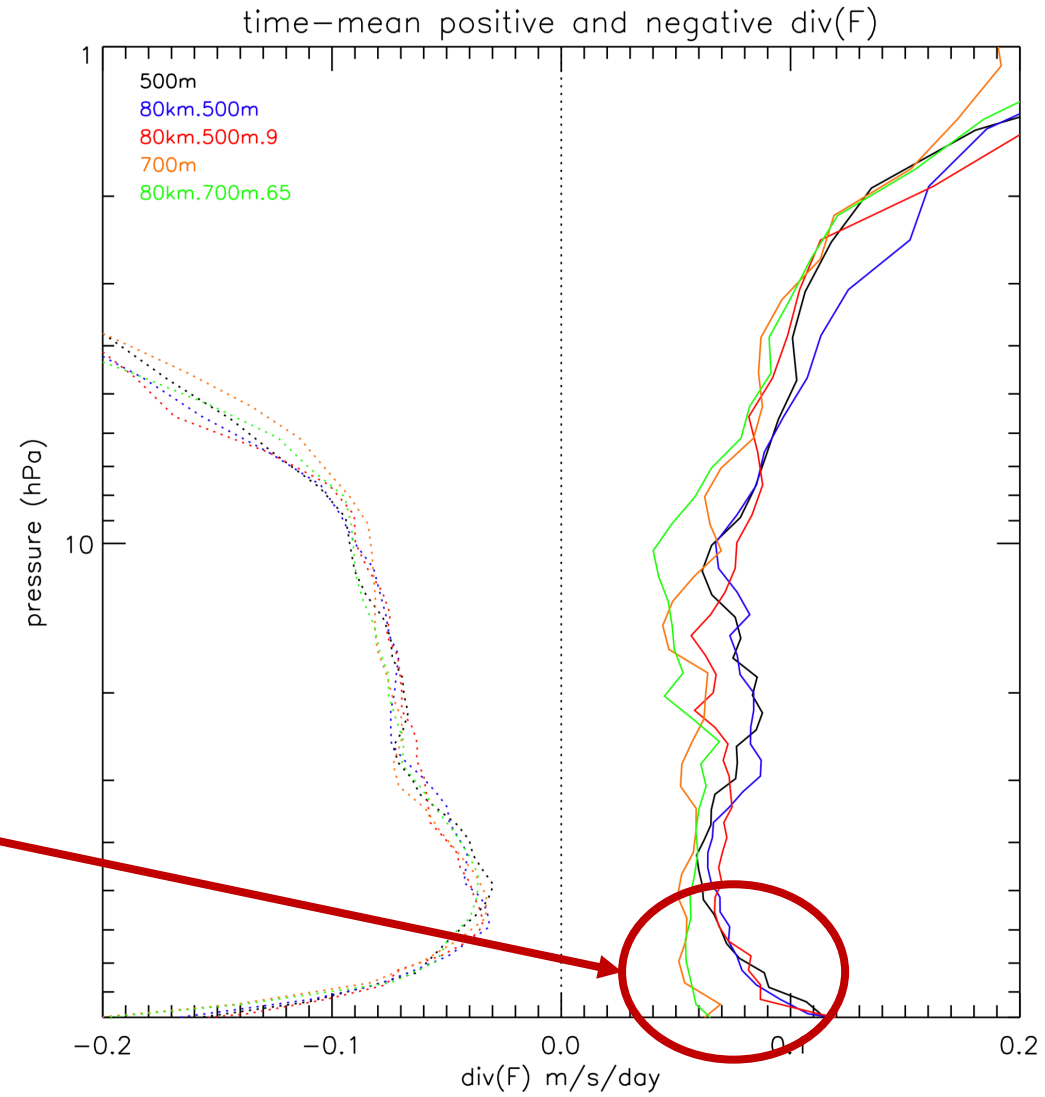


Figure credit: Rolando Garcia

MJO (standard deviation of MJO filtered OLR, DJF)

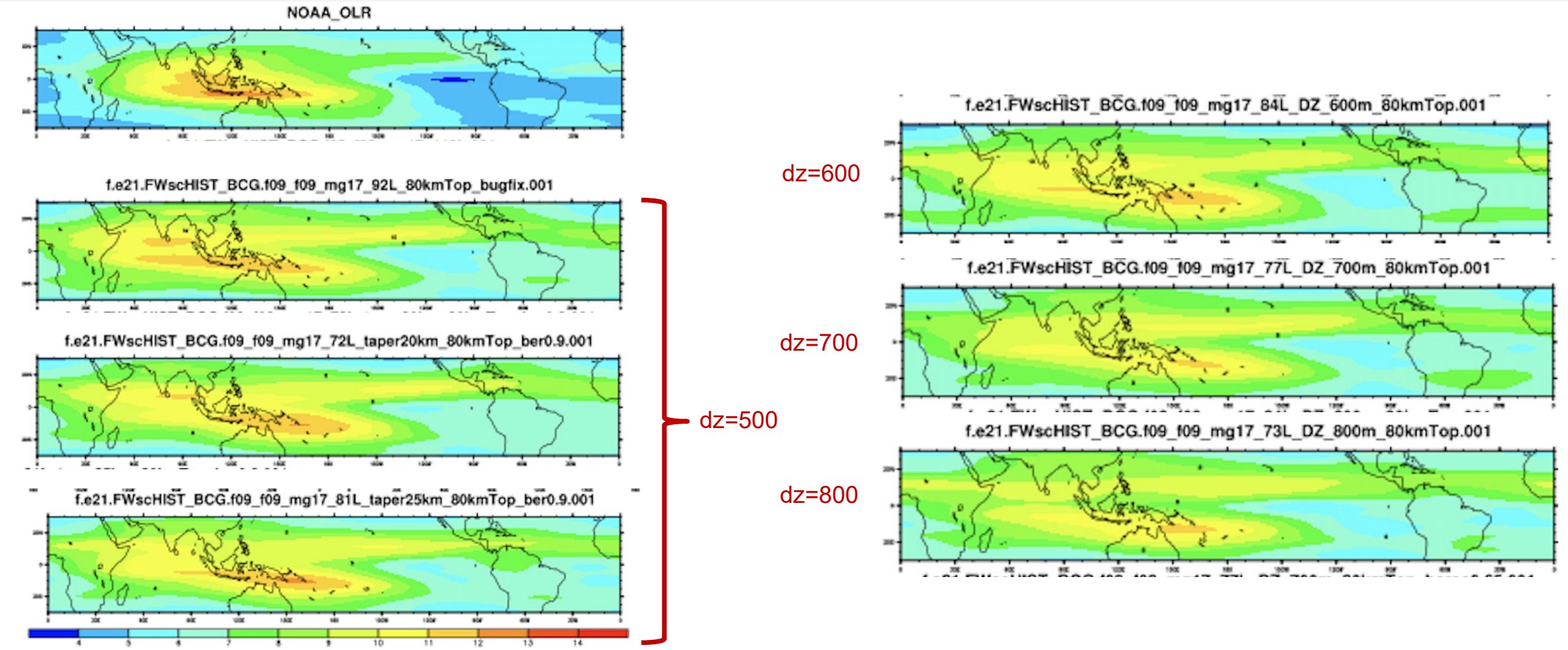
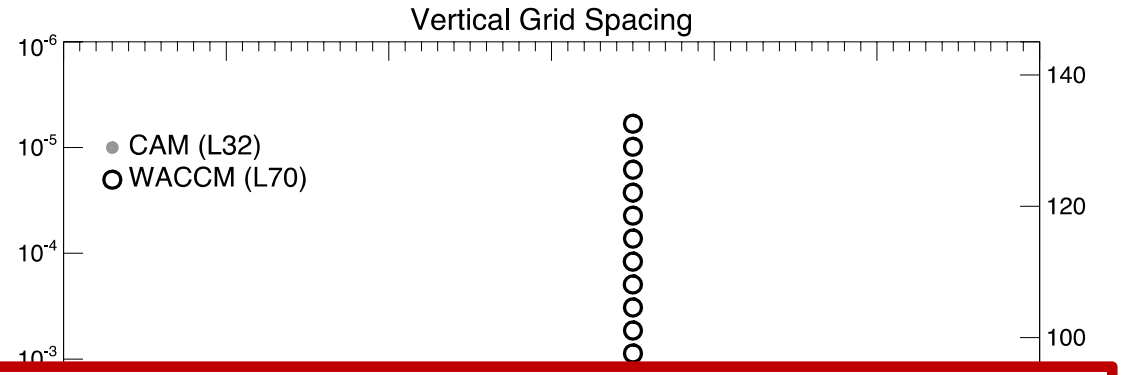


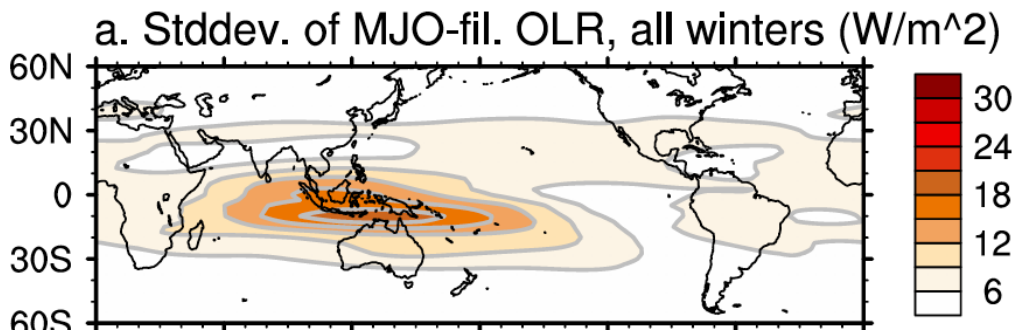
Figure Credit: Julie Caron

Motivation

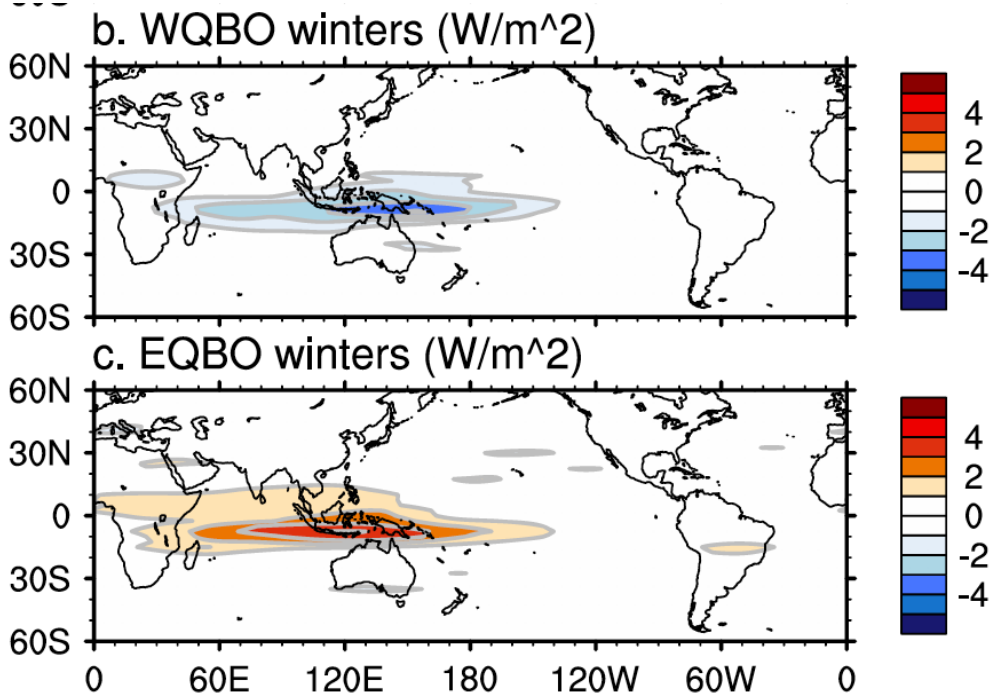
- We currently run both WACCM and CAM for the CMIP exercises.
- WACCM still doesn't have a high enough vertical resolution to adequately represent the QBO



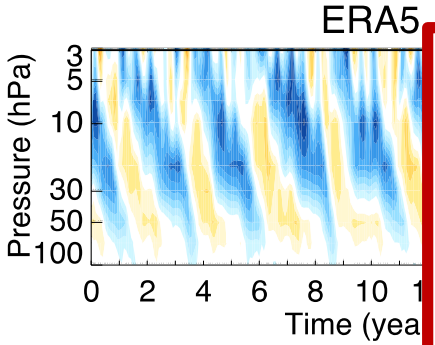
Observed influence of the QBO on MJO variability (Yoo and Son 2016)



Strong MJO activity in easterly QBO than westerly QBO.
Robust (although not well understood) in observations but absent in models (Kim et al 2020)



The representation of the QBO



- All configurations have a QBO of some form
- Some sensitivity of the period to resolution. But this tuned with gravity wave drag changes

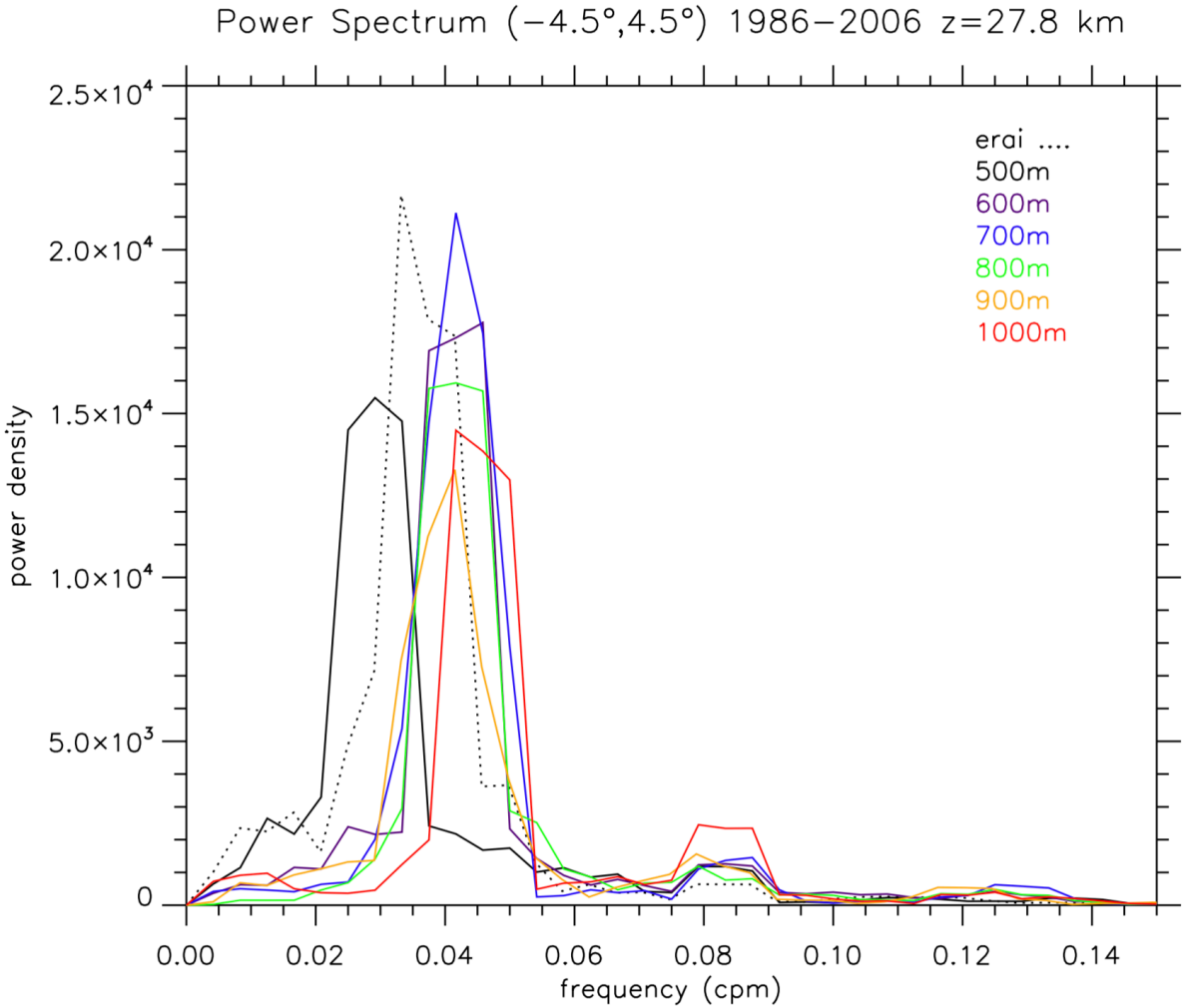
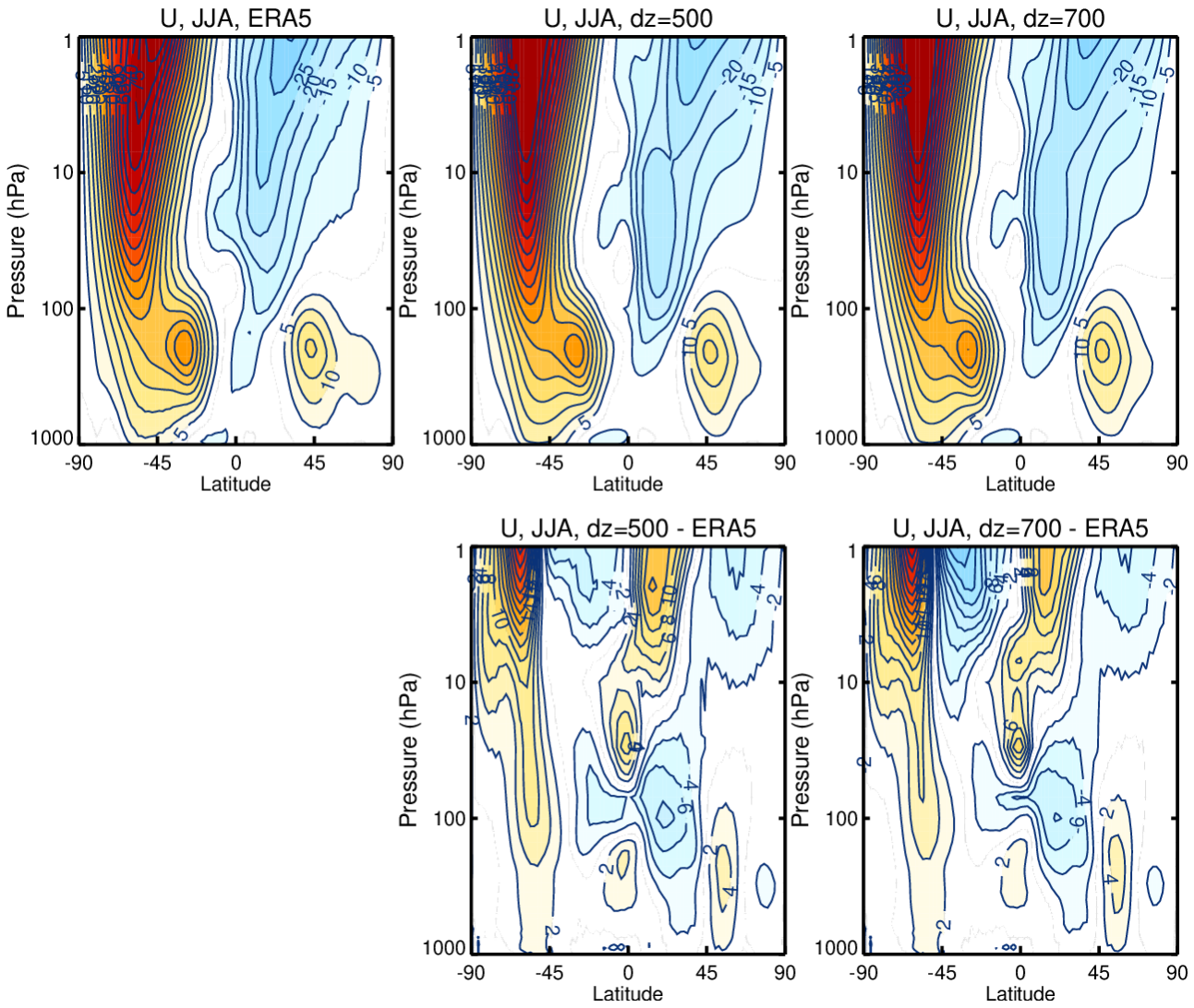


Figure credit: Rolando Garcia

Not much difference elsewhere

ERA5 dz=500 dz=700

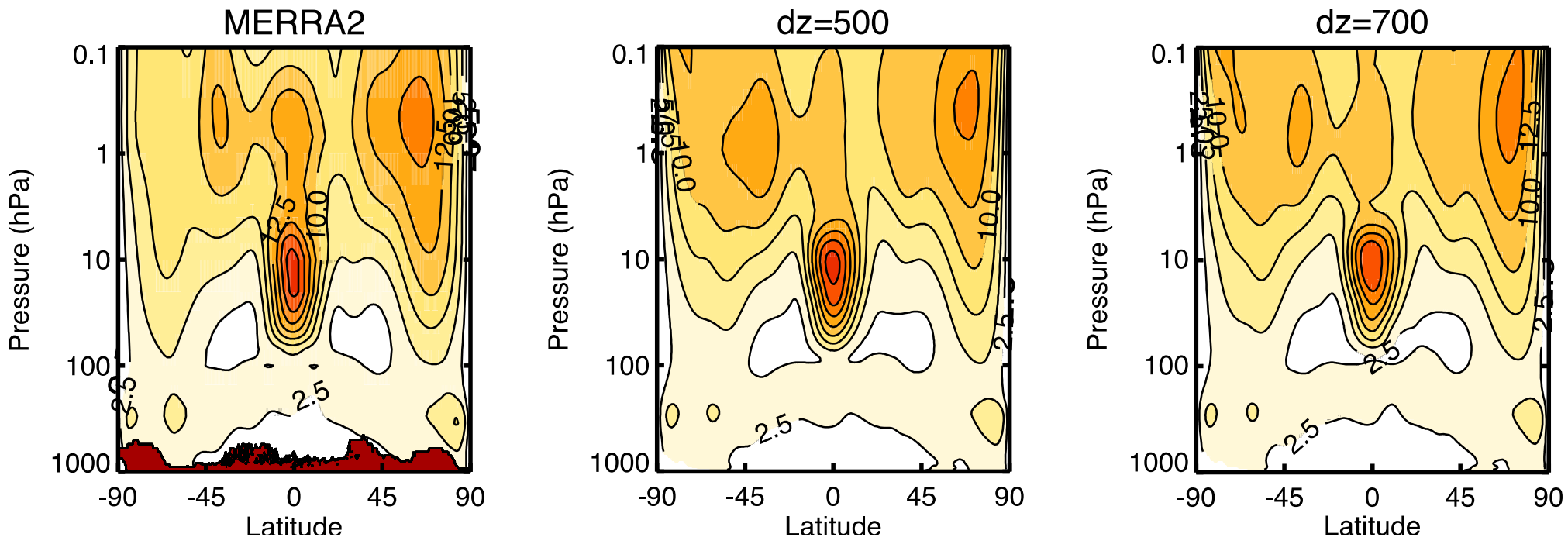


SH winter zonal mean zonal wind

← Climatology

← Difference from ERA5

Not much difference elsewhere



MERRA2

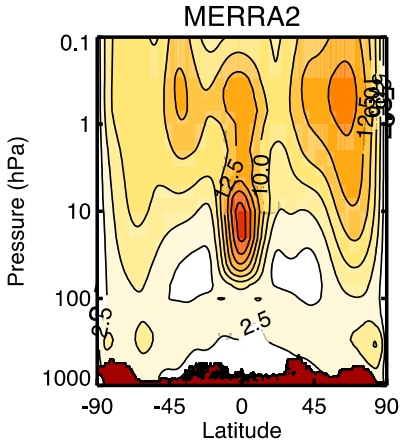
dz=500

dz=700

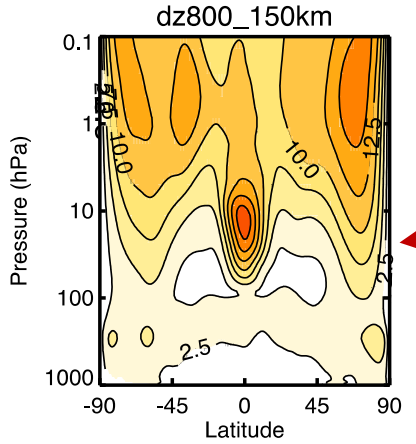
Standard deviation of daily zonal mean zonal wind variability

chopping investigations

- Ran four of the cases with the lid chopped off at 80km. No substantial differences found below 1hPa.

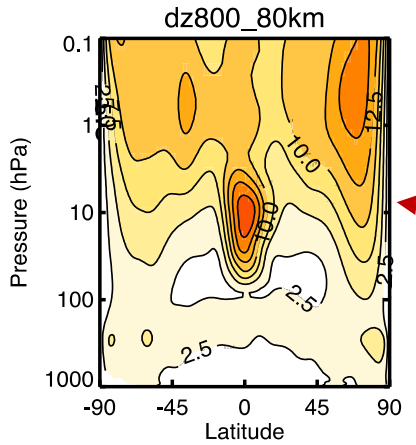


Standard deviation of daily de-seasonalized zonal mean zonal wind

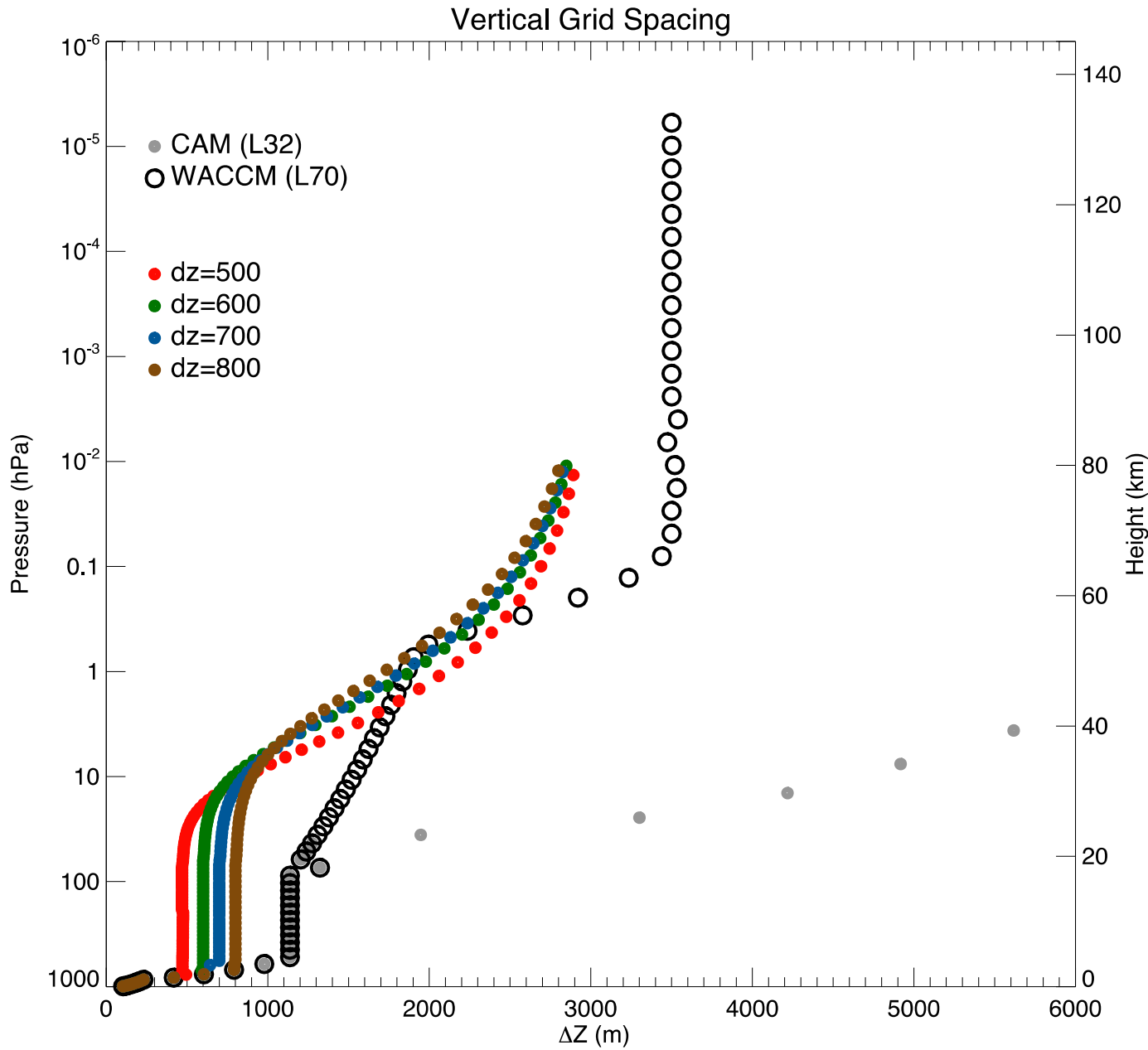


150km top

dz=800

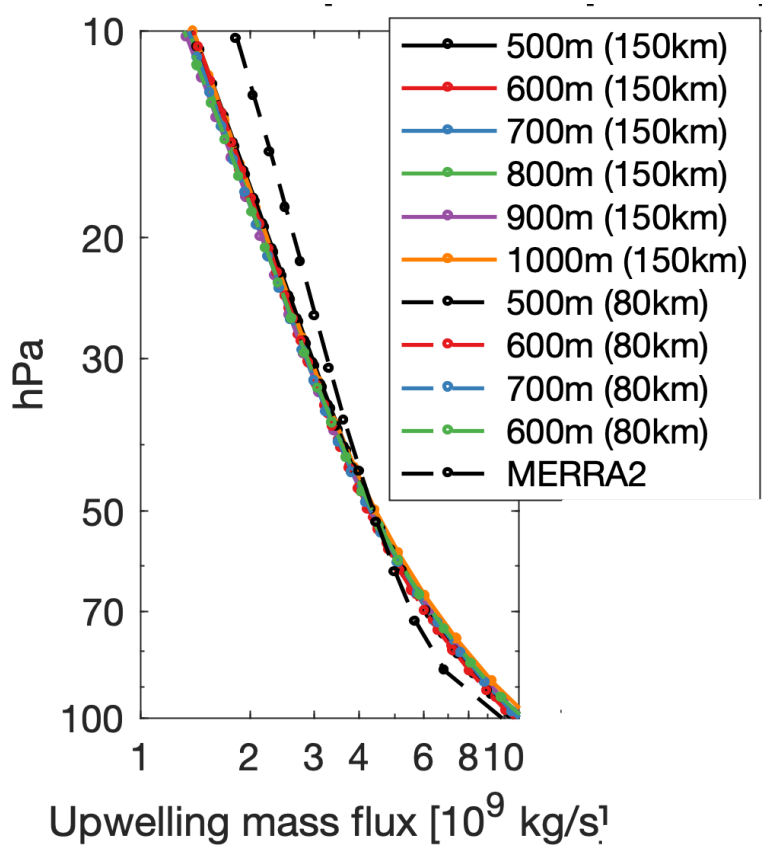


80km top



chopping investigations

- Ran four of the cases with the lid chopped off at 80km. No substantial differences found below 1hPa.



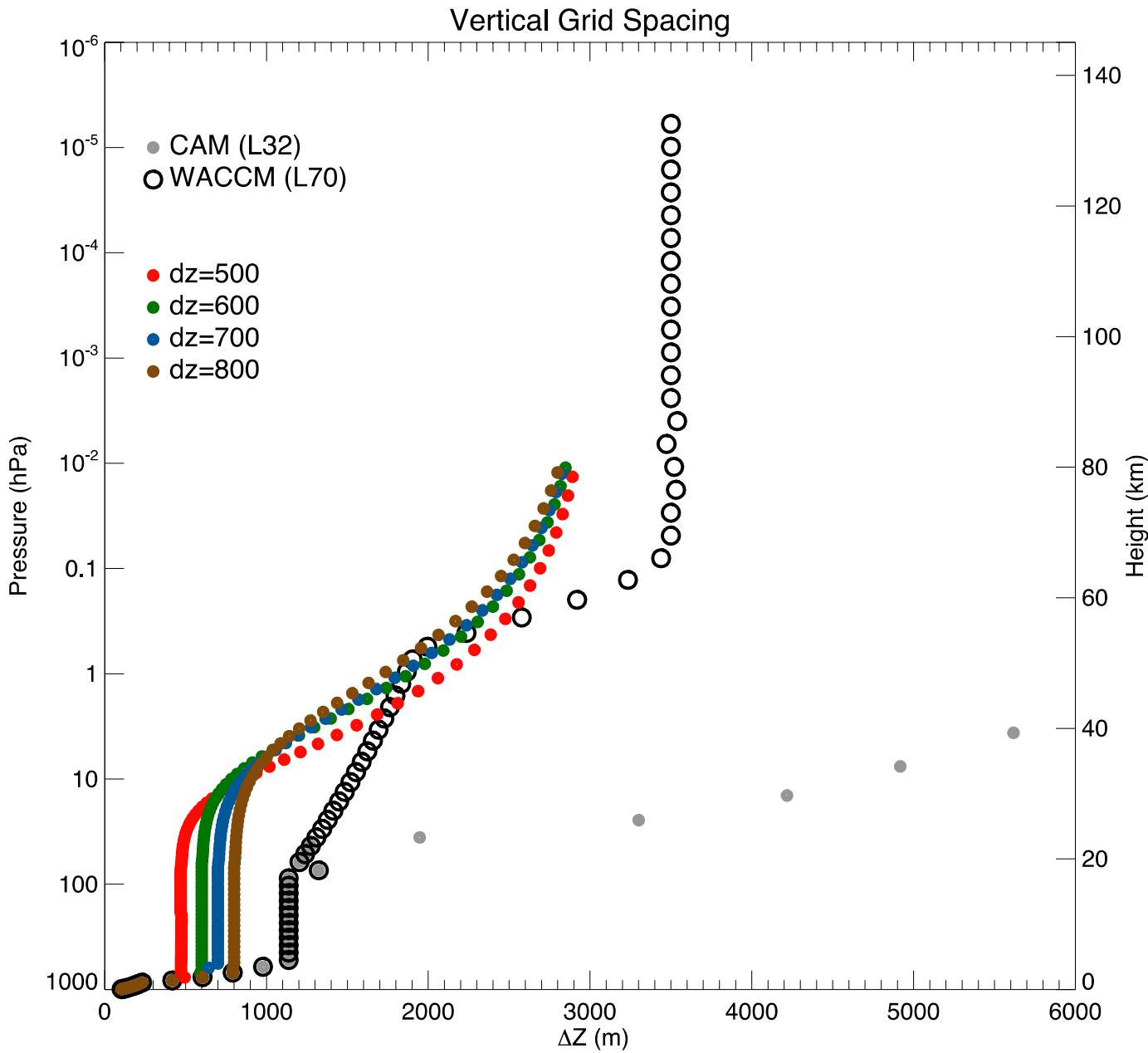
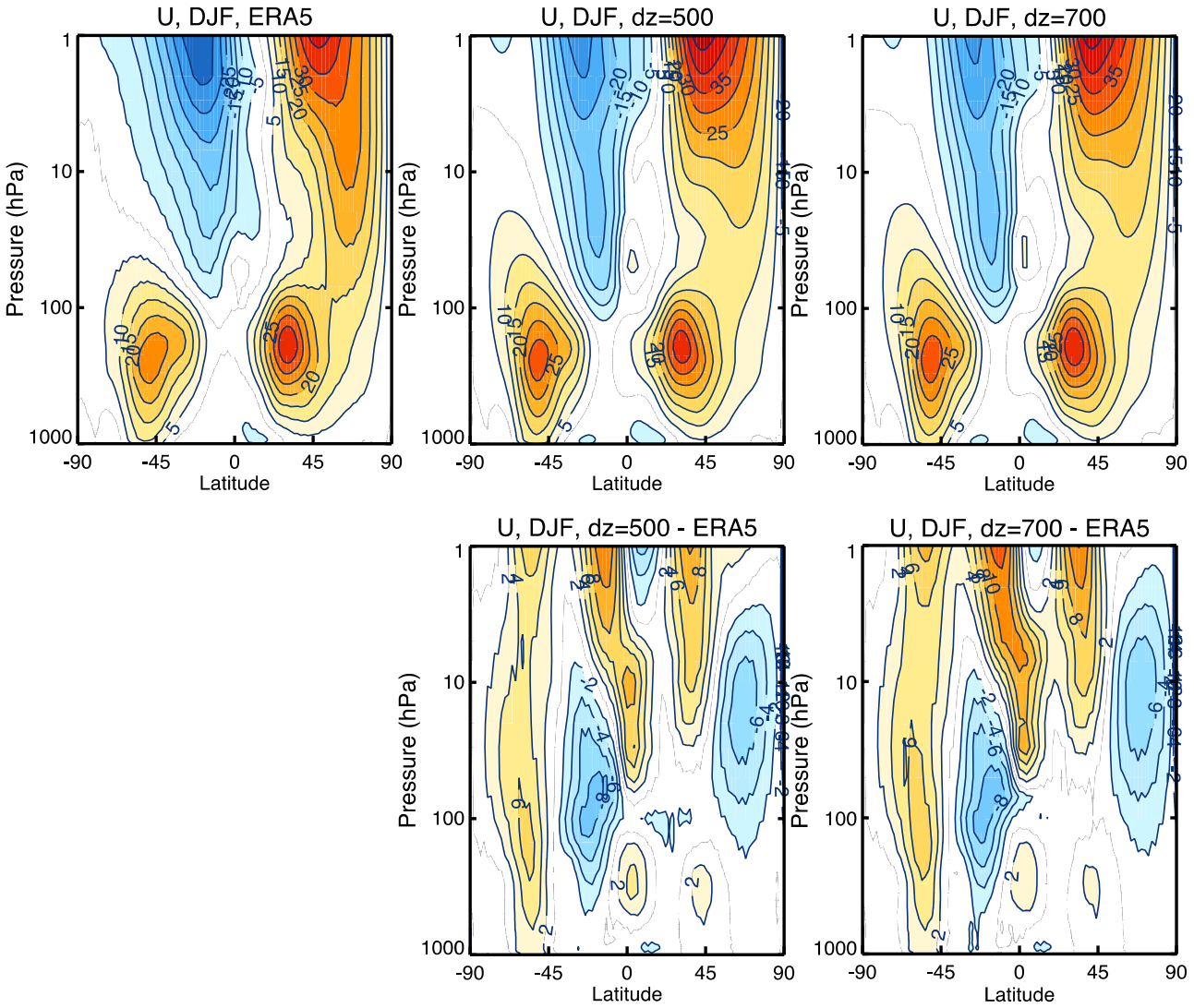


Figure credit: Nick Davis

Not much difference elsewhere

ERA5 dz=500 dz=700

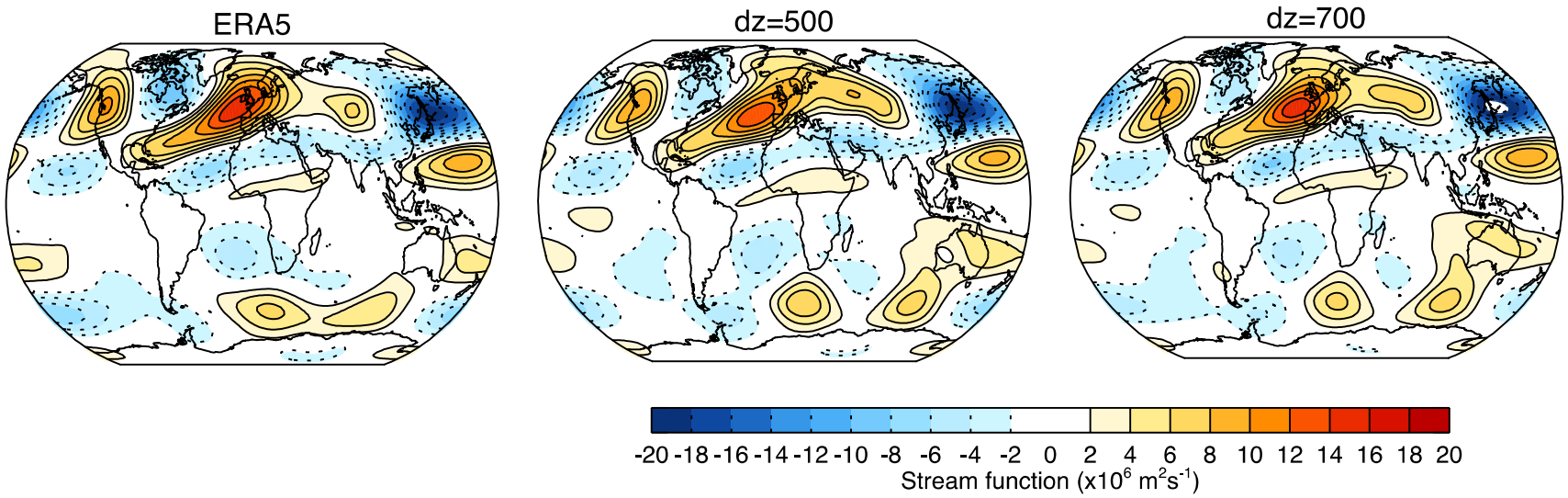


NH winter zonal mean zonal wind

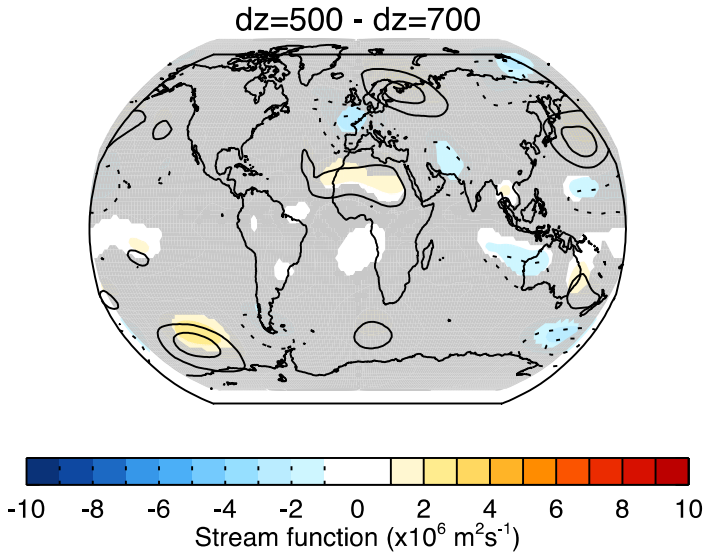
Climatology

Difference from ERA5

Not much difference elsewhere



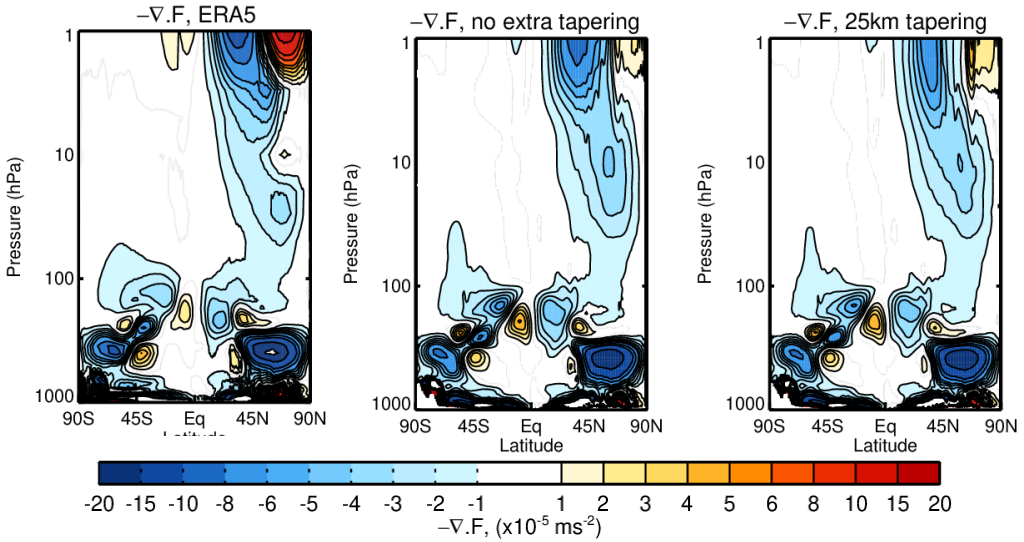
500hPa eddy stream function, DJF



Gray = not statistically significant difference based on the distribution of differences among CESM1 LENS members

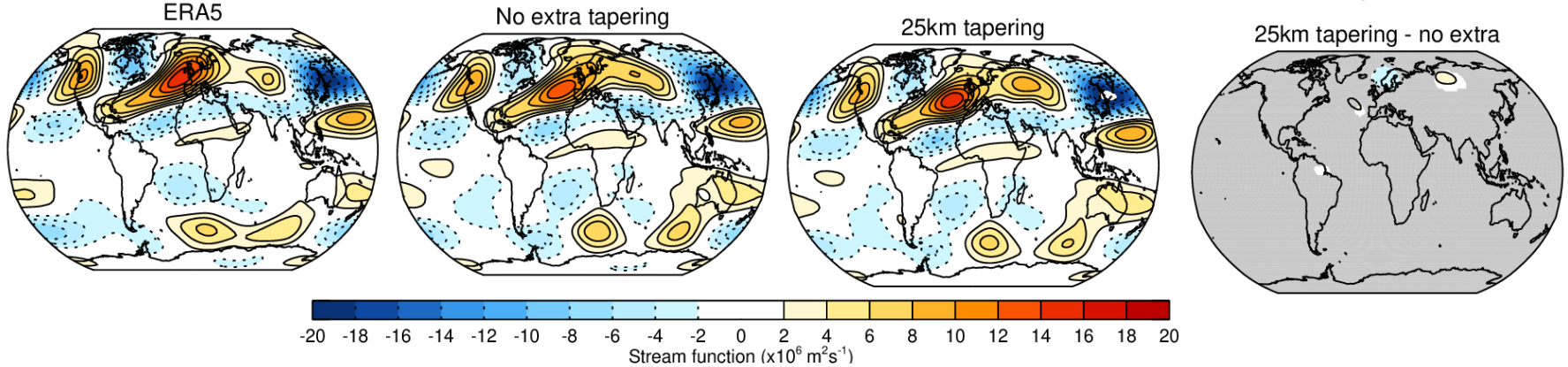
No drastic influence on other things found yet

ERA5 | No extra tapering | Tapering at 25km



Zonal mean zonal wind tendency due to resolved wave drag, DJF

ERA5 | No extra tapering | Tapering at 25km | Tapering influence



500hPa eddy stream function, DJF

Gray = not significant at the 95% level