WORKSHOP ON 18–21 NOV 2019

Stratospheric predictability and impact on the troposphere

Welcome

ECMWF

#StratosphericWS

Causes and fixes for stratospheric temperature biases in IFS and their impact on predictability

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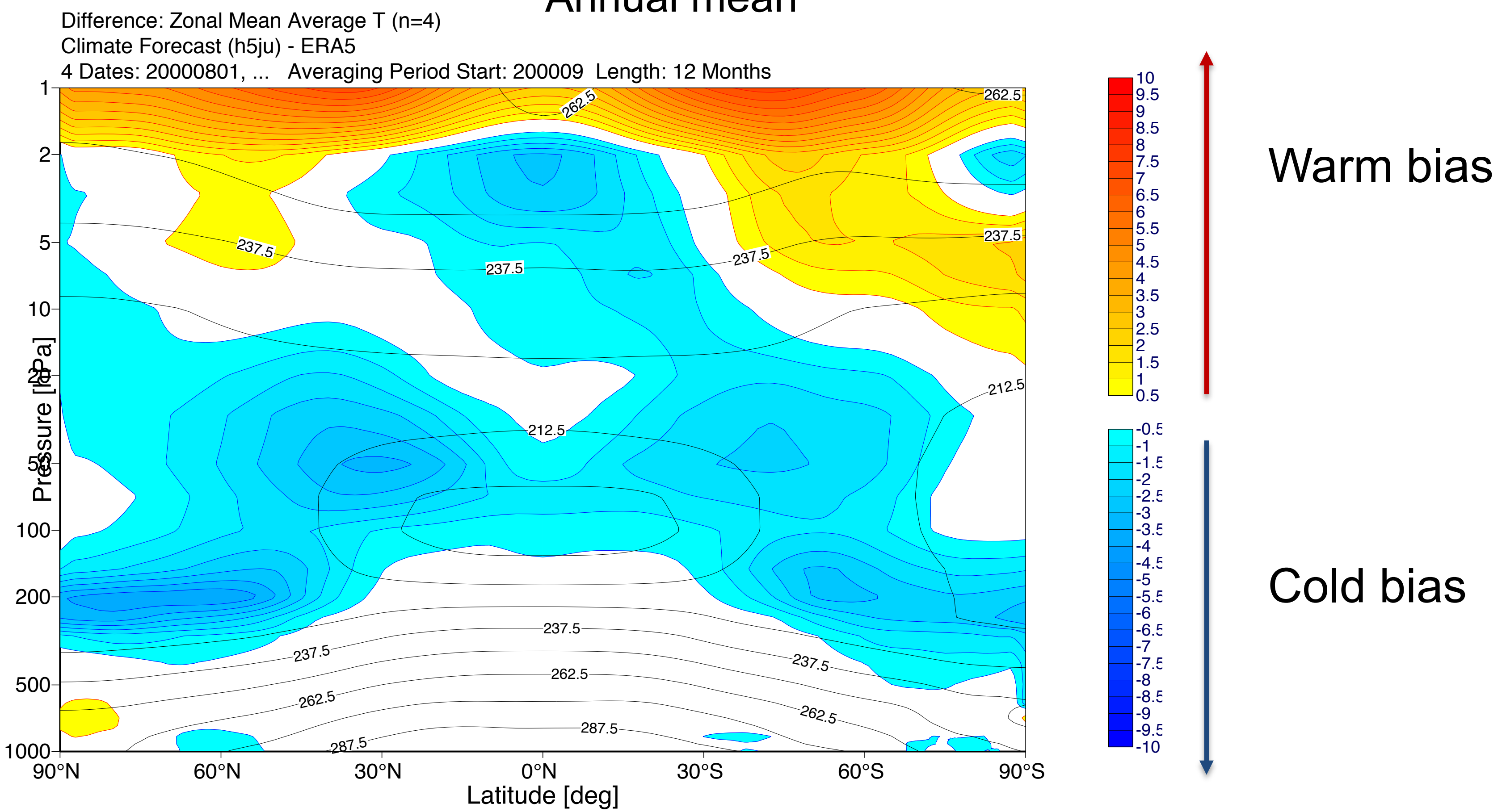
20 November 2019

Stratosphere in IFS: Temperature biases in 46R1 against ERA-5

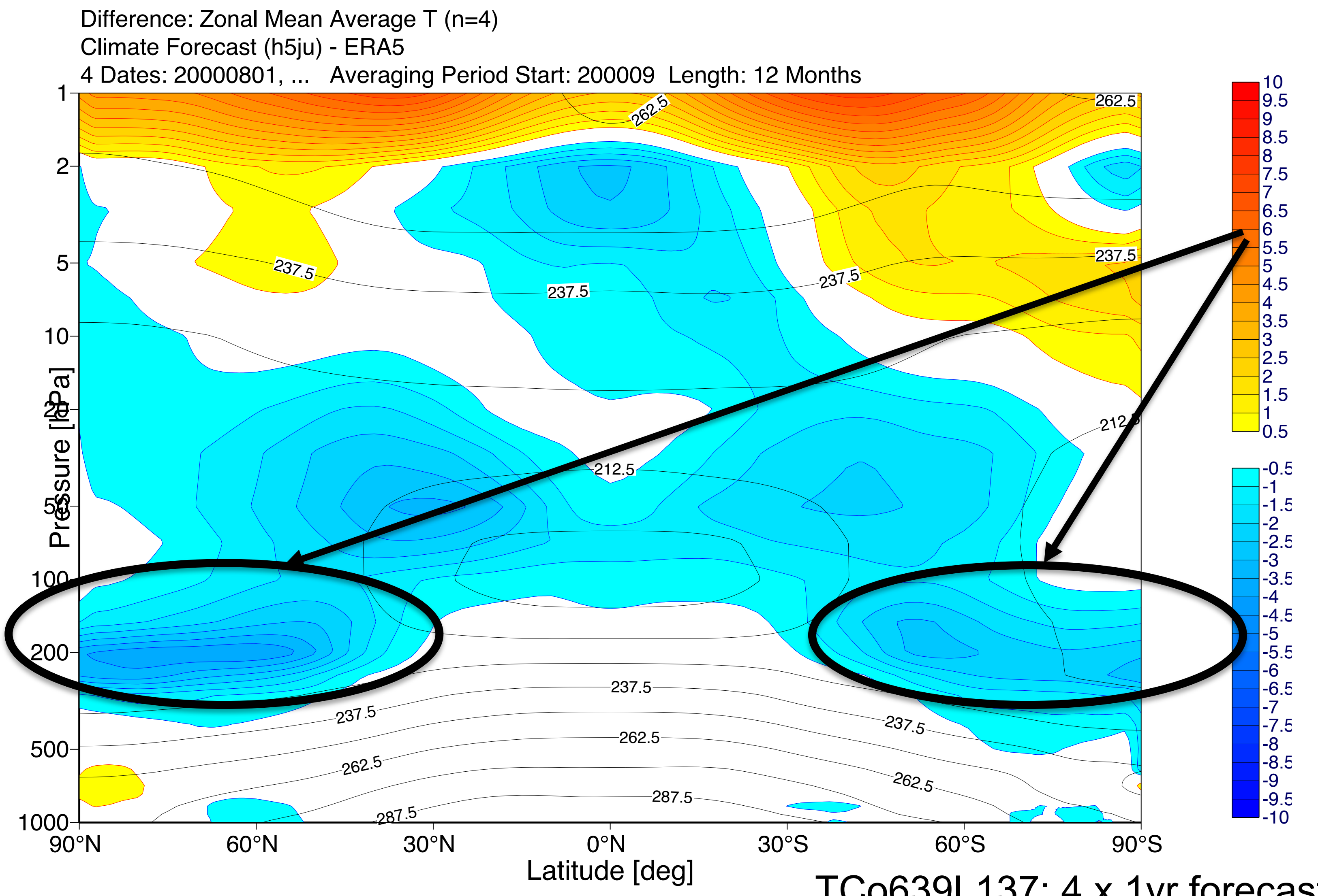
Annual mean



Biases even worse for older operational cycles!

TCo639L137: 4 x 1yr forecasts

Stratosphere in IFS: Temperature biases in 46R1 against ERA-5

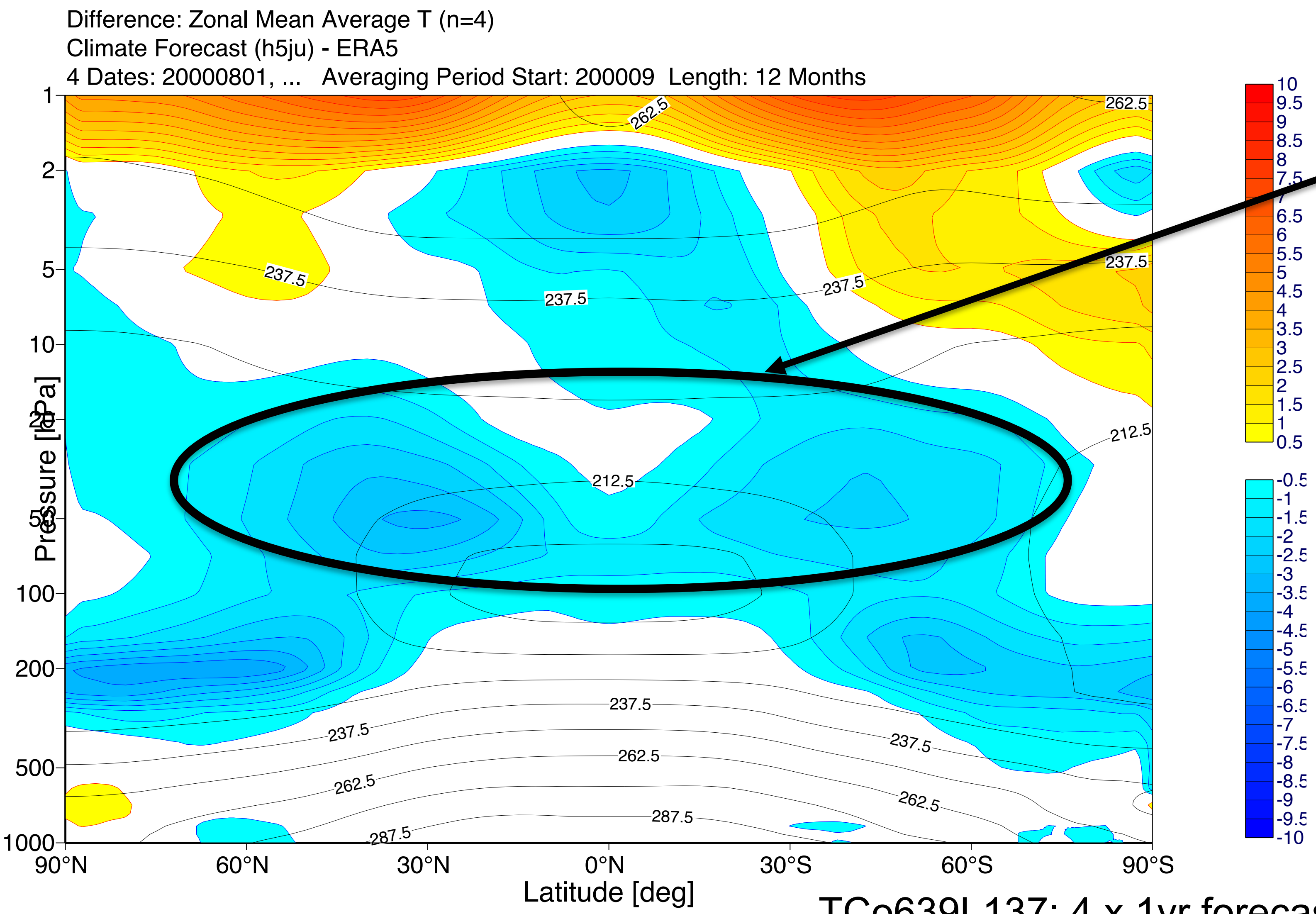


TCo639L137: 4 x 1yr forecasts

1) Cold polar lowermost stratosphere (LMS) bias of ~5K, maximizing in the Northern Hemisphere summer.

Related to excessive water vapor and too much longwave cooling in this region (Stenke et al., 2008).

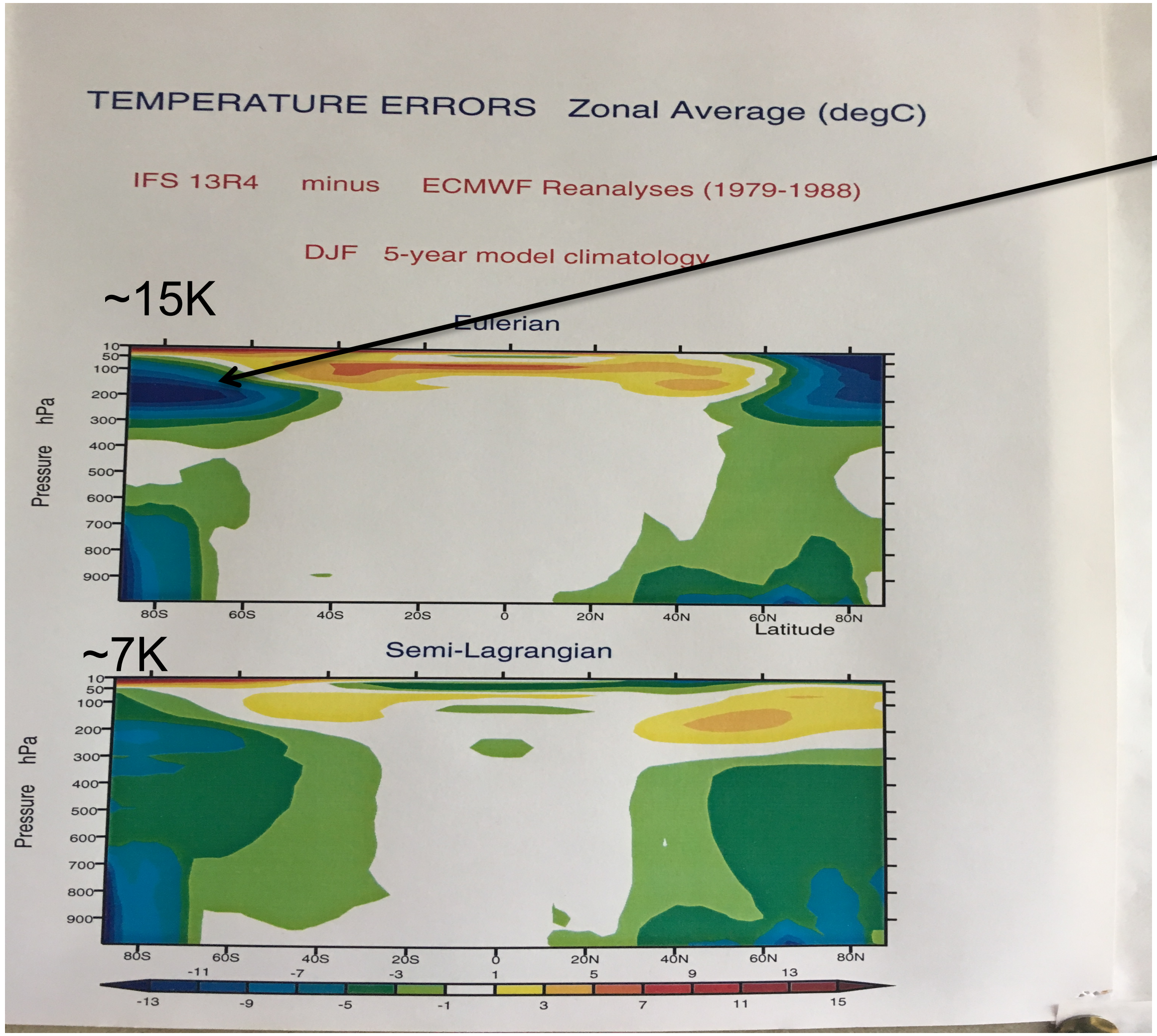
Stratosphere in IFS: Temperature biases in 46R1 against ERA-5



2) Cold mid- to lower stratosphere bias of ~3K. Worse at higher horizontal resolution.

TCo639L137: 4 x 1yr forecasts

1) Cold polar LMS bias: Historical perspective



Mike Blackburn’s office wall

Cold bias was present in IFS already in 1995. Bias was alleviated at T42L31 resolution by switching to **semi-Lagrangian dynamics** (SL) → water vapor advection better in SL scheme.

The cold tropopause bias is common to many models (e.g., Boer et al. 1992):

It is rather remarkable that all models simulate temperatures which are too cold in regions 1, 3, and 5 given the various numerical methods, resolutions, and physical parameterizations used in the different models. Such common model deficiencies are termed “systematic,” “tenacious,” “insensitive,” “universal,” or “essential.” Their existence suggests that all models suffer from a common deficiency in some aspect of their formulation.

1) Cold polar LMS bias: What else controls it?

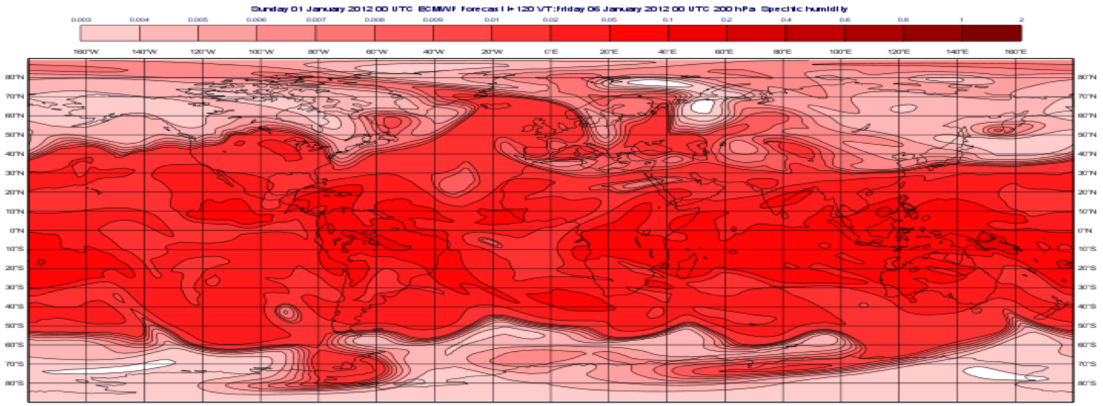
- Switching off **quasi-monotone filter** and **higher order SL interpolation** in the IFS at low horizontal resolutions < TCo255 (Diamantakis, 2014).

- Modest **increase in the vertical resolution** at low horizontal resolution (Pope et al., 2000).

- Move to **isentropic coordinates** in the stratosphere (Chen & Rasch, 2012).

Snapshot of 200hPa humidity at T+120
IFS TL255 (80km resolution)

More diffusive (linear interp. for advection of humidity)



Less diffusive (turn off quasi-monotone filter)

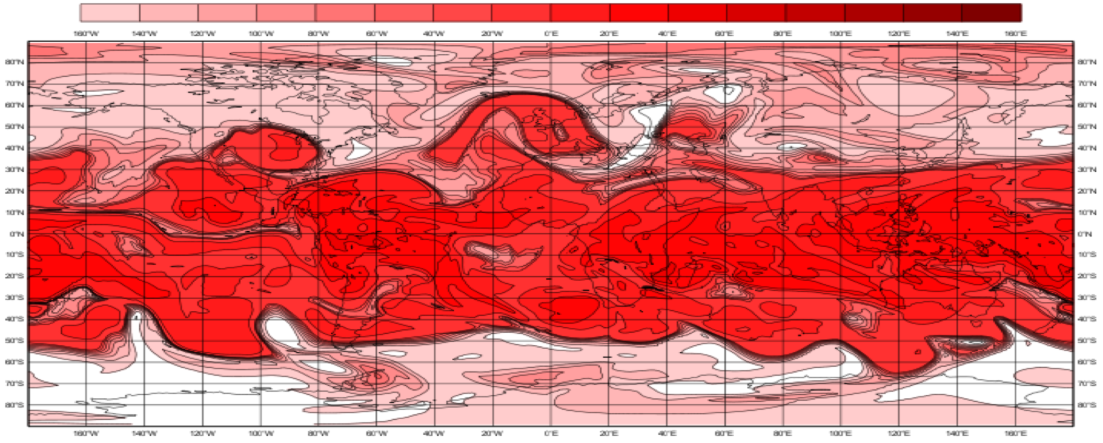
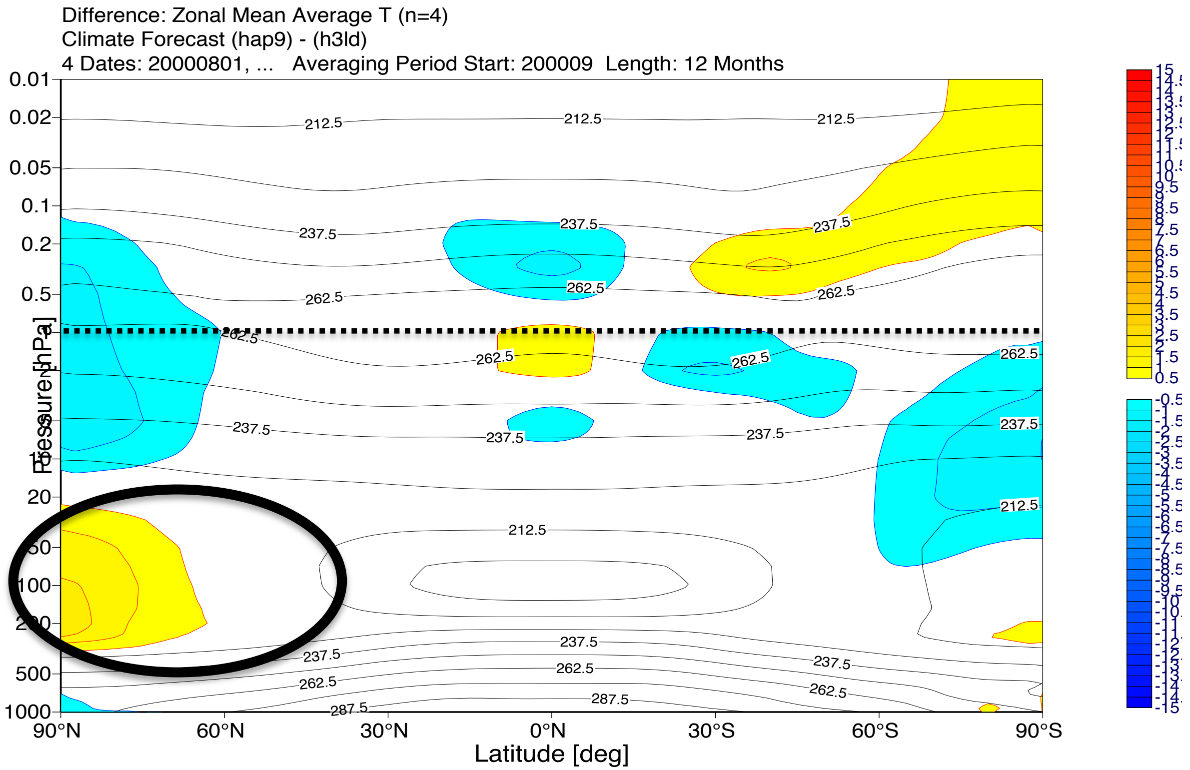


Figure courtesy: Richard Forbes

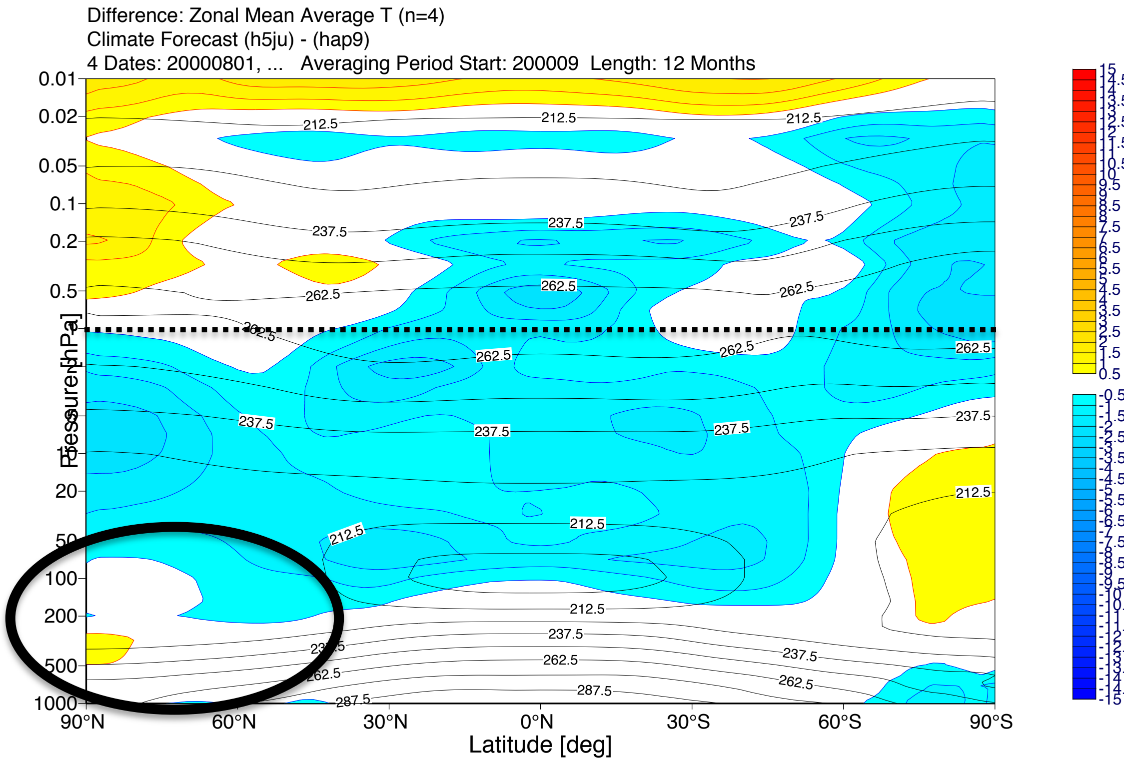
1) Cold polar LMS bias: Resolution sensitivity in IFS

- For horizontal resolutions higher than TCo319 (36km) **not much improvement**.
- For **vertical resolutions** higher than 400m (or L137) also no improvement.

TCo319-TL255 (36km-80km)



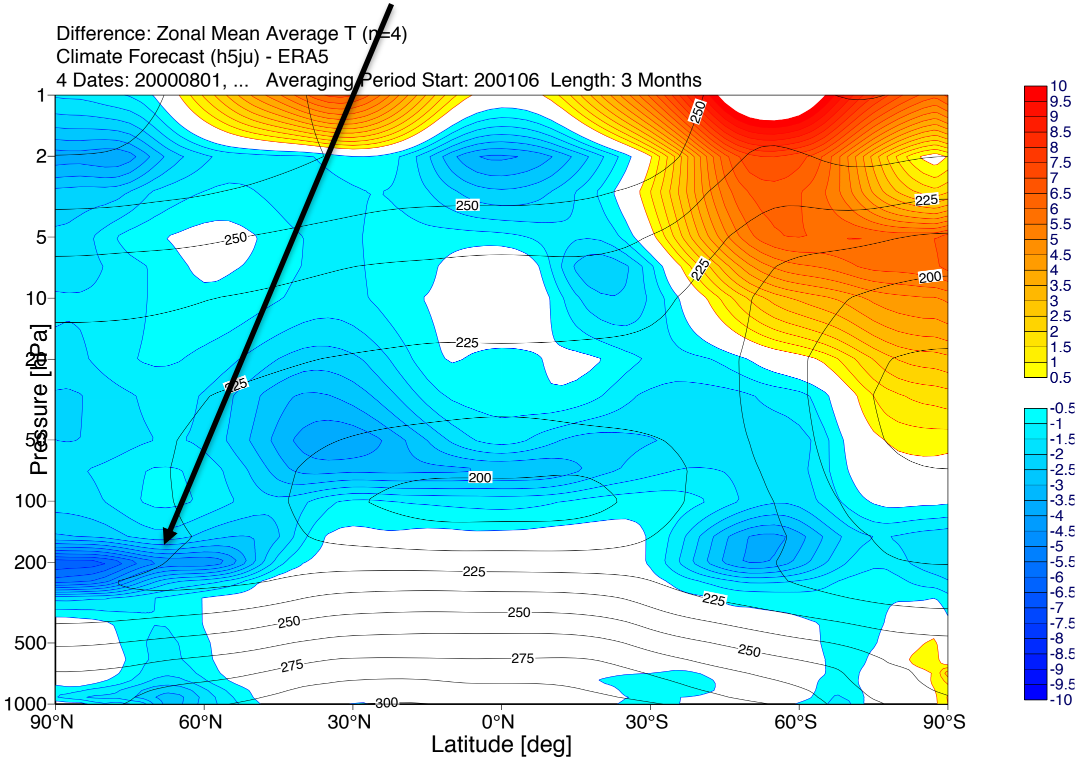
TCo639-TCo319 (18km –36km)



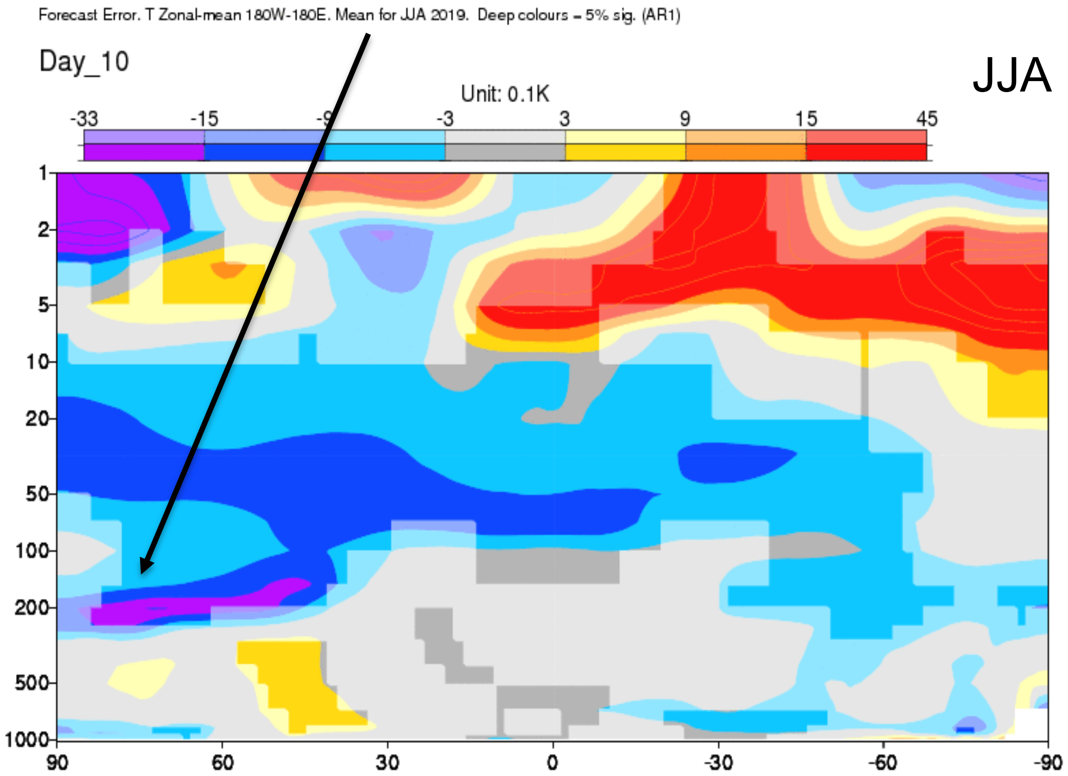
1) Cold polar LMS bias: Why still there at high resolution and in medium-range forecasts?

- At 9-18km horizontal resolution and 300m vertical resolution, hygropause gradients should be well resolved and numerics much less diffusive.

TCo639L137 (18km horiz. res.)



TCo1279L137 (9km horiz. res.)

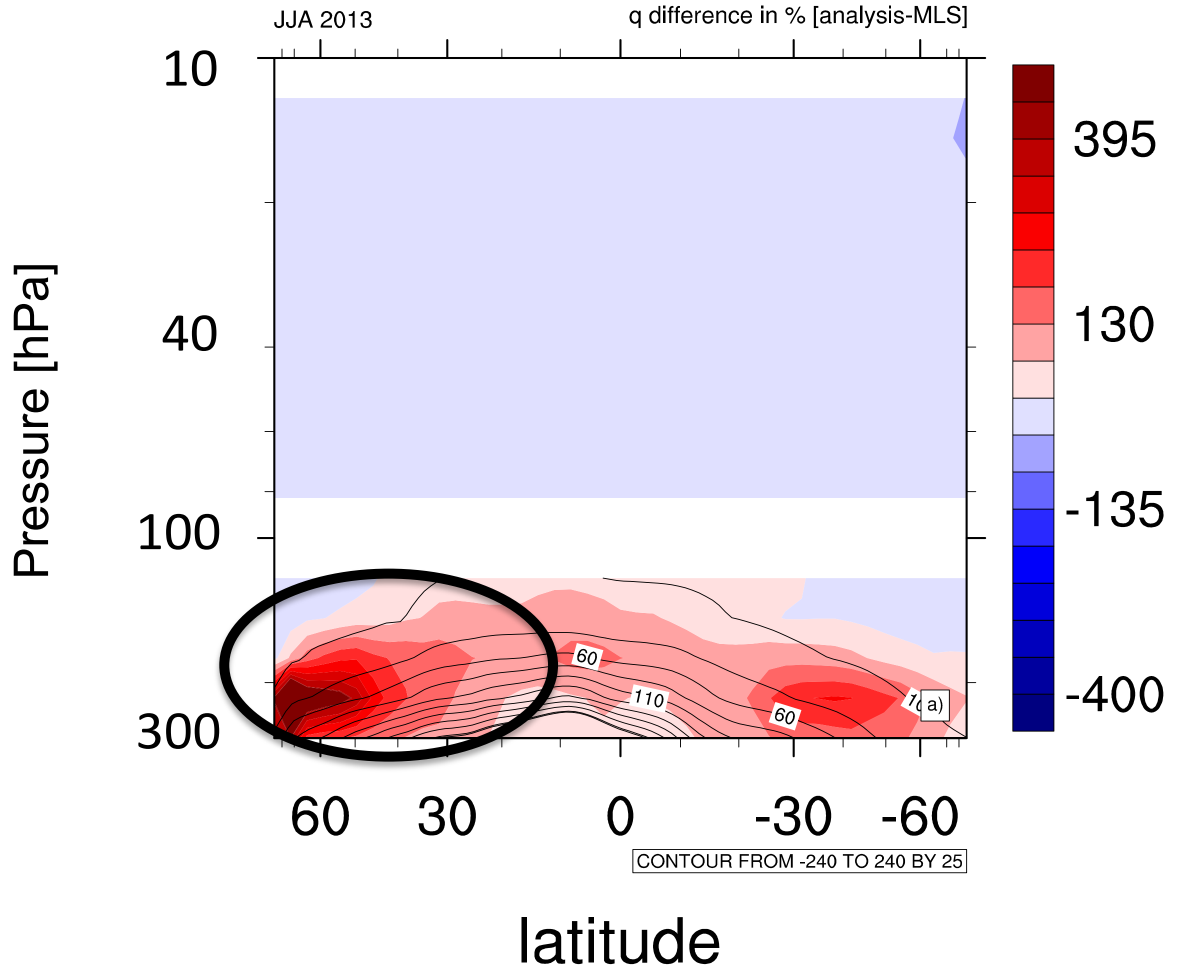


1) Cold polar LMS bias: Analysis too moist

- ECMWF analysis **too moist** in the lowermost polar stratosphere when compared to Microwave Limb Sounder (MLS).

- Similar conclusions from comparison to aircraft observations (Dyroff et al., 2015) and to high vertical resolution **Gimballed Limb Observer for Radiance Imaging of the Atmosphere** (GLORIA) observations (see talk by Wolfgang Woiwode).

ECMWF analysis - MLS



Shepherd et al. (2018, TM)

1) Cold polar LMS bias: Impact of fixing the bias on the troposphere

- Artificially reducing specific humidity seen by the radiation scheme eliminates the bias.
- Removing the bias improves **extended range** forecast skill scores (RPSS) in Europe in the troposphere in weeks 2-3.

T: fixed-control

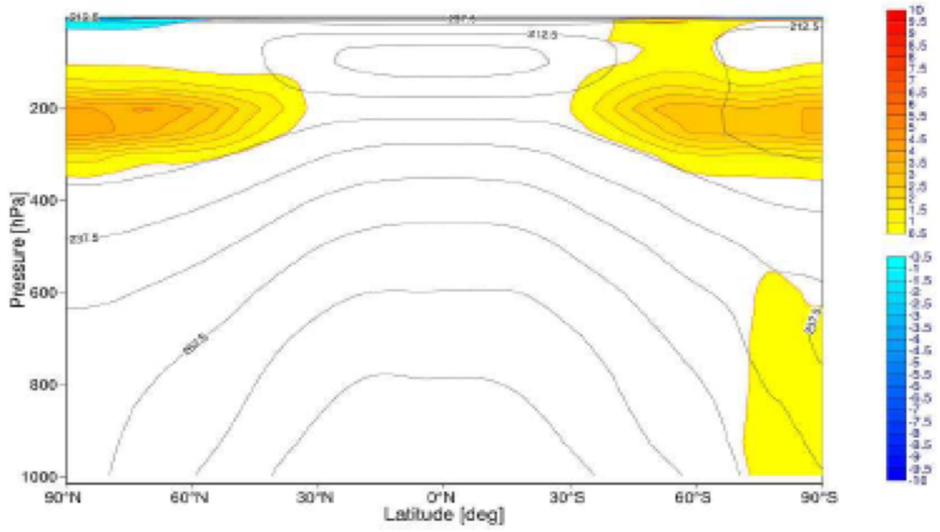


Figure courtesy: Robin Hogan

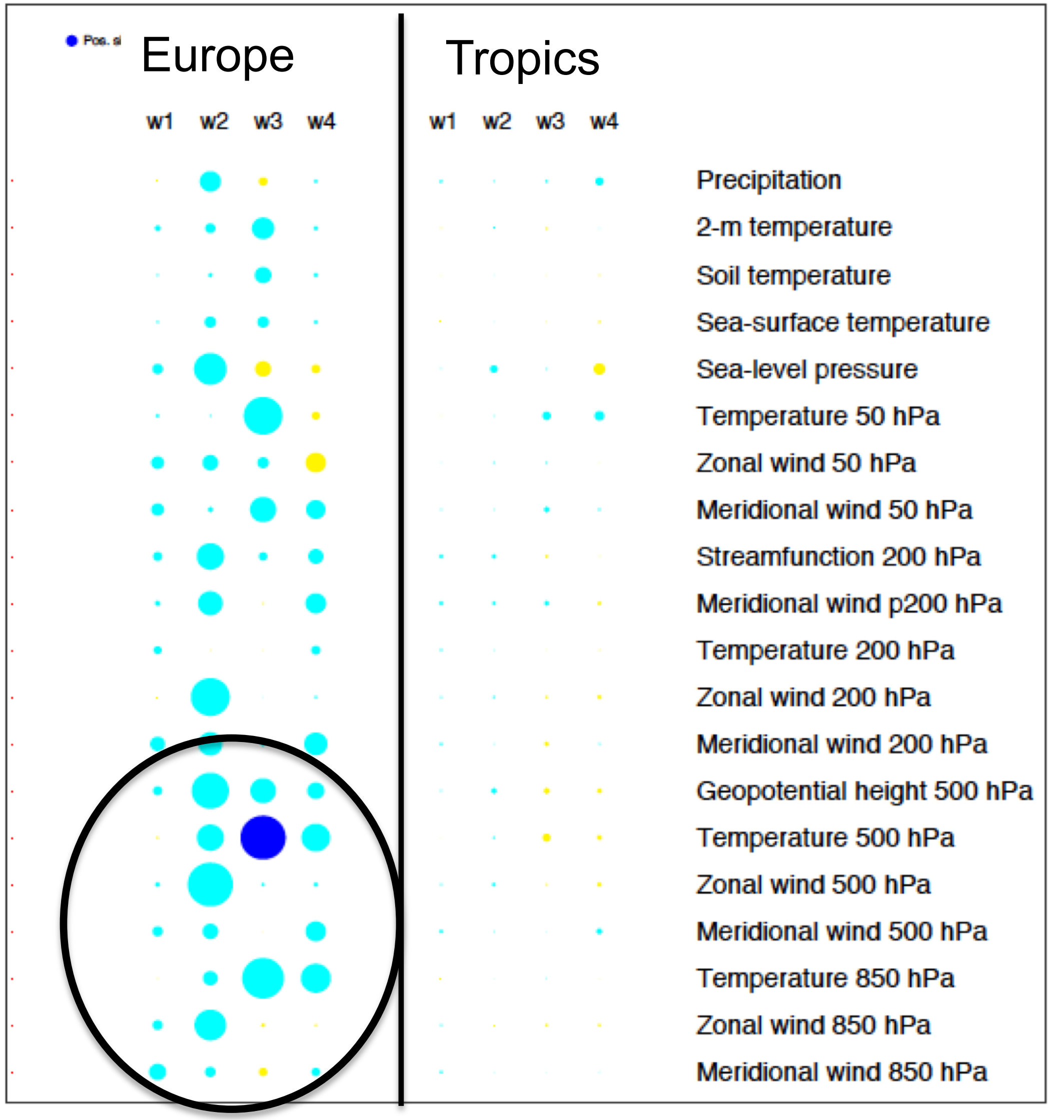
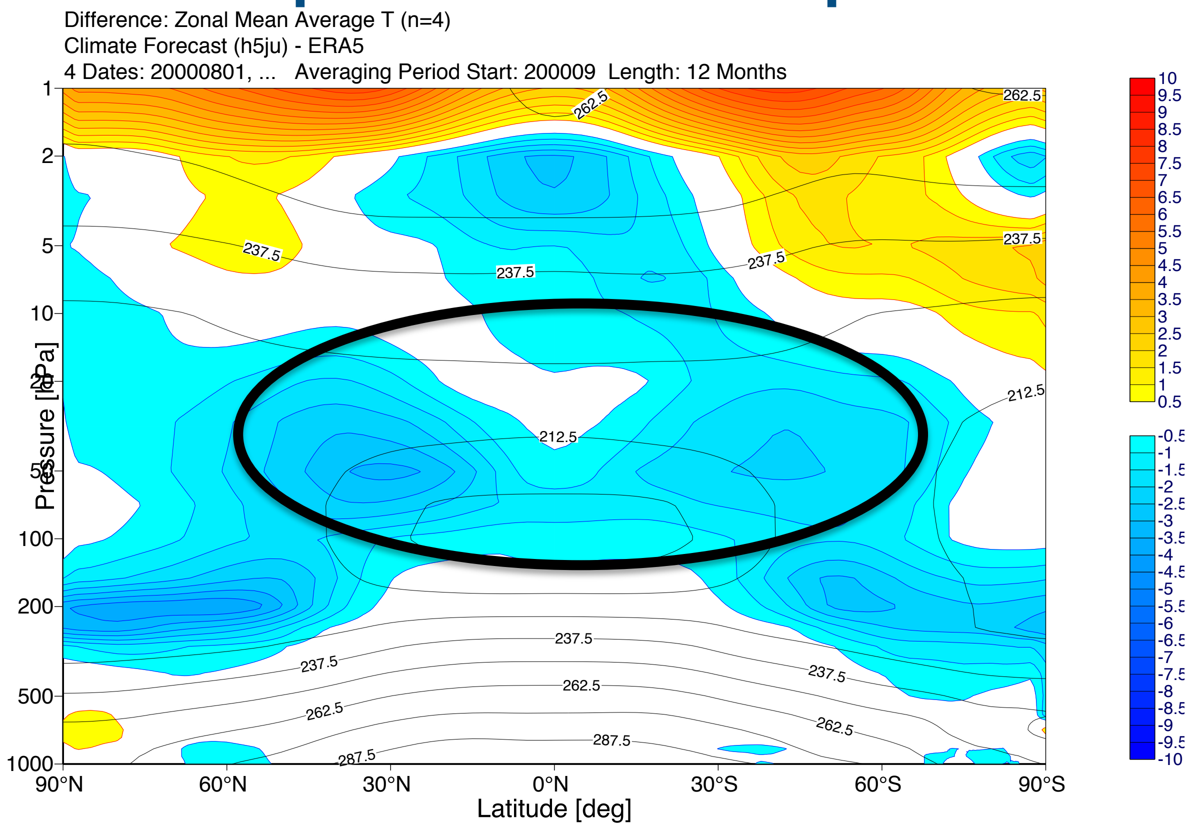


Figure courtesy: Frederic Vitart

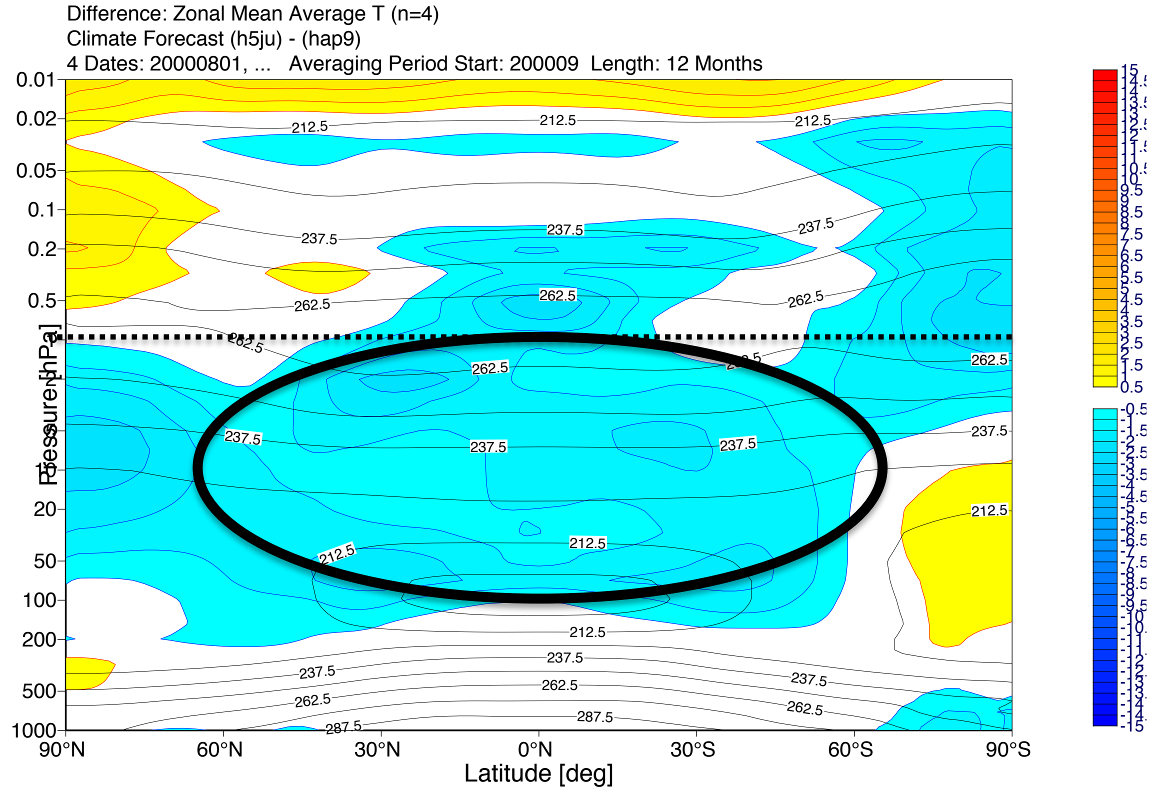
1) Cold polar LMS bias: Summary

- A cold polar lowermost stratosphere bias exists in many global models.
- Present in the IFS at **all resolutions** and **all forecast lead times**.
- An overestimate of water vapour in the lowermost stratosphere leads to too strong LW cooling.
- Reasons for the temperature and water vapour bias:
  - **Analysis too moist** (due to lack of constraint from observations): Affects medium-range
  - **Water vapour leakage** from moist troposphere to dry stratosphere
- Fixing the bias has a positive impact on tropospheric predictability over Europe in extended-range forecasts.

Stratosphere in IFS: Temperature biases in 46R1 against ERA-5



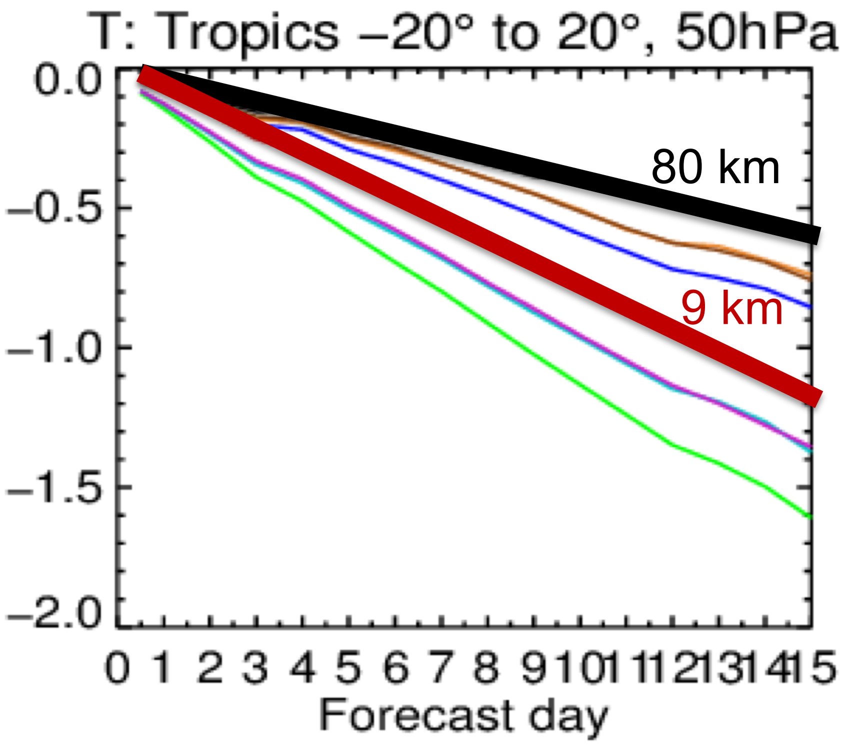
TCo639-TCo319 (18km –36km)



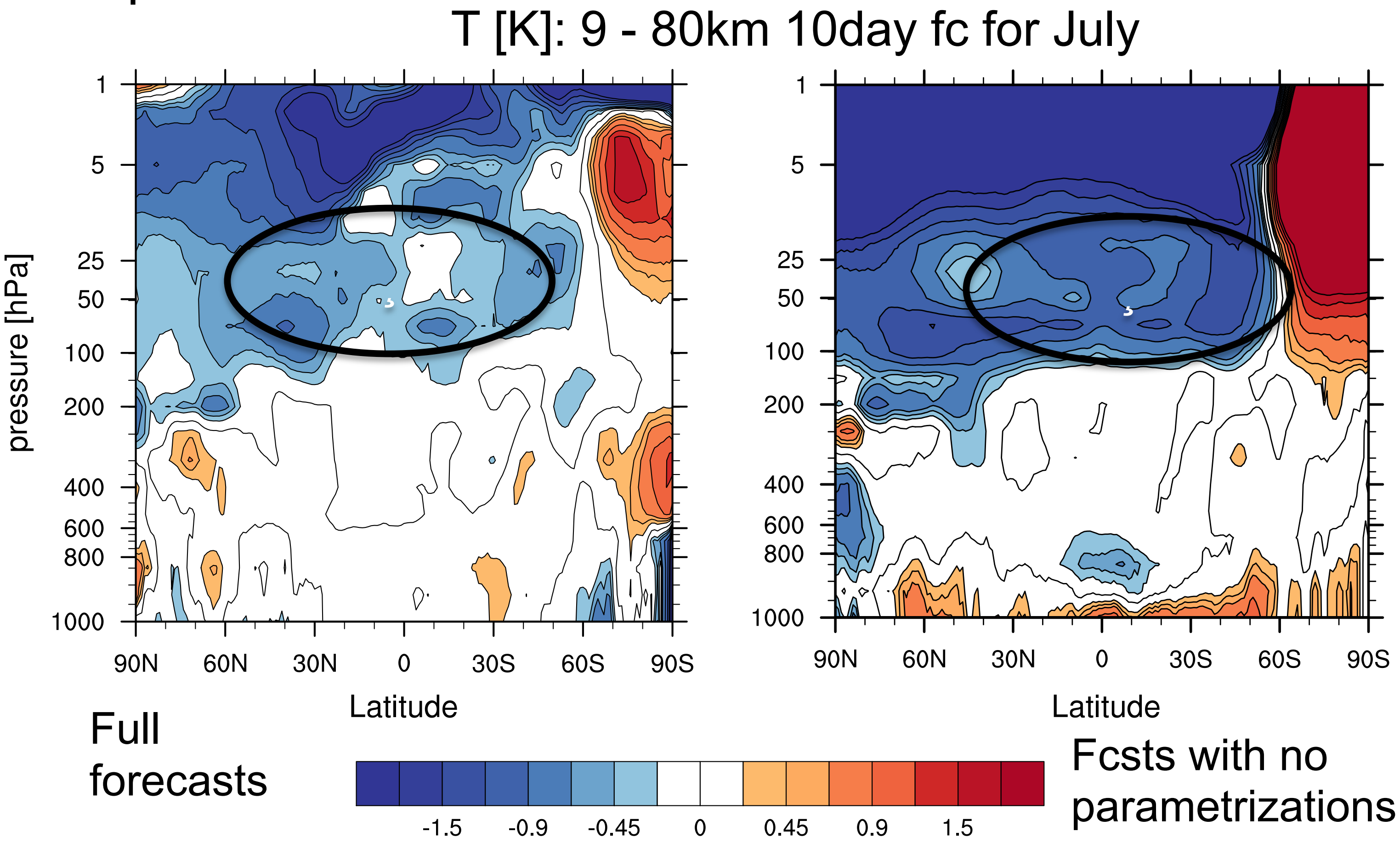
2) Cold mid- to lower stratosphere bias: Horizontal resolution sensitivity

- Stratosphere cools in the global mean with increase **in horizontal resolution →** biases **worse**. Affects all forecast ranges, from medium to seasonal.

- **Resolved dynamics** the culprit. Forecasts with no physical parametrizations, show the same horizontal resolution dependence.



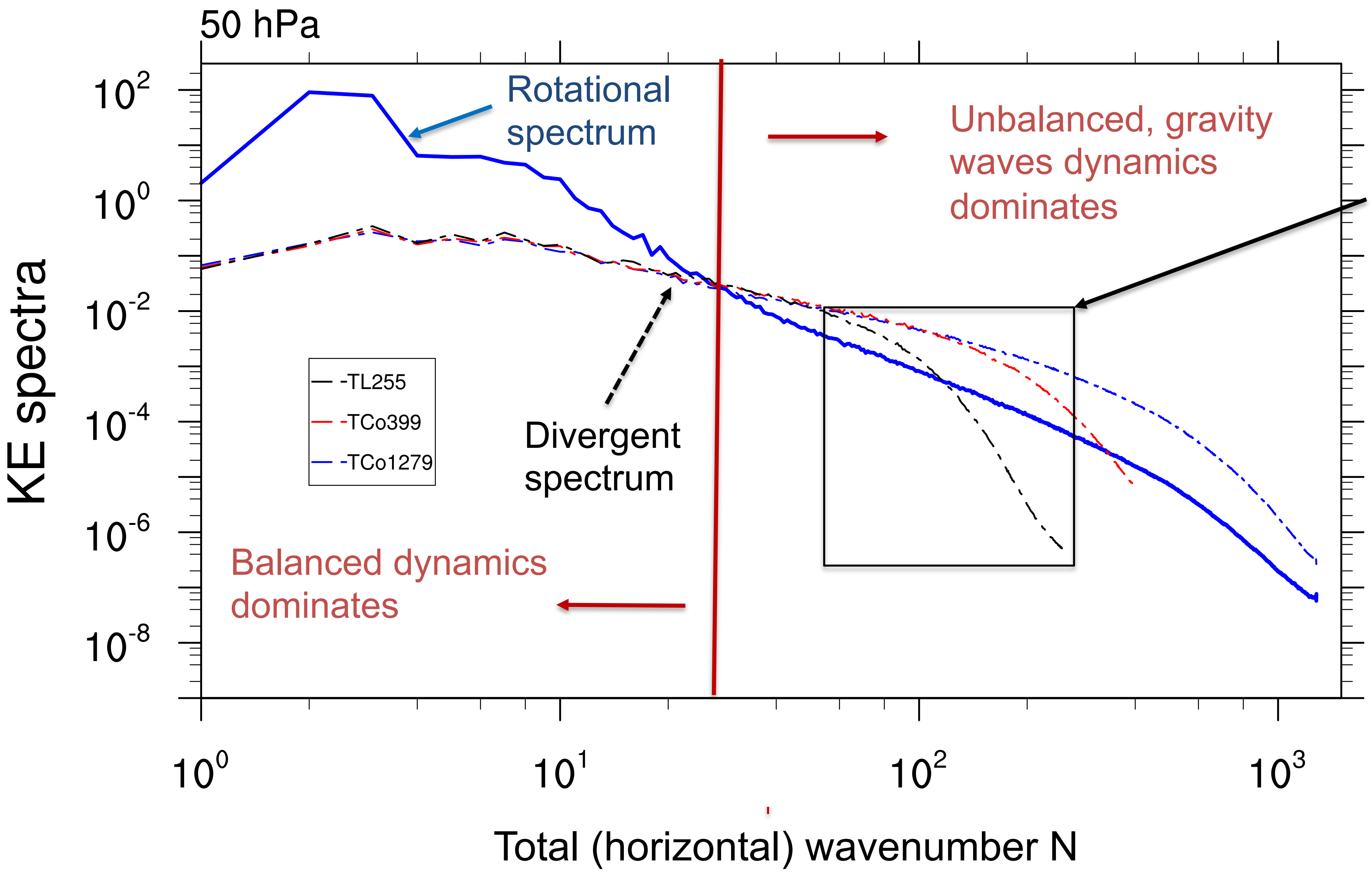
Verification against analysis



Full forecasts

Fcsts with no parametrizations

2) Cold mid- to lower stratosphere bias: Kinetic energy spectrum

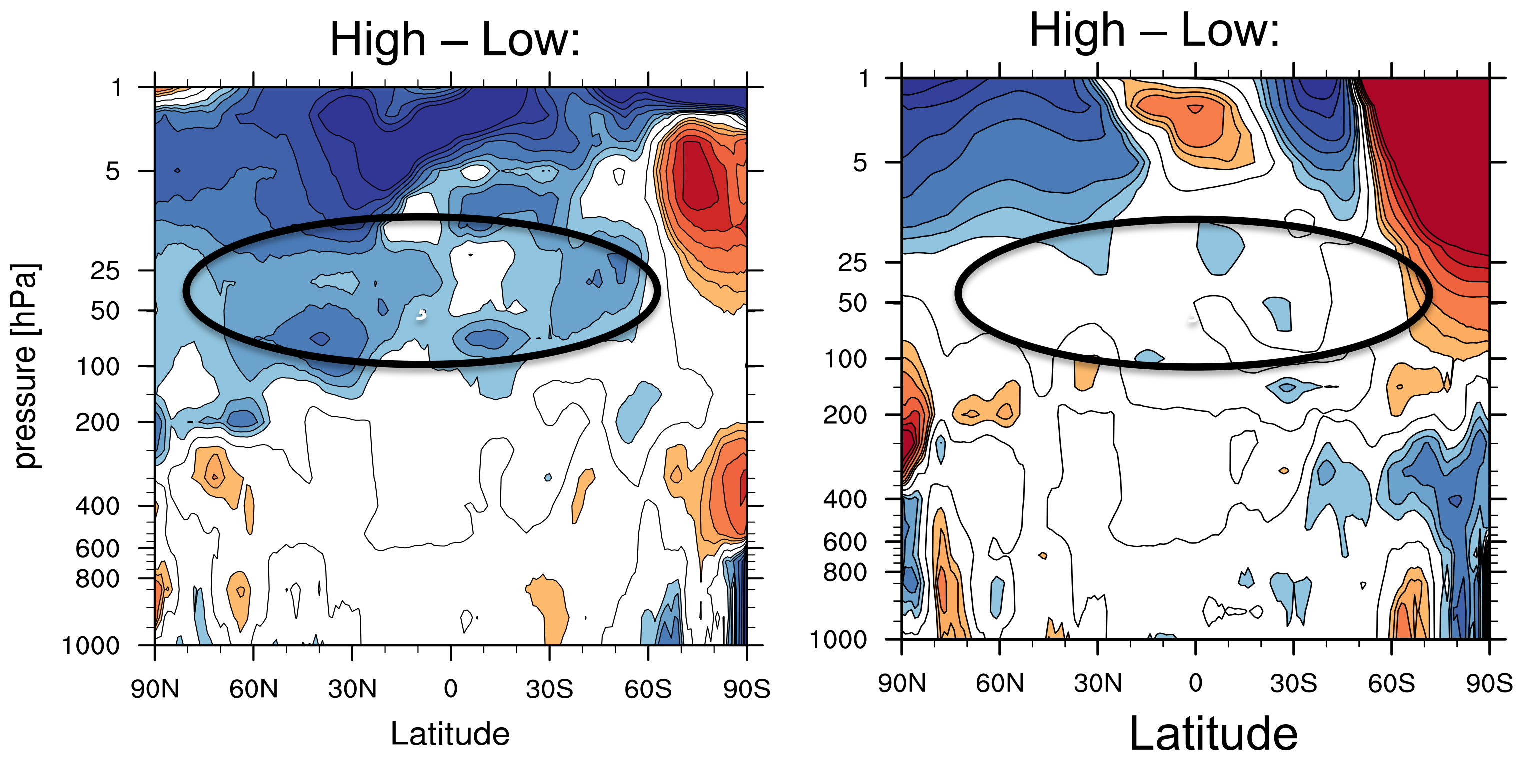


At higher horizontal resolution, more energy in the **divergent** part of the spectrum → more of **gravity wave** spectrum is resolved.

2) Cold mid- to lower stratosphere bias: Role of gravity waves

- **Filter** gravity waves out → reduces horizontal resolution sensitivity in the mid- to lower stratosphere.

- Total wavenumbers **40<N<300** (wavelengths:100-1000km) cool at high TCo1279 horizontal resolution. Such scales are well resolved → **not** due to truncation errors in the horizontal direction.



Average over 31 forecasts in July at 10-day lead time.

Polichtchouk et al. (2019, TM)

2) Theoretical considerations: horizontal to vertical resolution aspect ratio

- Aspect ratio relevant for balanced **quasi-geostrophic** dynamics (Lindzen & Fox-Rabinovitz, 1989) and **inertia-gravity** wave dispersion relation

$$\frac{\Delta z}{\Delta x} \sim \frac{f}{N} \qquad \Delta z \sim 200 \text{ m}$$

Other arguments:

- **Stratified turbulence** develops shear layer of thickness (e.g., Waite & Bartello, 2004)

$$L_b \equiv 2\pi U / N \longrightarrow$$

In the stratosphere, L_b ~ 1km, need Δz ~200m to resolve properly.

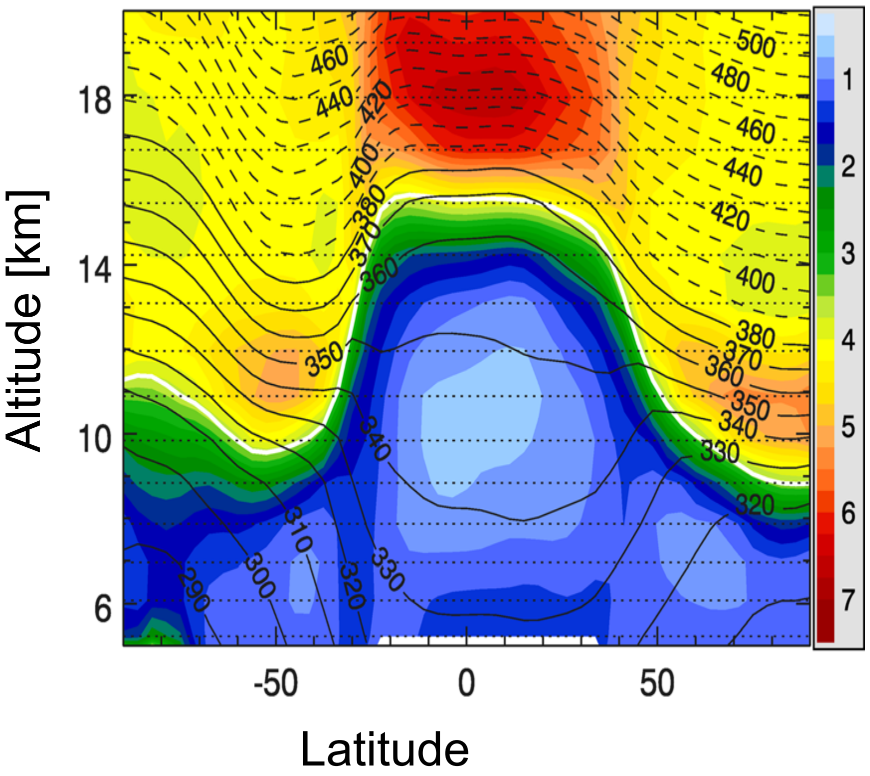
- **Gravity wave propagation** through the stratosphere:

Dispersion relation (medium-frequency): $|\lambda_z| \sim |c-U|/N$

2) Theoretical considerations: Gravity wave propagation

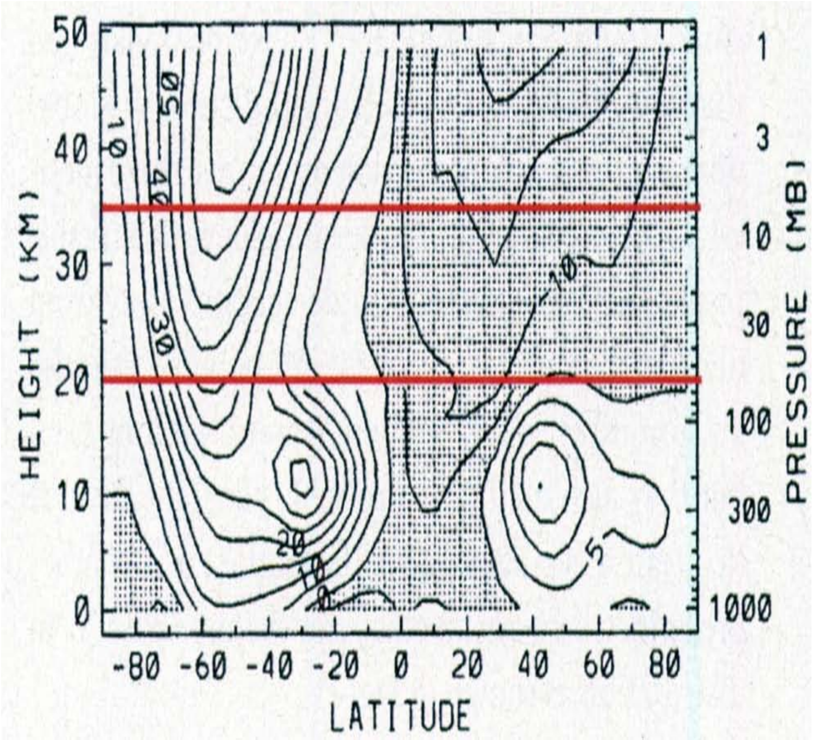
- Spatial distribution of resolution sensitivity likely a result of background conditions.
  Large **increase in N** and small changes to **U** in the tropical lower stratosphere.

N^2, climatology for July



Birner (GRL, 2006)

U, climatology for July



Randel (NCAR Tech. memo,1992)

$|\lambda_z| \sim |c-U|/N$

- Increase in N→ decrease in λ_z.
- Increase in U→ increase in λ_z.

2) Cold mid- to lower stratosphere bias: Vertical resolution sensitivity

- **Question:** Does increasing **vertical resolution** eliminate the horizontal resolution sensitivity?
- 200m vertical resolution in the 150-50hPa region enough to eliminate horizontal resolution sensitivity (up to 9km horizontal res.).

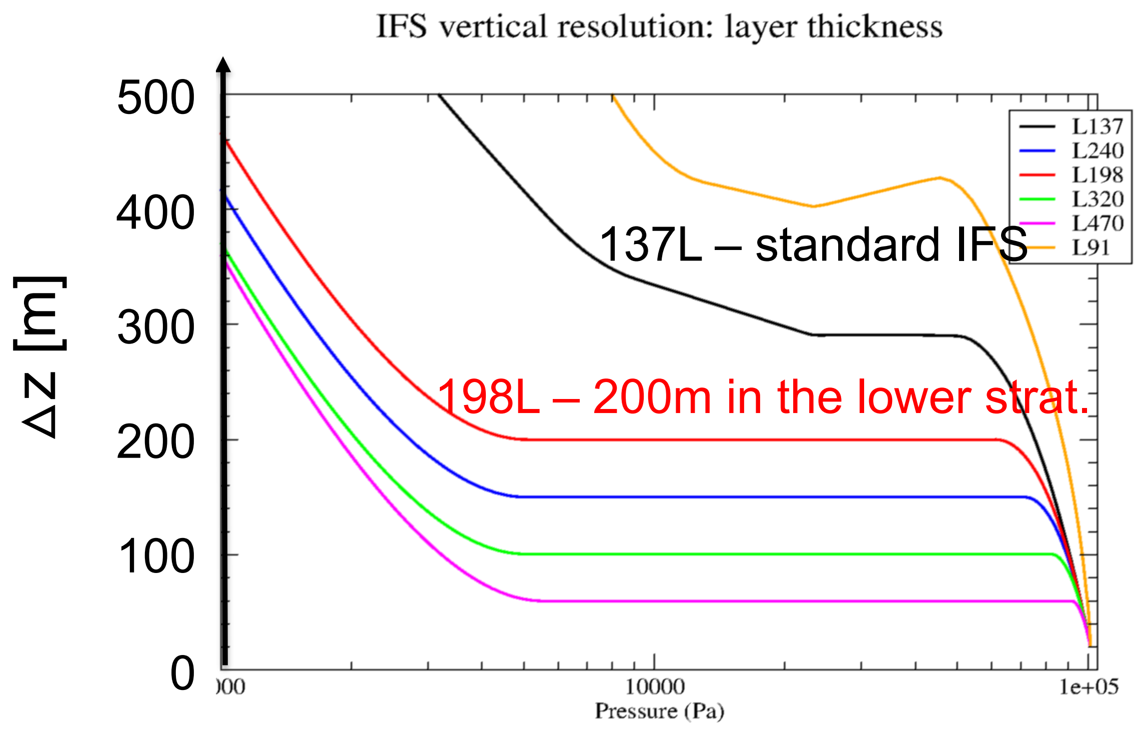
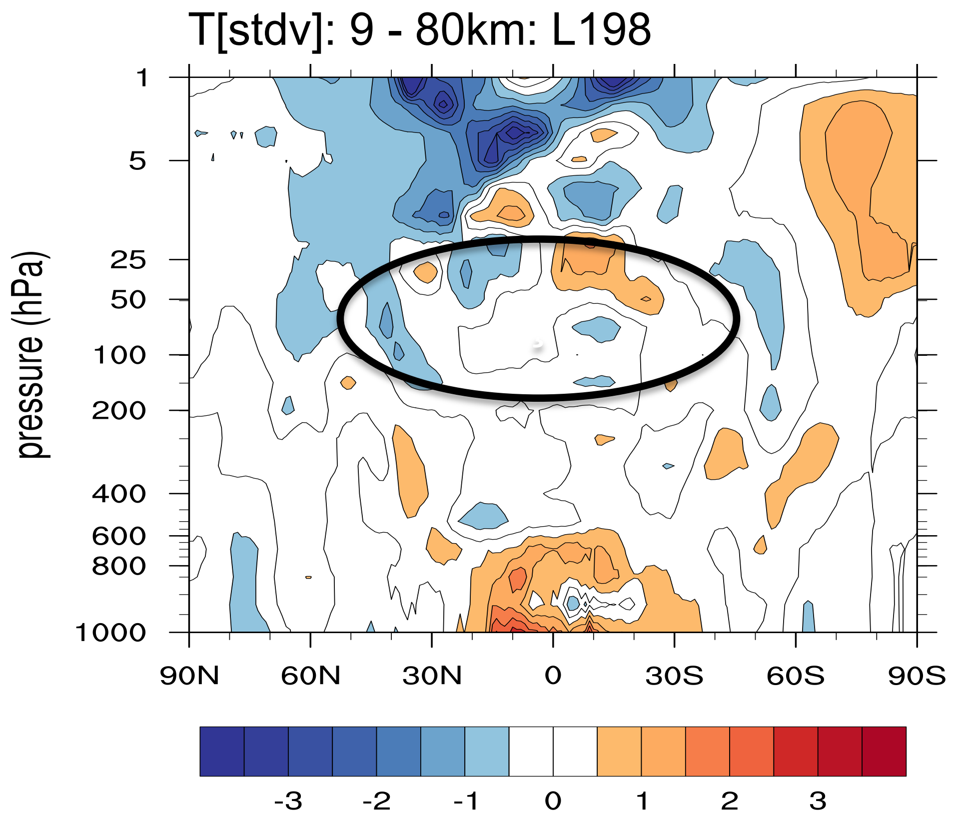
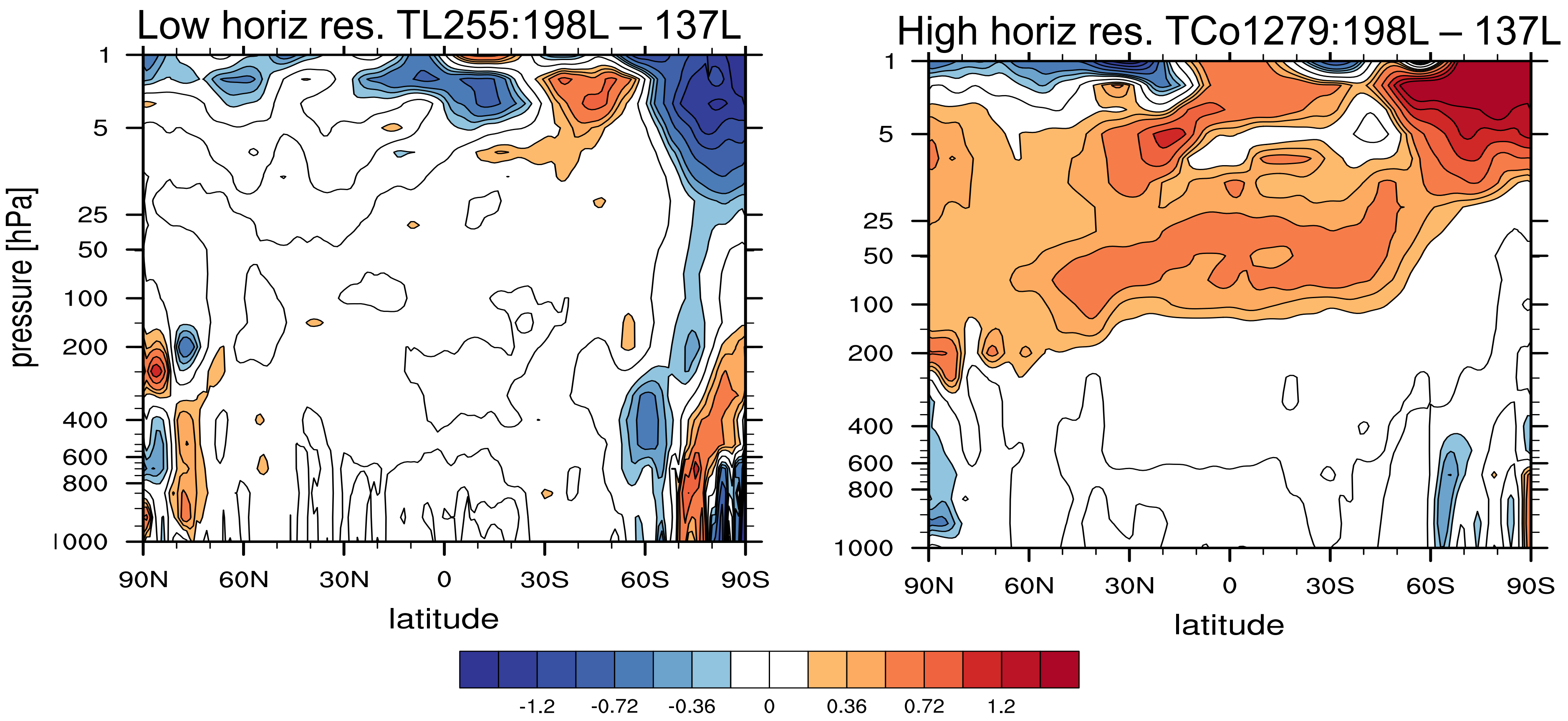


Figure courtesy: Tim Stockdale



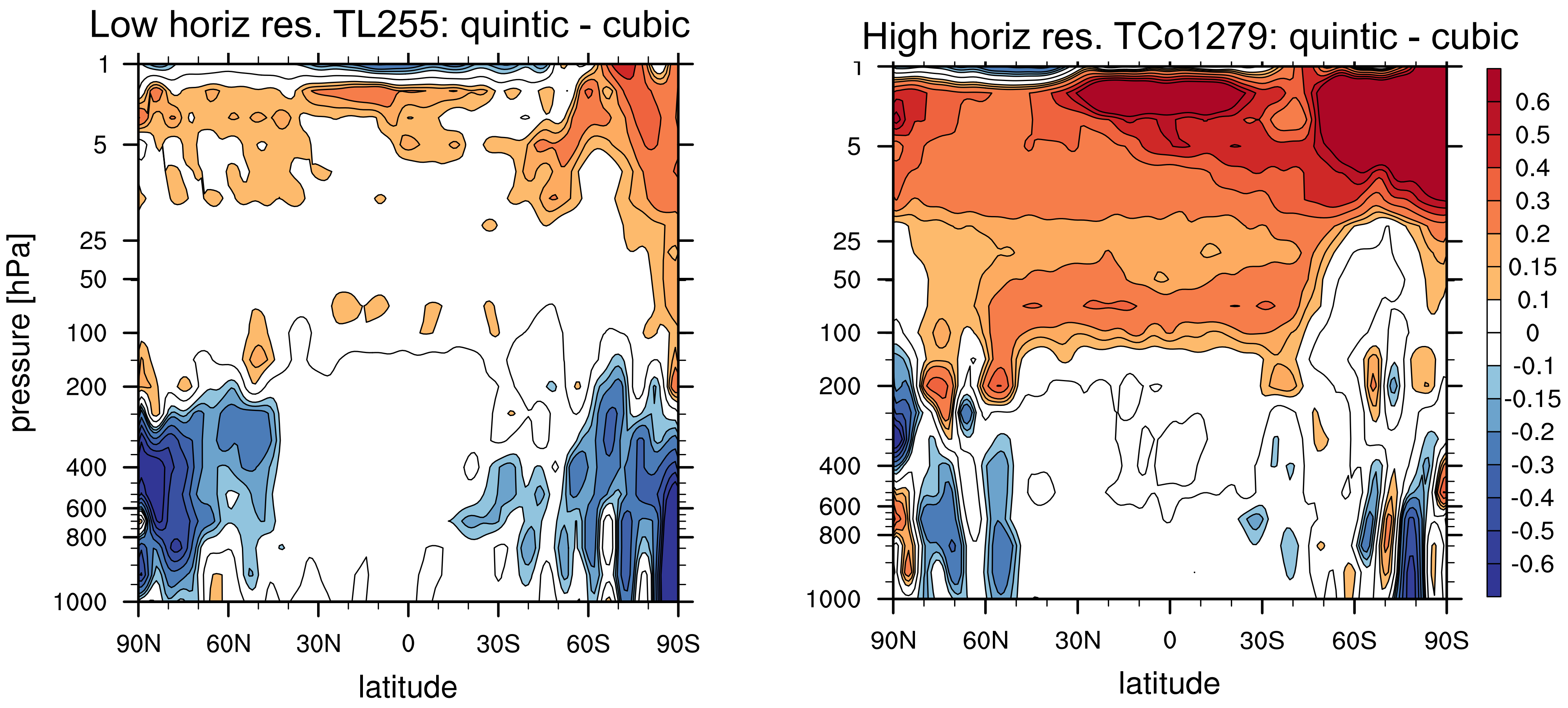
2) Cold mid- to lower stratosphere bias: Vertical resolution sensitivity

- Increase in **vertical resolution** leads to warming in the stratosphere at **high horizontal resolution.** No impact at low horizontal resolution.



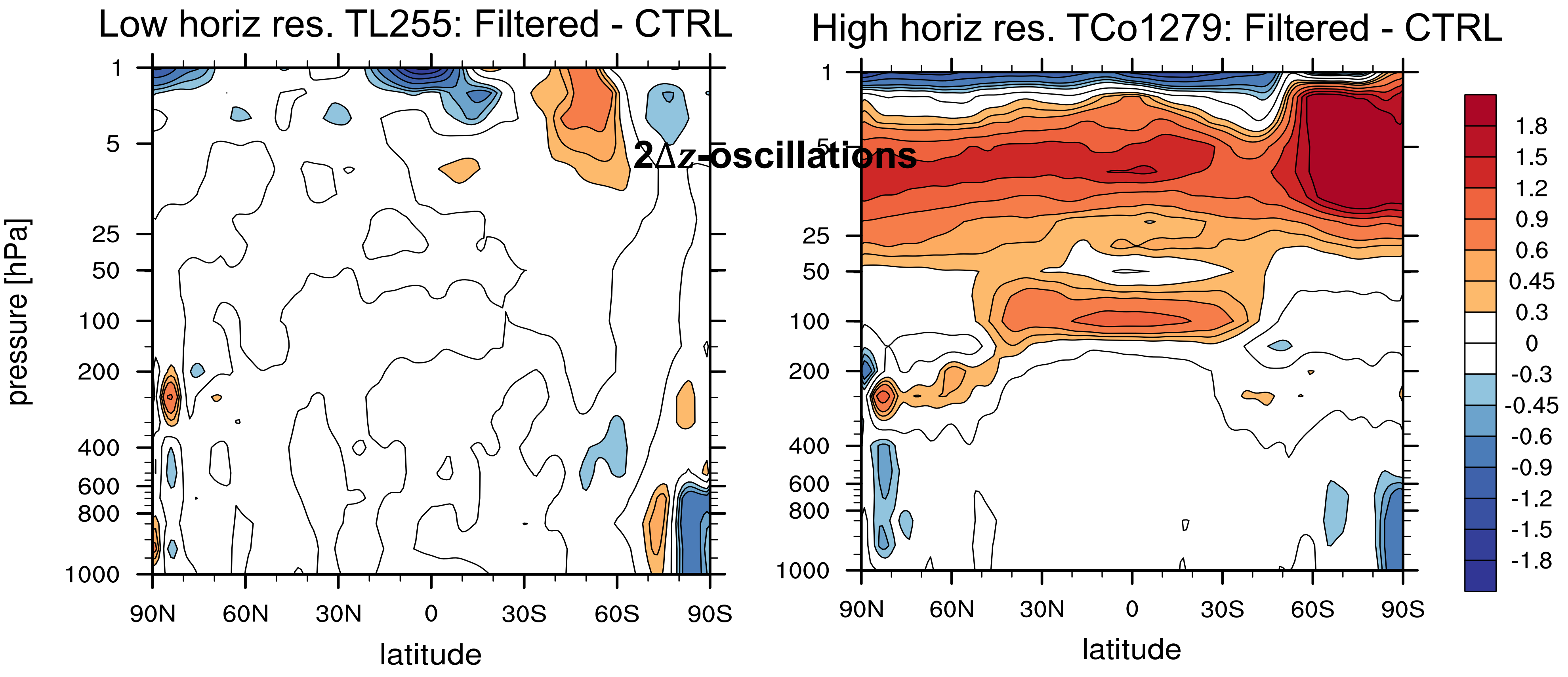
2) Cold mid- to lower stratosphere bias: Higher order vertical SL interpolation

- **Question:** Does improving accuracy of vertical semi-Lagrangian advection help?
- Going from **3rd to 5th** order vertical interpolation helps → Stratosphere warms with higher order interpolation at high horizontal resolution.



2) Cold mid- to lower stratosphere bias: Filtering $2\Delta z$ waves out

- **Question:** Does filtering $2\Delta z$-oscillations in temperature via semi-Lagrangian vertical filter help horizontal resolution sensitivity?
- Filtering warms high horizontal resolution forecasts, no impact on low horizontal resolution.



2) Cold mid- to lower stratosphere bias: Impact on the troposphere

- **Quintic vertical interpolation** applied on temperature and specific humidity alleviates the bias.

- Alleviating the bias has **no statistically significant impact on extended range** forecast skill scores (RPSS) in the Northern Hemisphere or on **medium-range** skill scores in the troposphere.

TCo319L137

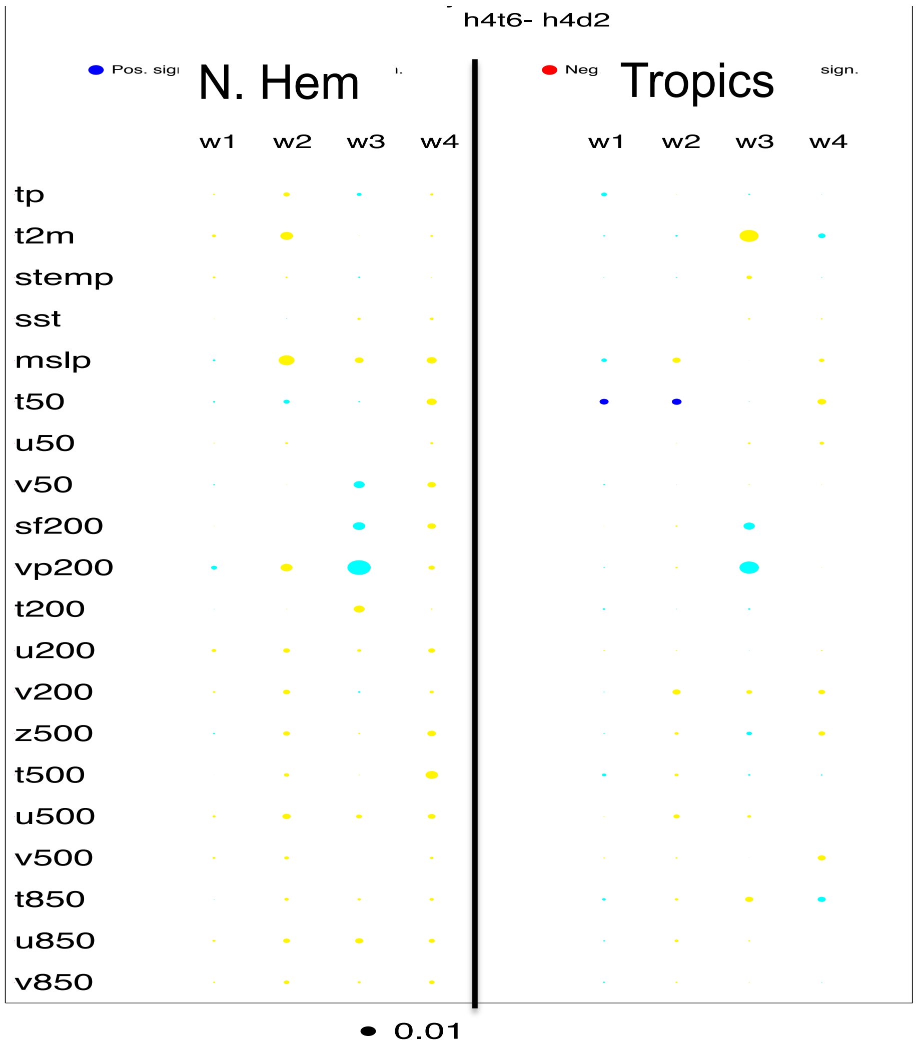


Figure courtesy: Frederic Vitart

2) Cold mid- to lower stratosphere bias: Summary

- At **higher horizontal resolution**, IFS **cools in the global mean** in the stratosphere → cold bias in the 150-50hPa region worse. Affects all forecast ranges.
- Behaviour linked to **2Δz-oscillations** in the vertical arising from **inconsistent vertical to horizontal resolution aspect ratio**.
- Increasing the **vertical resolution** to 200m eliminates the global mean cooling at **higher horizontal resolution**.
- **Filtering out 2Δz-oscillations** or increasing the **order of SL interpolation** also alleviate the global mean cooling at **high horizontal resolution**.
- Alleviating the bias (via quintic vertical interpolation or modest vertical resolution increase) has **no statistically significant** impact on tropospheric skill scores.