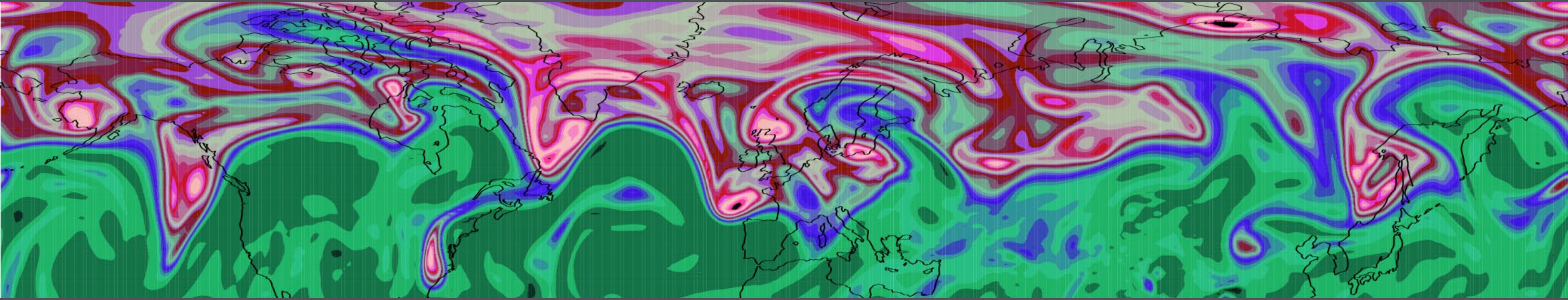
Department of Meteorology

University of Reading

Observations distinguishing processes that affect weather system dynamics



John Methven, University of Reading

Thanks to Ben Harvey, Andreas Schaefler, Jake Bland, Suzanne Gray and Richard Forbes

Observations distinguishing processes acting

1. **Motivation**: aim to *improve prediction* by making observations that can distinguishing processes acting
   a. Improve predictions directly by assimilating those observations
   b. Improve models using physical insight from those observations

2. But, measurements are of current state (or fluxes)
   - *processes are inferred* given some form of model: conceptual, theoretical, numerical, data driven (or combination)

3. How can we design observations to distinguish processes?
   - Propose different theories/models which give distinct predictions
   - Look for signatures of those distinct predictions
   - Identify “unphysical” behaviour where a model violates physical constraints

Diabatic influences near the tropopause affecting the jet stream and disturbances on large scales

Campaign: North Atlantic Waveguide and Downstream Impacts Experiment (NAWDEX, 2016)
(and follow on, NAWDIC, 2026)

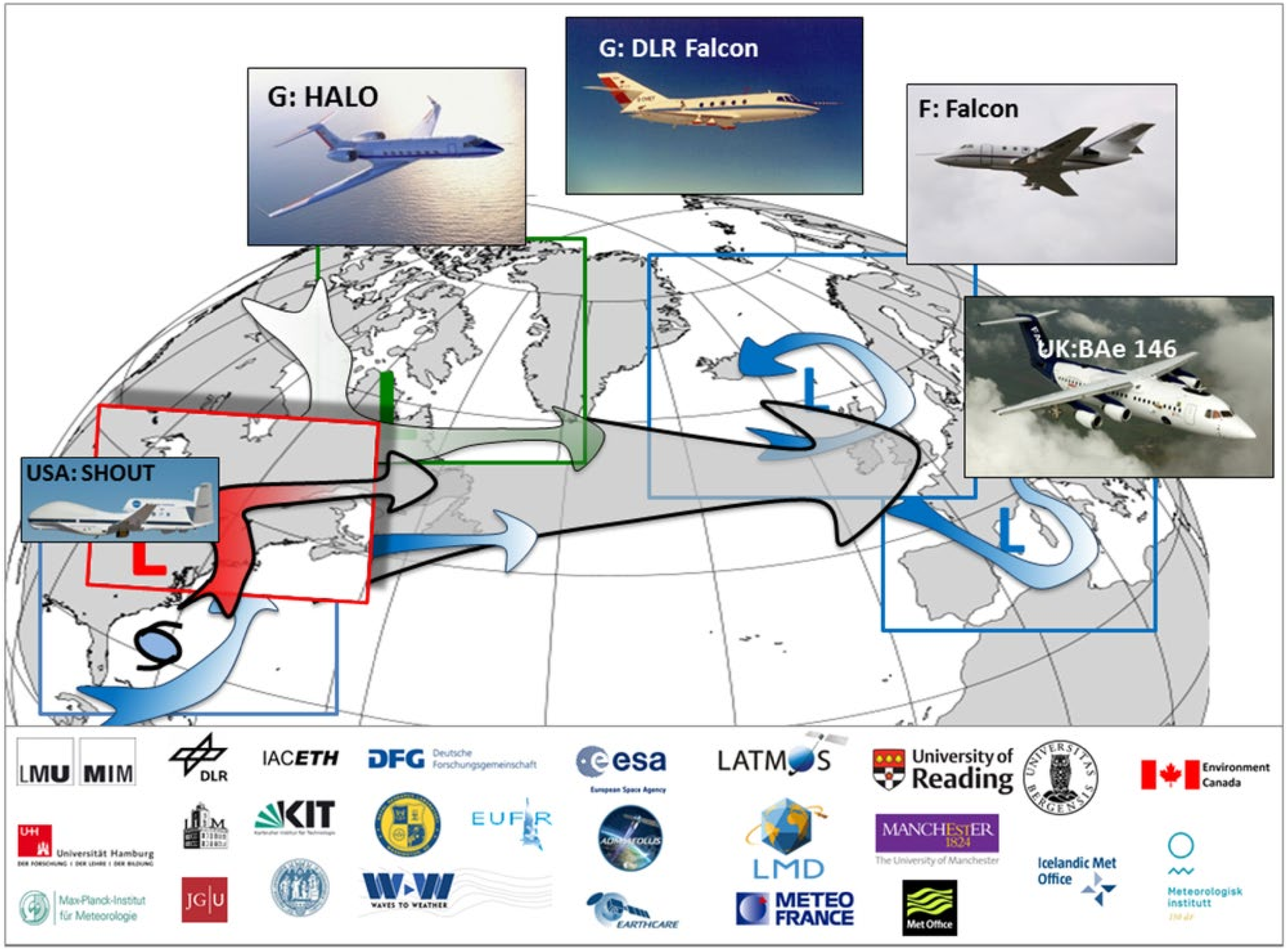
Focus on **wind, temperature** and **humidity** observations near the jet stream

Insights from the observations

1. ***Wind errors can be large on the west flank of ridges in the jet stream***
   a. *PV is used to demonstrate the action of diabatic processes on jet structure*
   b. *Two mechanisms have been identified and can be distinguished using the observations*

2. ***Analyses and forecasts have a large moist bias above the tropopause***
   a. *It is shown how forecast temperature bias grows as a result*
   b. *Forecast improvement through correction of the moist bias is demonstrated*

North Atlantic Waveguide and Downstream Impacts Experiment (NAWDEX)

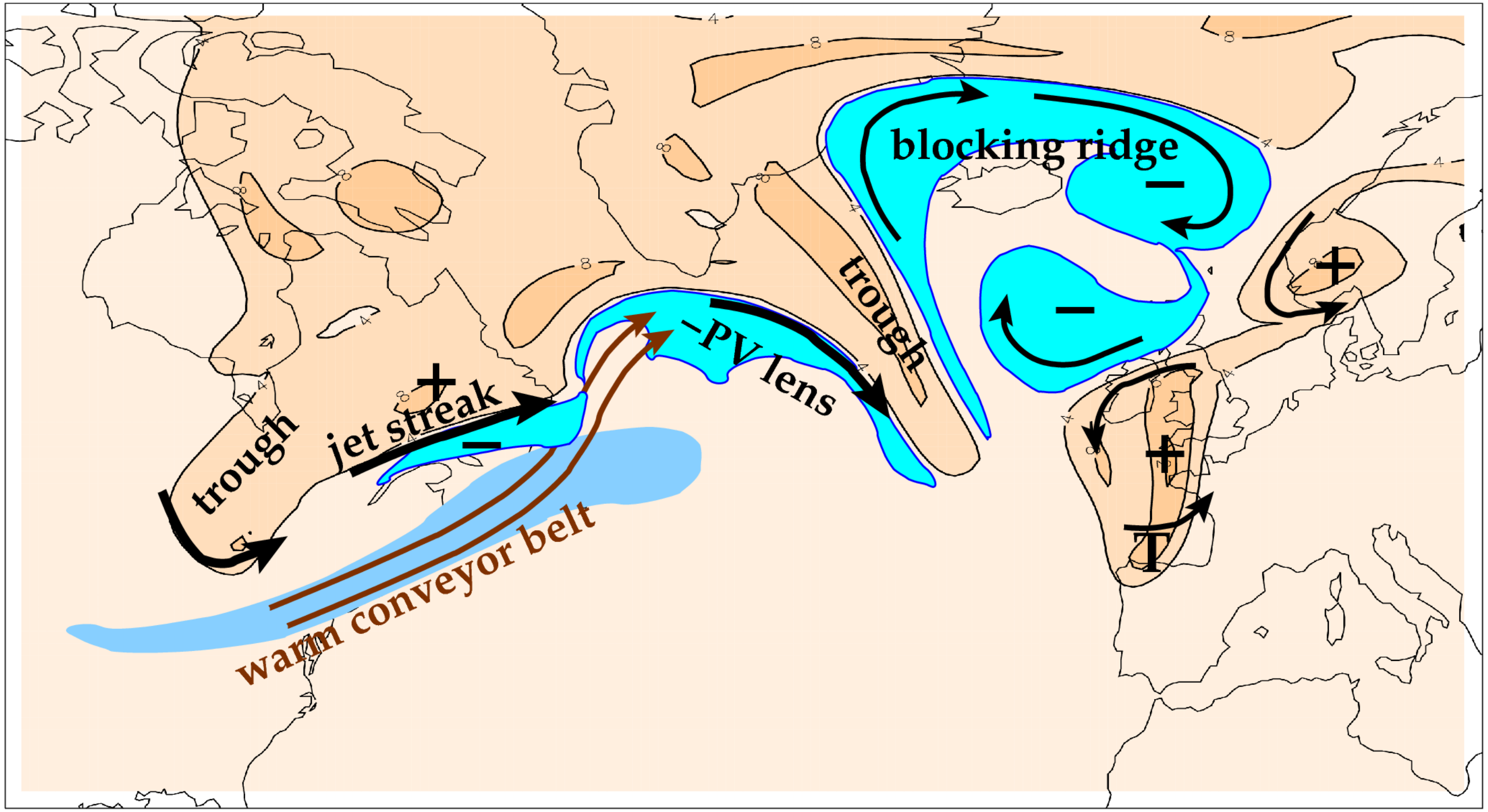


Iceland 2016

- Initiated 2008 during WWRP THORPEX
- Realised in Sept/October 2016
- Focus on diabatic processes, ascent in WCBs and influence on outflow and jet stream disturbances

Overarching scientific aim of NAWDEX:

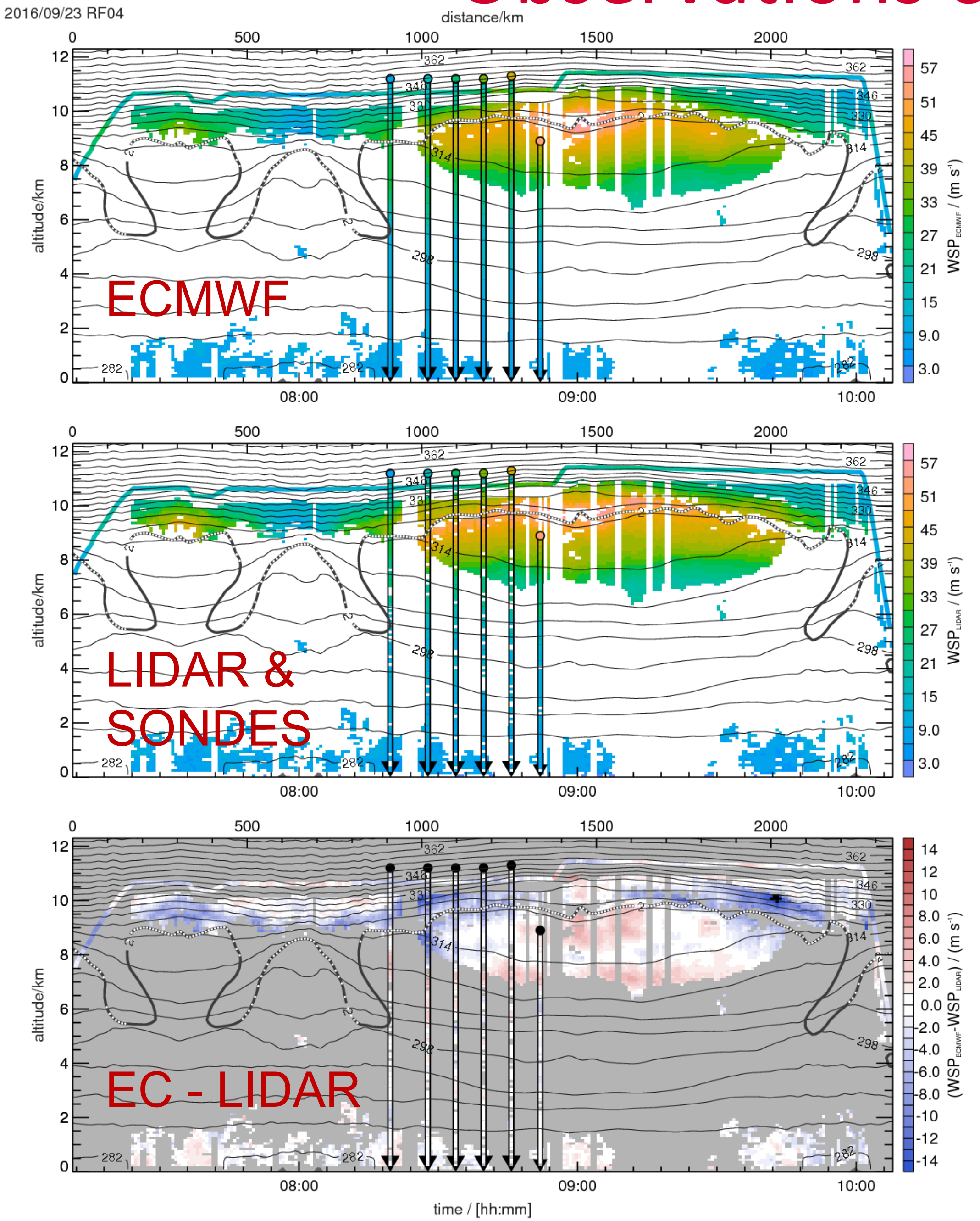
to quantify the effects of diabatic processes on disturbances to the jet stream near North America, their influence on downstream propagation across the North Atlantic, and consequences for high-impact weather in Europe.



Features related to the meandering tropopause and jet stream

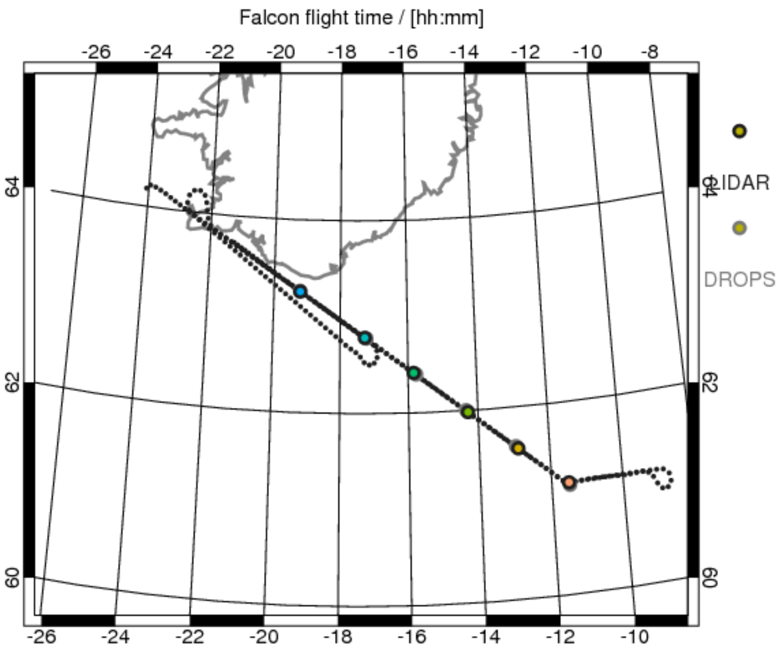
(orange is stratospheric air; cyan marks upper tropospheric PV anomalies)

Observations of jet structure



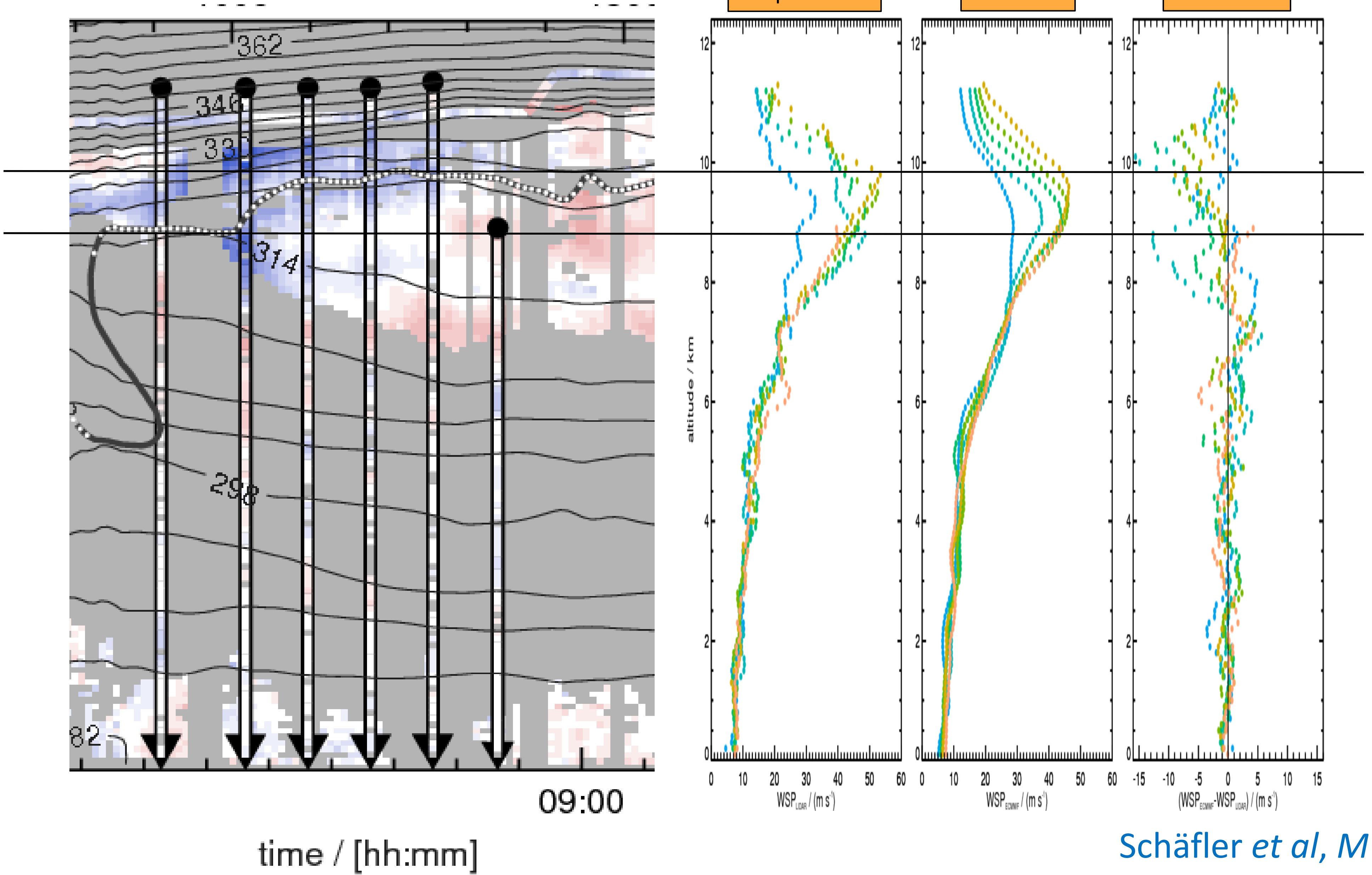
Lidar and dropsonde wind measurements are much closer to each other than analysis.

Structure of error similar in ECMWF and Met Office analyses



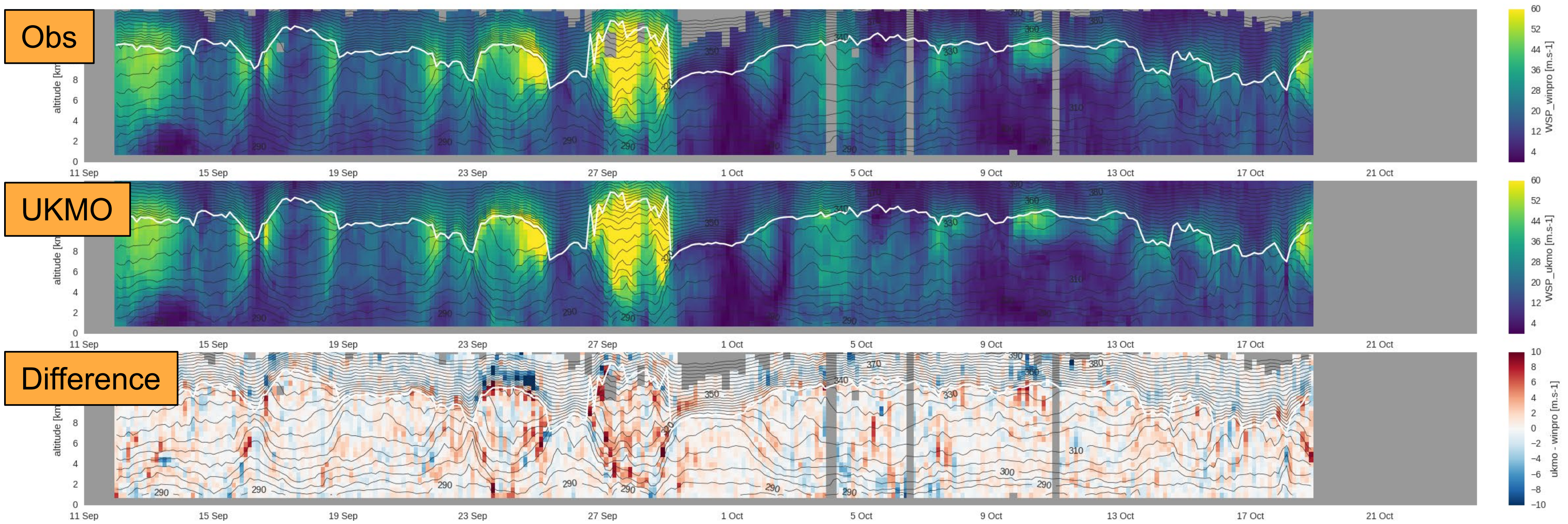
Schäfler *et al*, *MWR* (2020)

RF04: 23/9/16, wind speed: analysis – aircraft lidar obs



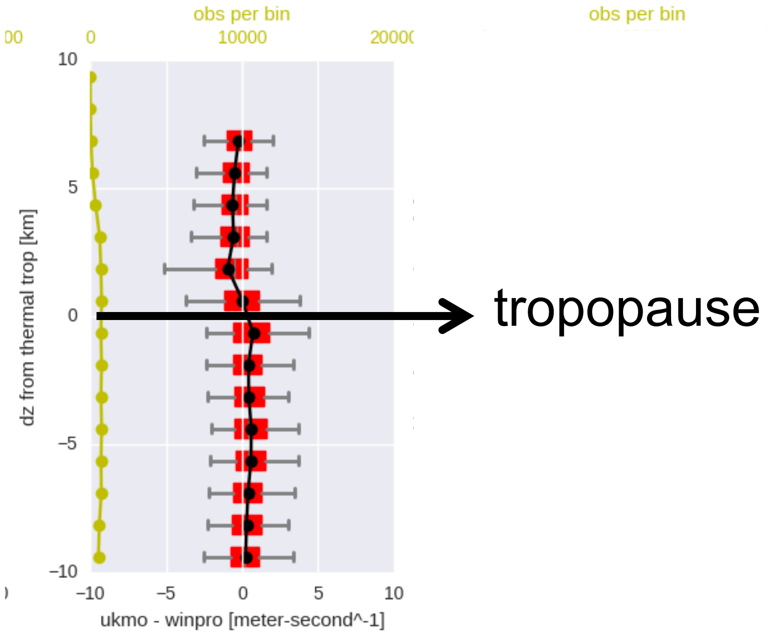
Schäfler *et al*, *MWR* (2020)

Obs vs model at T+0 Wind profiler @ South Uist

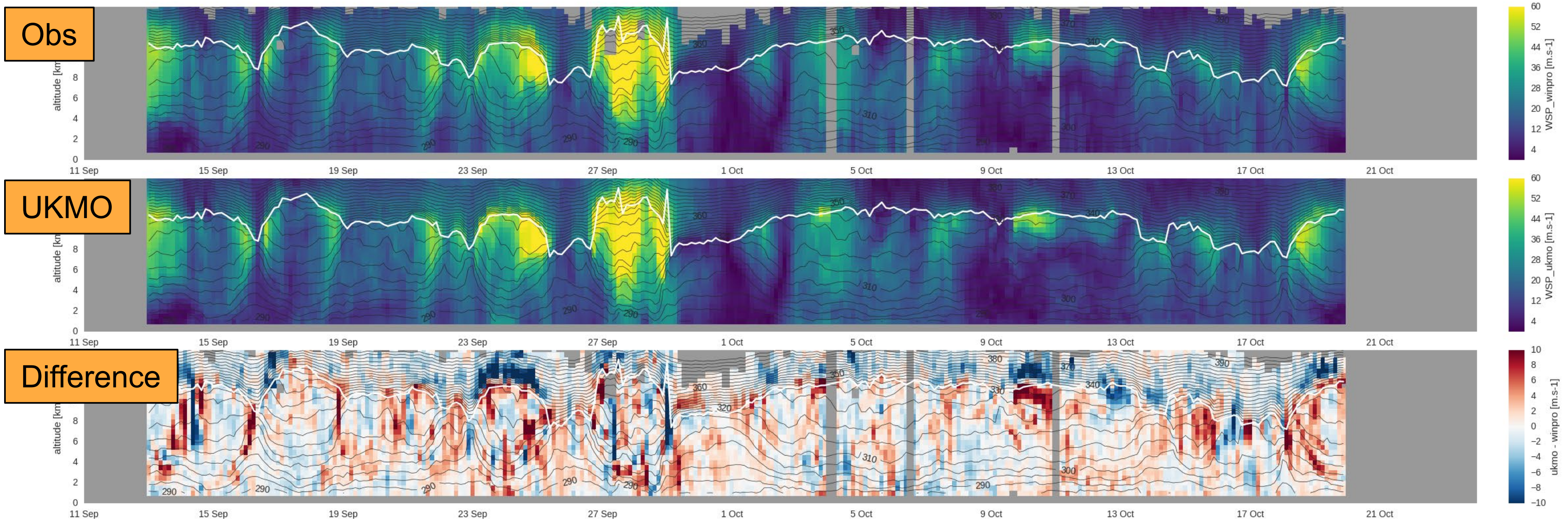


Wind profiler (ST radar) and analyses compared.

Composite relative to height of the tropopause on each profile.



Obs vs model at T+24



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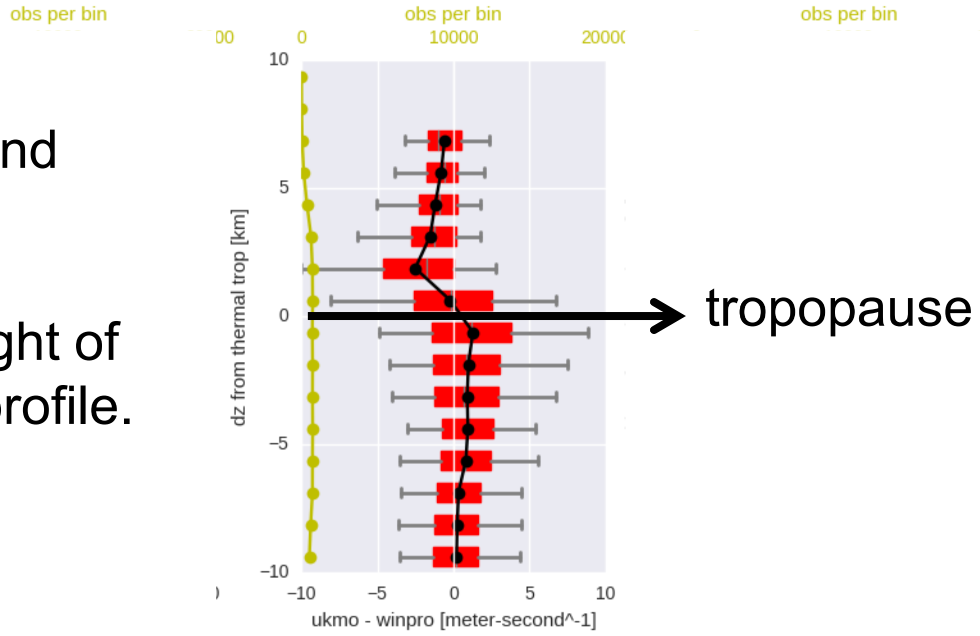


Observed jet stream is “sharper”

What are ramifications for forecast evolution?

In vertical profiles, especially on the flanks of tropopause ridges,
wind shear is observed to be much sharper than in analyses and forecasts.

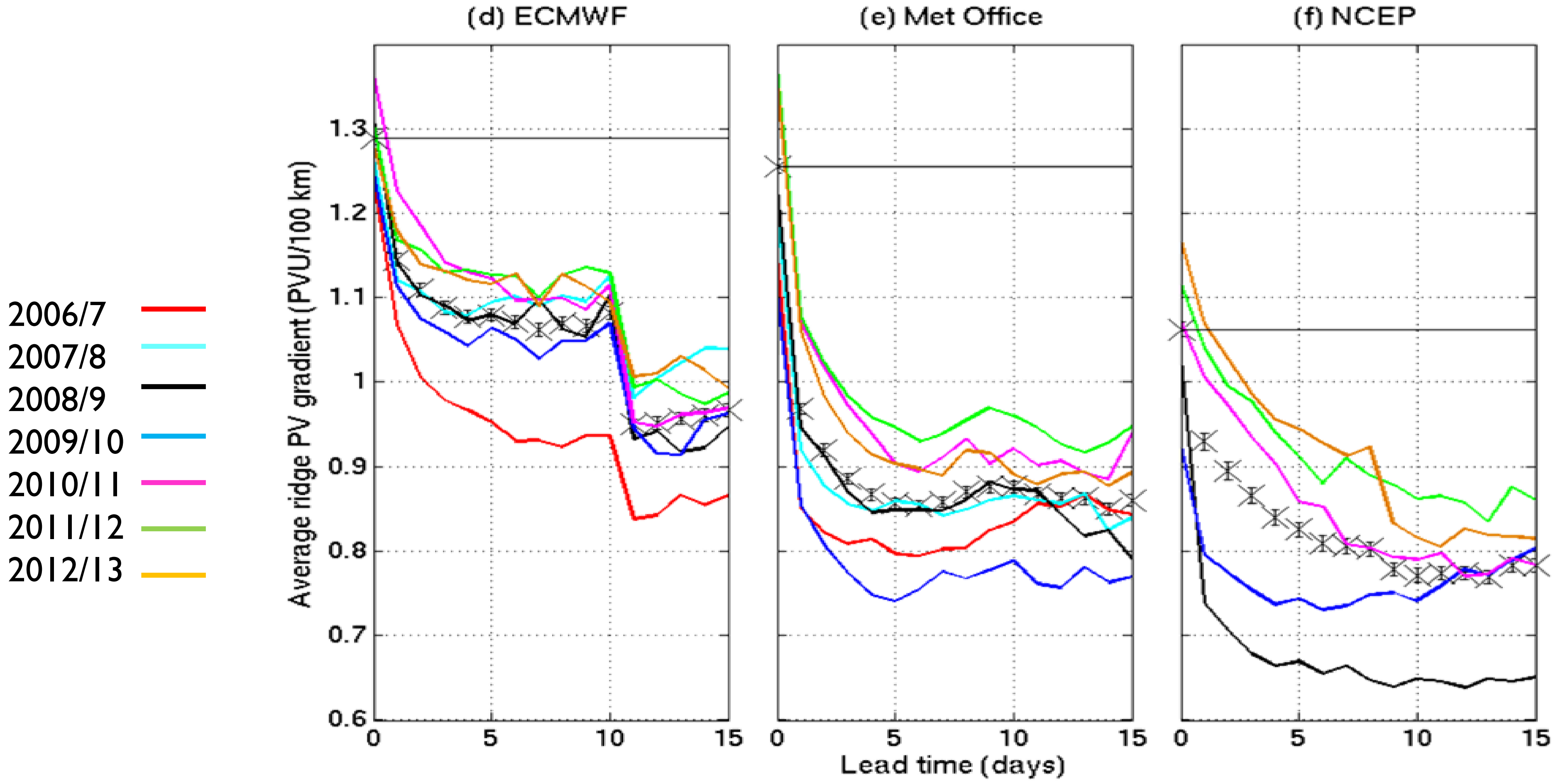
Under quasi-geostrophic approximation (for zonal flow):

Meridional PV gradient, $$\frac{\partial \bar{q}}{\partial y} = \beta - \frac{\partial}{\partial y}\left(\frac{\partial \bar{u}}{\partial y}\right) - \frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho \frac{f^2}{N^2}\frac{\partial \bar{u}}{\partial z}\right)$$

Therefore, PV gradient must be too smooth in models

- How fast does PV gradient decrease with lead time?
- How does this affect Rossby waves?

Forecast of horizontal PV gradient across the tropopause (from TIGGE)



Gray, Dunning, Methven, Masato and Chagnon (2014), *GRL*

RW propagation on smooth PV step

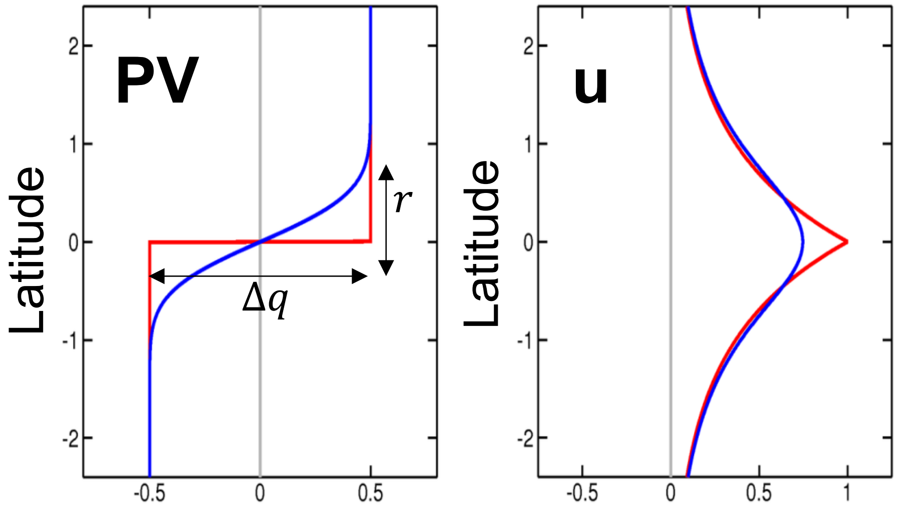
Single step in PV is smoothed by convolution with a weight.

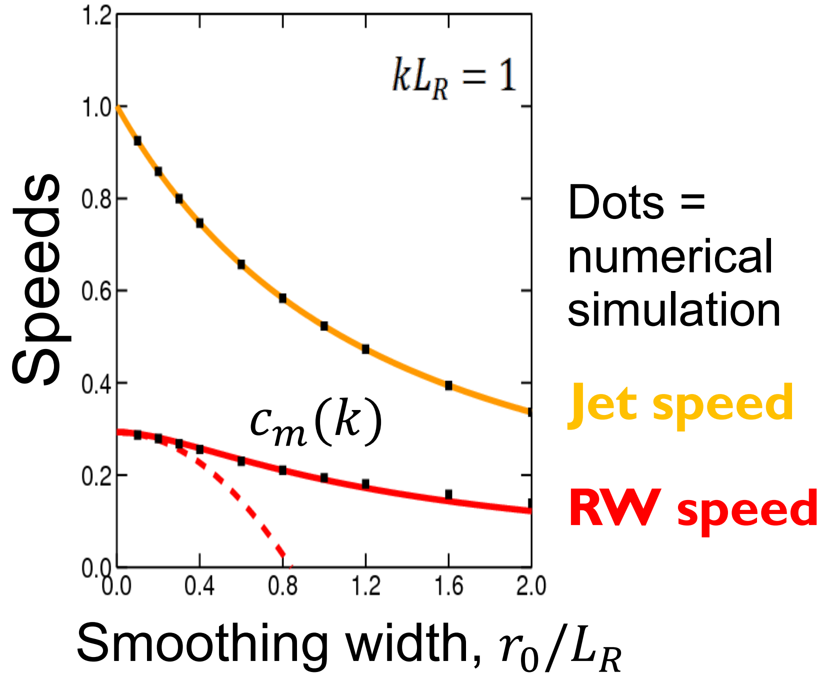
Solution obtained in limit where tropopause width is narrow compared with wavelength ($kr_0 \ll 1$)

General conclusion: smoothing PV gradient reduces both jet maximum and counter-propagation rate … but jet decrease is greater

$\Rightarrow$ phase speed reduces

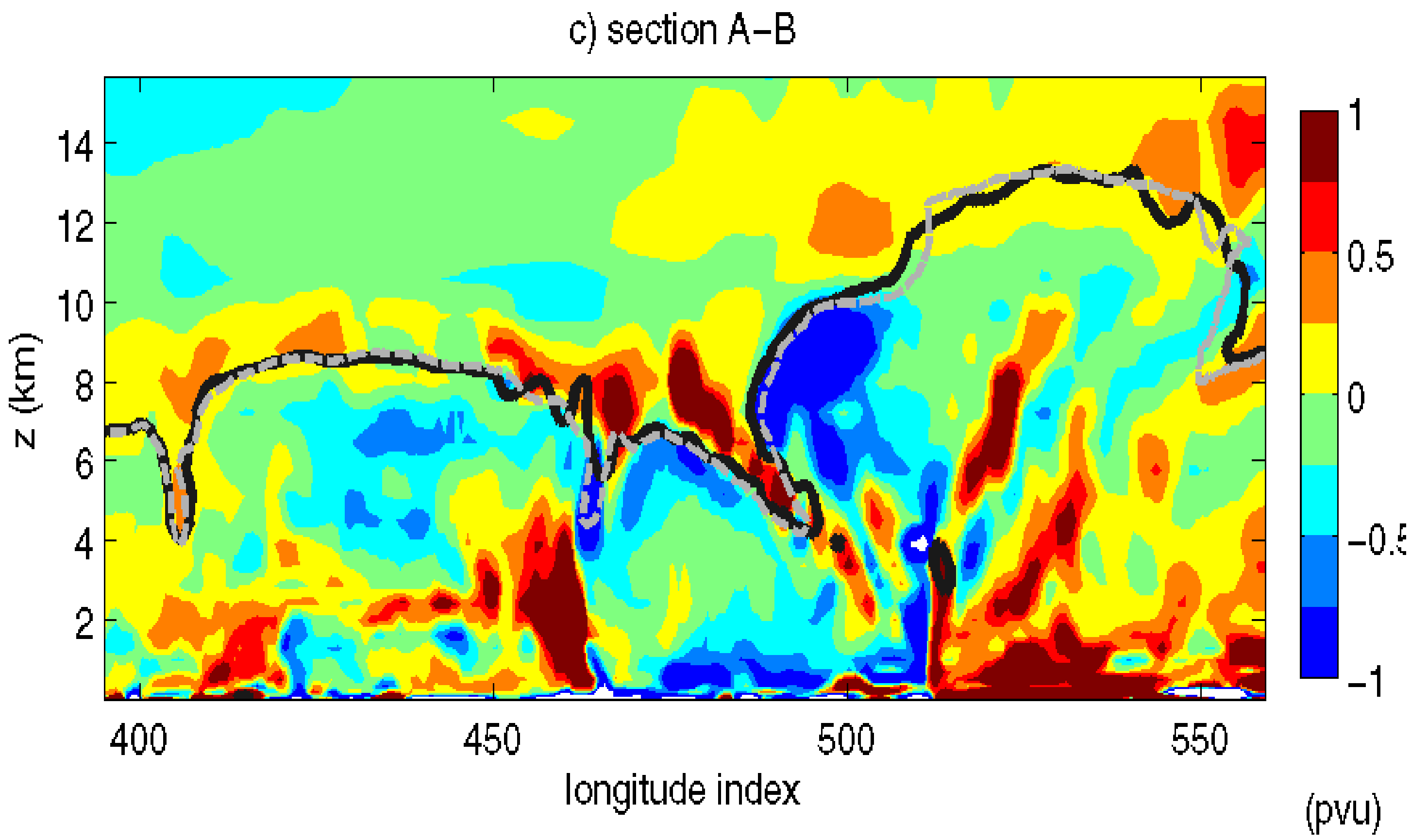
$\Rightarrow$ affects shorter waves more, increasing dispersion





Harvey *et al*, *J. F. Mech.* (2016)

Radiative maintenance of PV contrast across tropopause



- Positive *diabatic PV* above (on strat side) of tropopause
- Negative *diabatic PV* beneath (on trop side) of tropopause
- Tropopause elevation not significantly altered by **direct diabatic PV modification**

Chagnon, Gray and Methven (2013), *Q J R Met S*

Distinguishing processes modifying PV

Alternative Lagrangian form of PV equation.

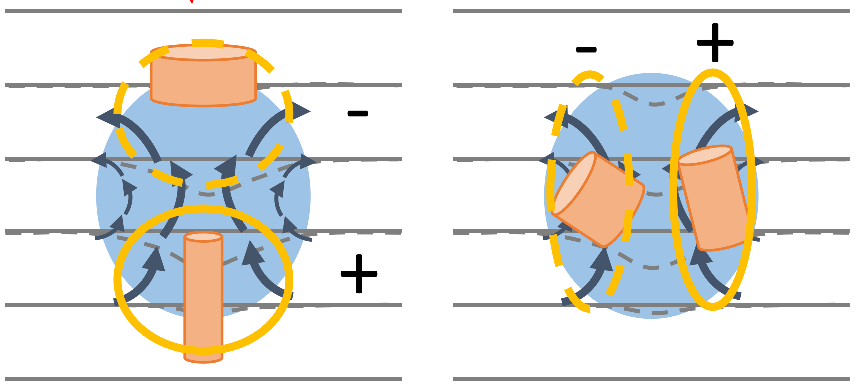
Evolution following flow within an isentropic layer

$$\frac{\tilde{D}}{Dt} = \frac{\partial}{\partial t} + \tilde{\boldsymbol{u}} \cdot \nabla$$

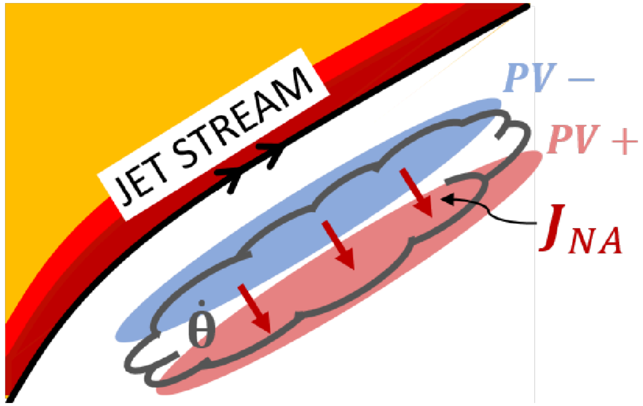
$$\rho \frac{\tilde{D}P}{Dt} = P\nabla \cdot (\rho \boldsymbol{u}_J) + \nabla \cdot (\boldsymbol{\zeta}_{//}\dot{\theta} + \boldsymbol{F} \times \nabla\theta)$$

Concentration/dilution of PV below/above heating

Non-advective transport of PV along θ surfaces



Only this term can create negative PV



Negative PV cannot arise through diabatic mass flux convergence

If P>0 initially, it must remain positive through the first term on right.

Harvey *et al*, *Q. J. R. Met. S.* (2020)

Two distinct mechanisms creating jet disturbances

University of Reading

Heating in vertical wind shear below jet

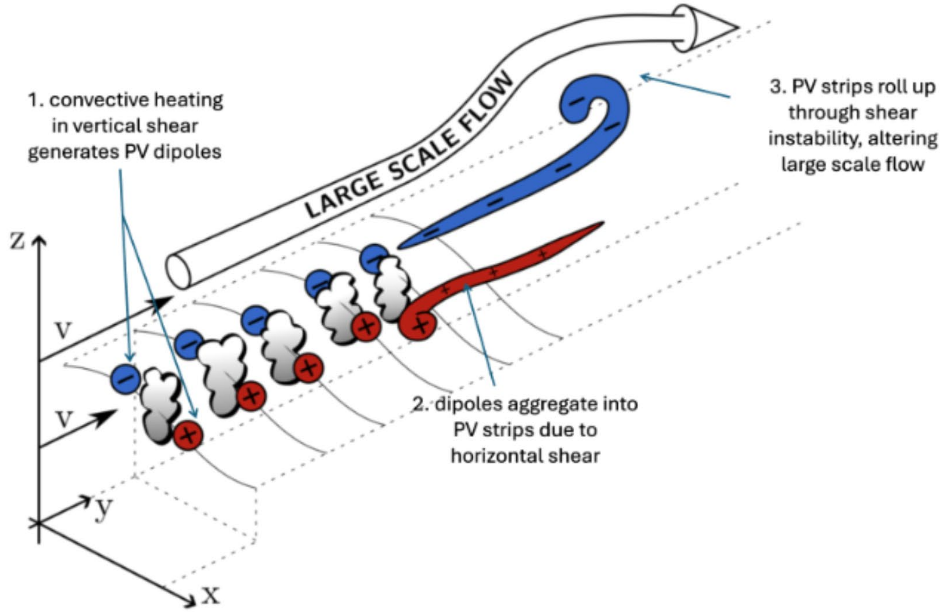
⇒ ***non-advective PV flux*** *generates PV dipoles on isentropic surfaces*

Shear stretches them into – and + strips

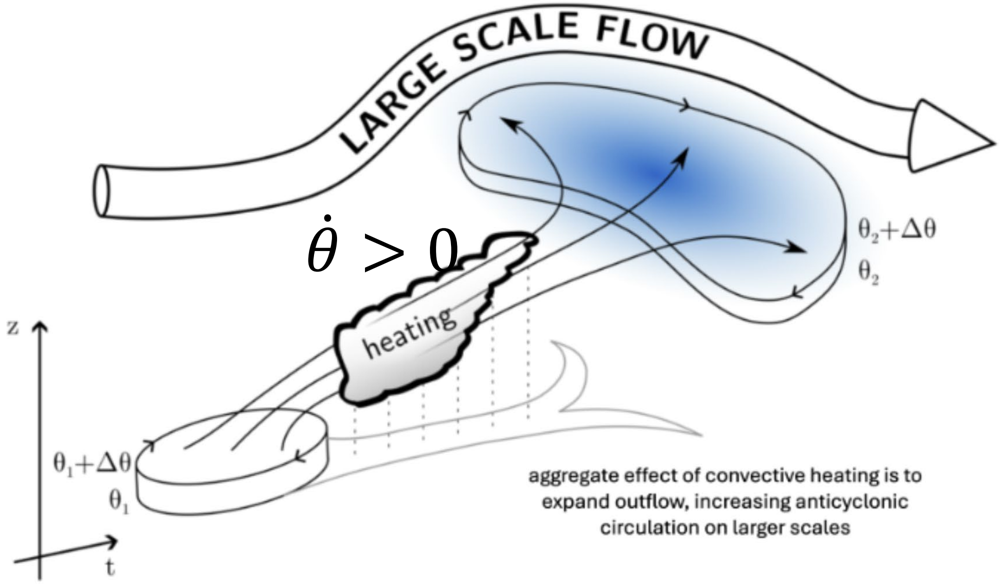
Heating ⇒ **diabatic mass transport** from lower to upper volume

Concentrates PV substance of "inflow volume" and dilutes outflow PVS

i) PV strip roll-up

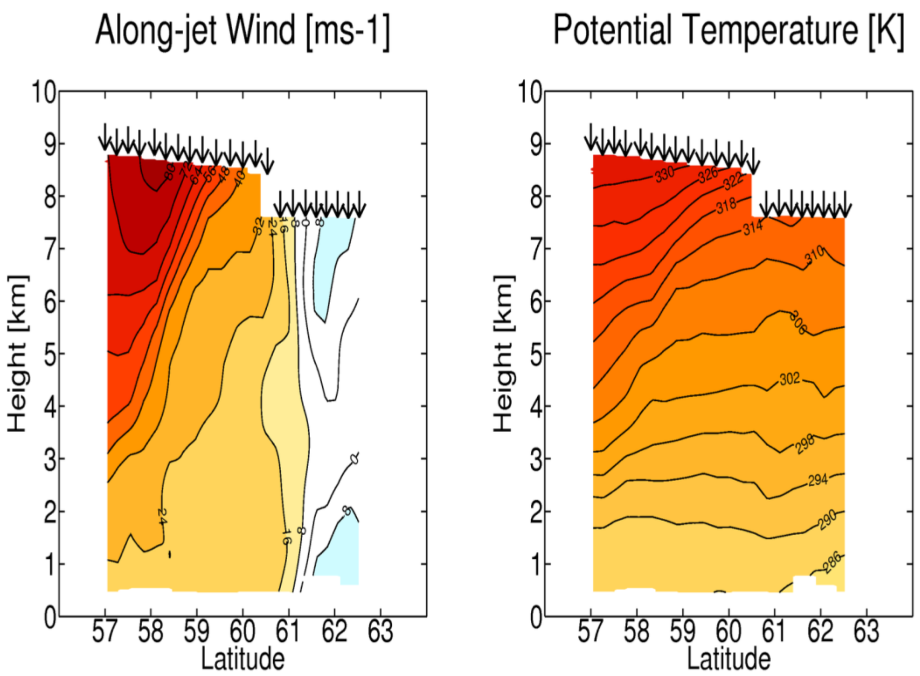


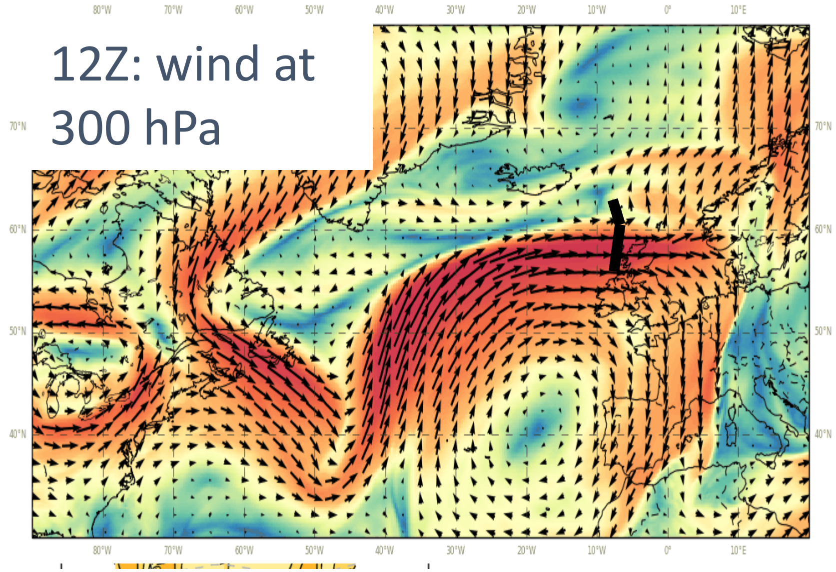
ii) expansion of convective outflow

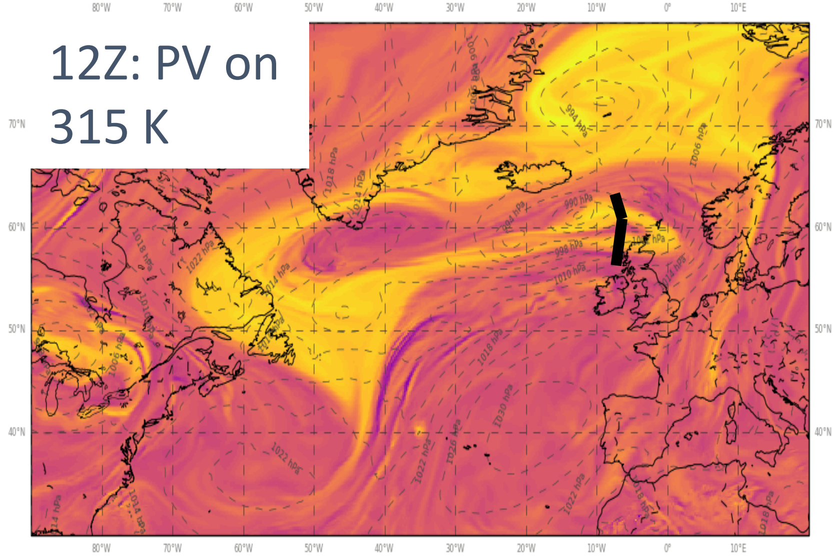


Methven, *Q. J. Royal Met. Soc. (2015)*

Confronted with new observations: NAWDEX jet streak case (ex-Karl)





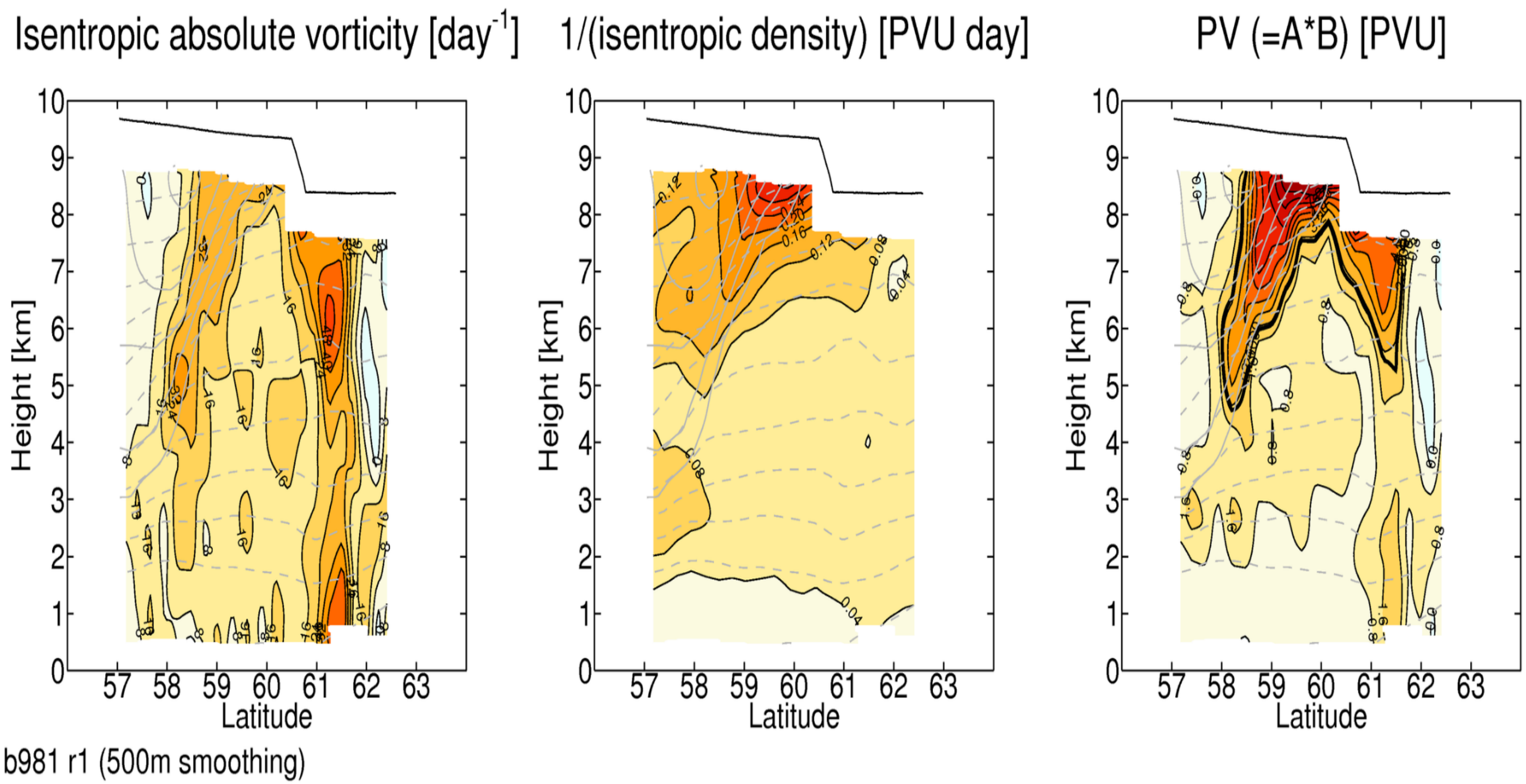


22 dropsondes on section crossing the jet stream

Harvey *et al*, *Q. J. R. Met. S.* (2020)

Negative PV observed with dropsondes

Signature of diabatic processes sharpening jet stream

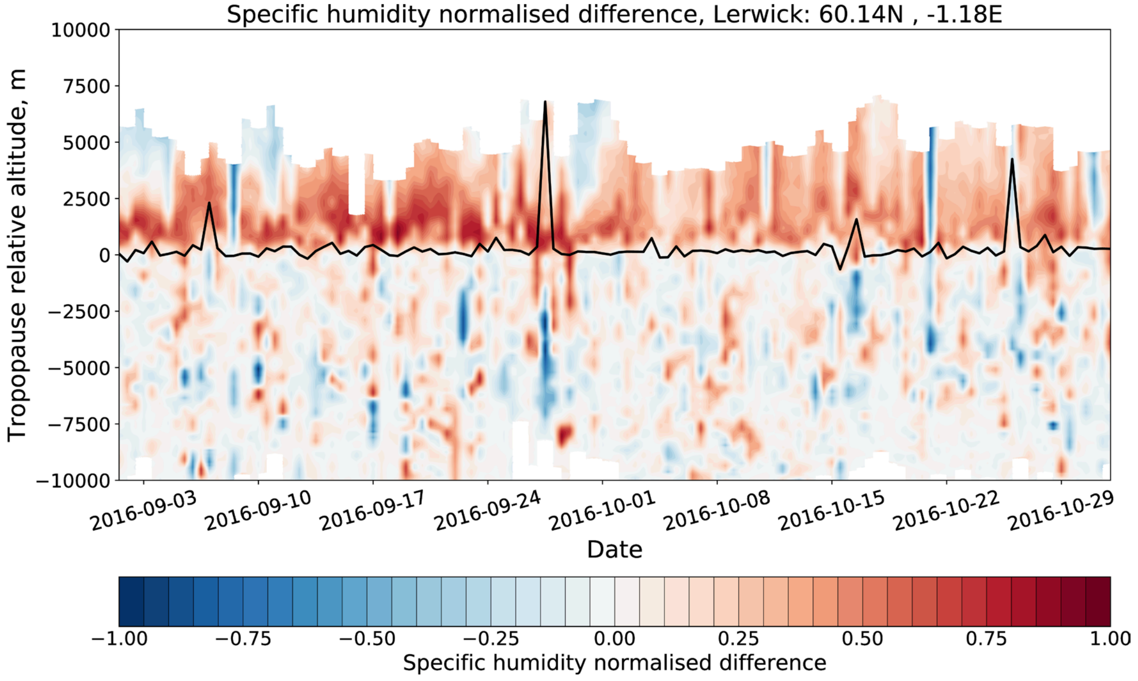


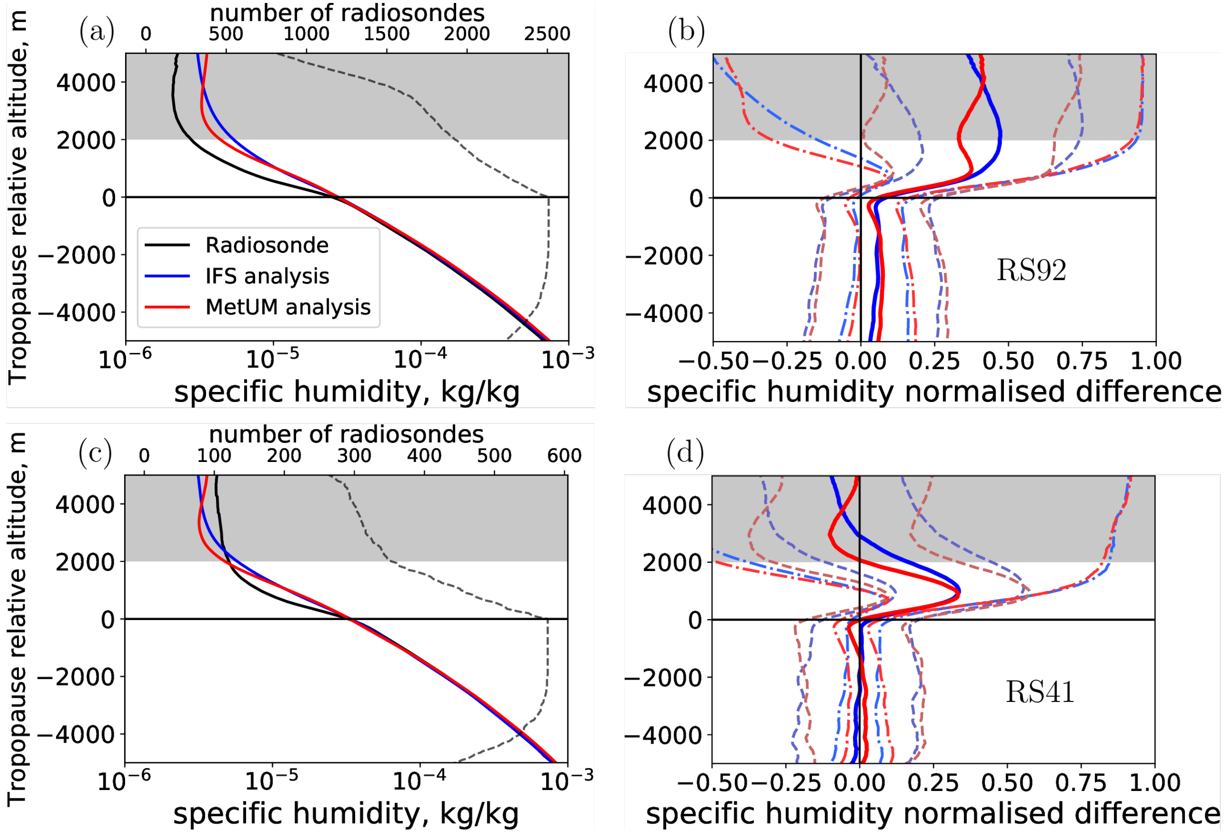
$$P = \frac{1}{\rho}\boldsymbol{\zeta} \cdot \nabla\theta = (\boldsymbol{\zeta} \cdot \boldsymbol{n})\frac{|\nabla\theta|}{\rho} \qquad \text{where} \qquad \boldsymbol{n} = \frac{\nabla\theta}{|\nabla\theta|}$$

Humidity bias (analysis-obs) above the extratropical tropopause

NAWDEX radiosondes reveal systematic moist bias of analyses in 2km above tpp.

What are the ramifications for forecasts?



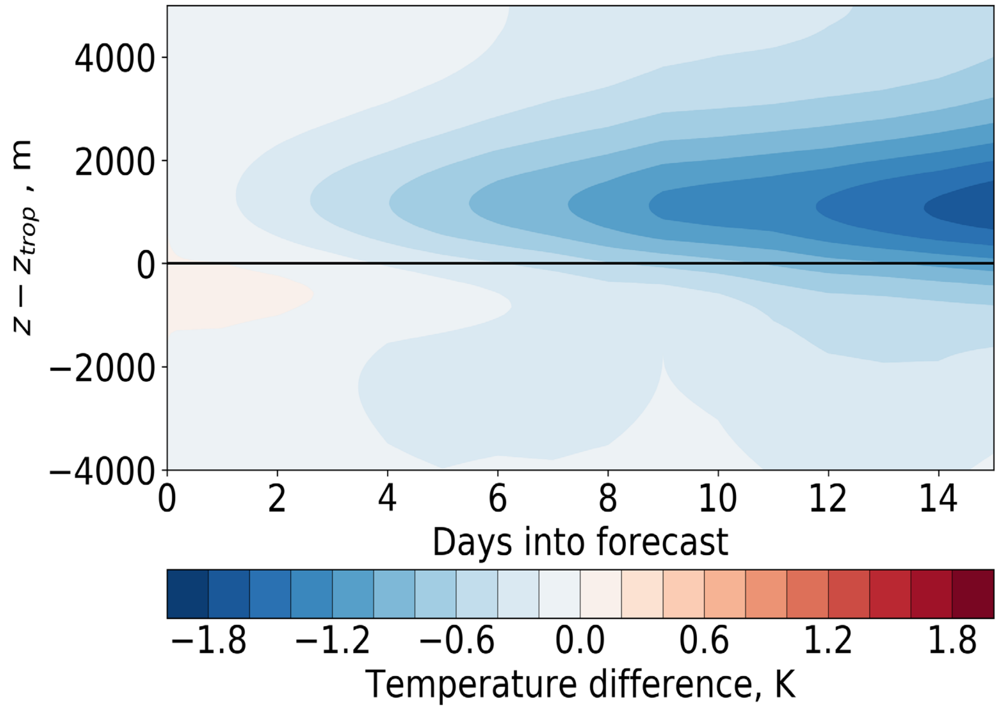


Bland *et al, Q. J. Royal Met. Soc. (2021)*

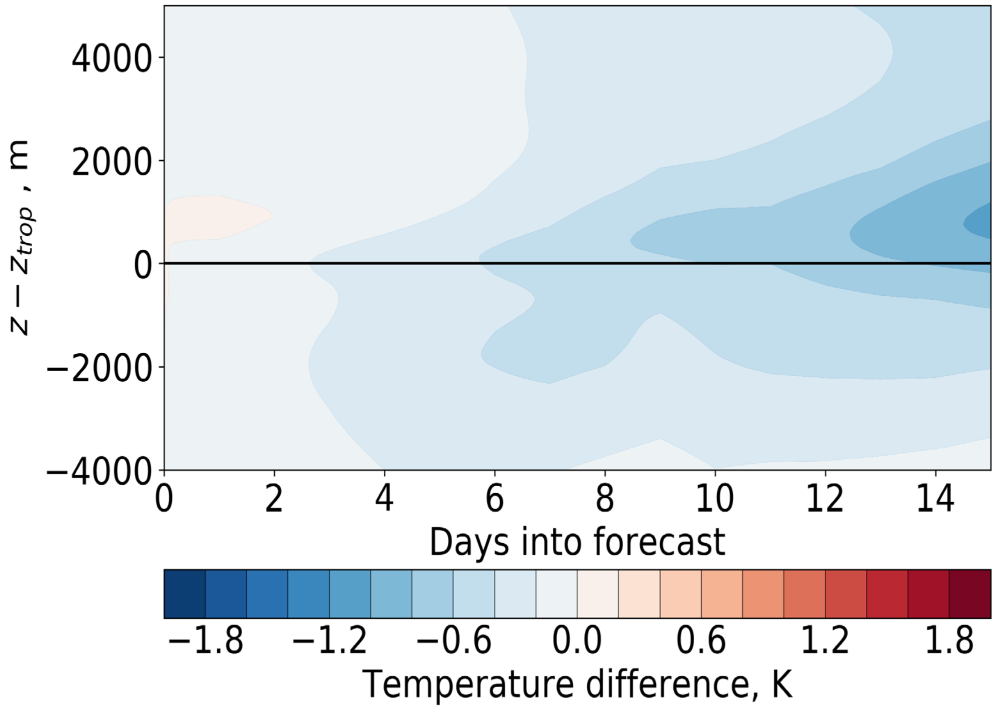
Effect of the humidity bias on temperature in forecasts

Plots show IFS model forecasts: forecast - analysis

Control: default IFS forecast

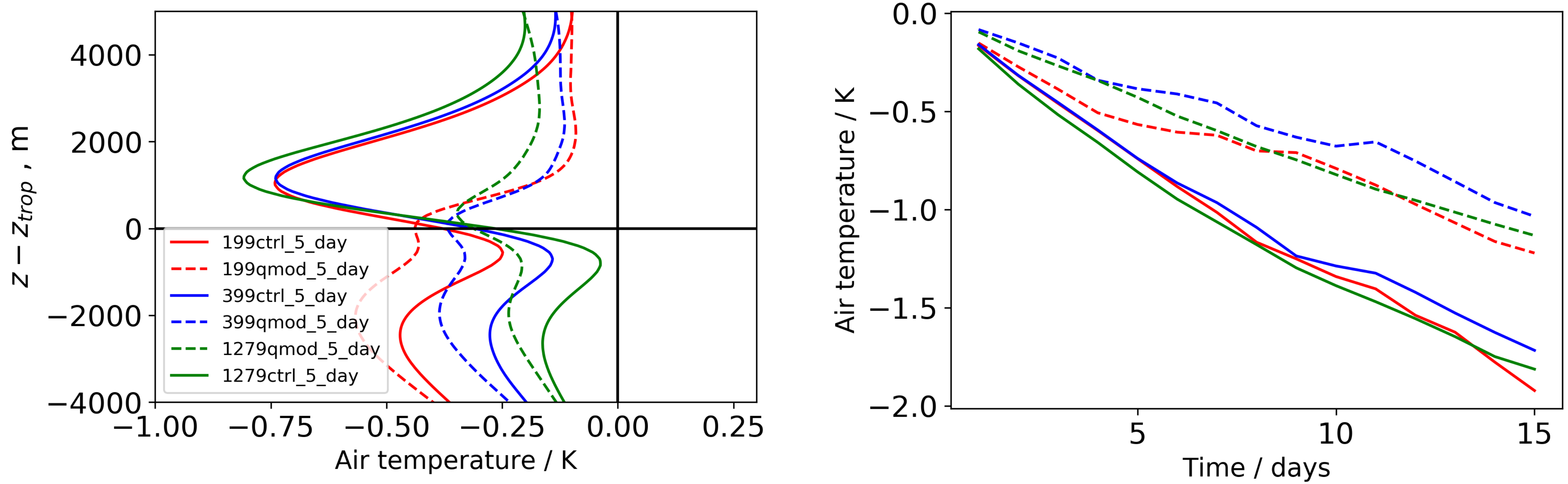


Expt: humidity seen by radiation scheme has average moist bias removed



Effect of the humidity bias on temperature is insensitive to horizontal resolution

Plots show IFS full 3-D model forecasts: forecast - analysis



Correcting the humidity seen by the radiation scheme improves forecast scores in all variables in weeks 2 & 3

Impact is seen particularly

In North Atlantic sector

Conclusions

1. **Vertical shear and PV gradient at tropopause is too weak** in global forecasts

   ⇒ expect Rossby waves to move eastwards too slowly in forecasts

   ⇒ Rossby wave amplitude declines (on average)

   Mixing too strong, or diabatic maintenance of PV contrast too weak?

2. **Negative PV** observed is a signature of diabatic "sharpening" of jet stream

   - via *non-advective PV flux* which requires heating in vertical wind shear

3. **Effects of heating in large-scale vertical wind shear are largest on west side of ridges**
   but model error may arise from heating profile and position relative to shear

4. **Moist bias in analyses above extratropical tropopause**

   - causes growth of a strong cold bias above tropopause via longwave cooling
   - if moisture seen by radiation scheme is bias corrected, forecasts improve to week 3
   - model moisture bias arises through vertical diffusion across tropopause with advection

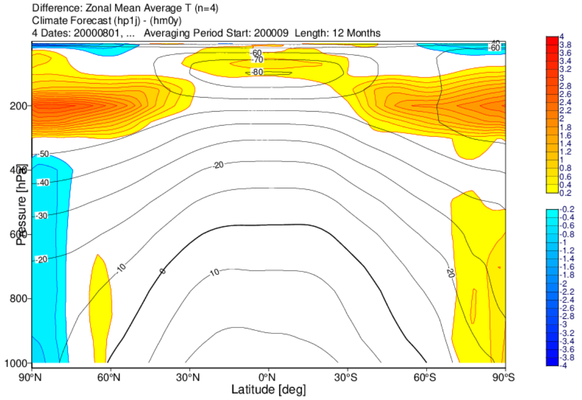
47r1 TCo255 1yr forecast
LMS humidity reduction
sensitivity experiments

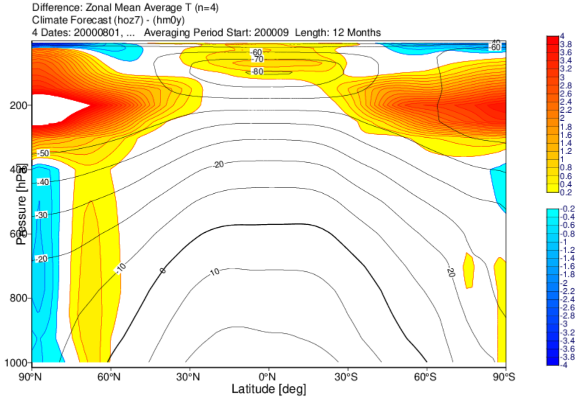
Annual mean T/U zonal
cross-section differences

55% reduction (hp1j)
in LMS humidity

75% reduction (hoz7)
in LMS humidity

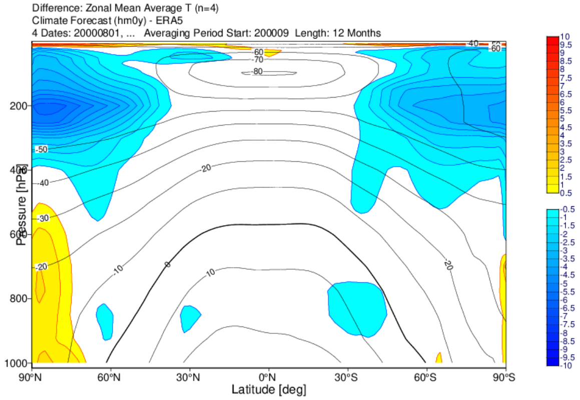
Temperature
Expt – Control

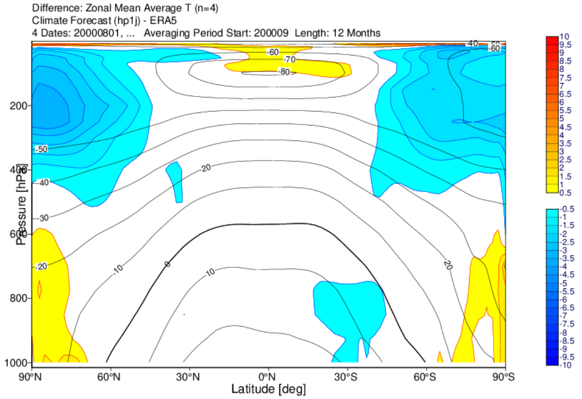


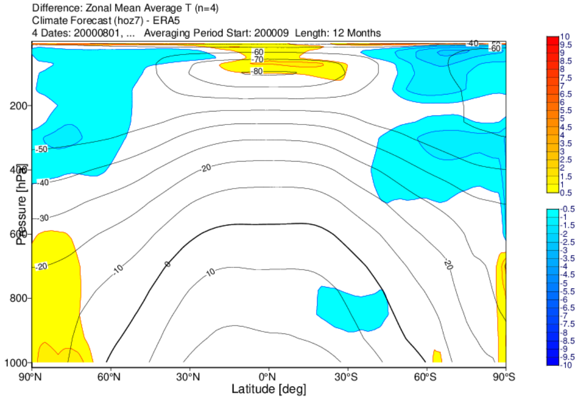


Control (hm0y)

Temperature
Expt – ERA5

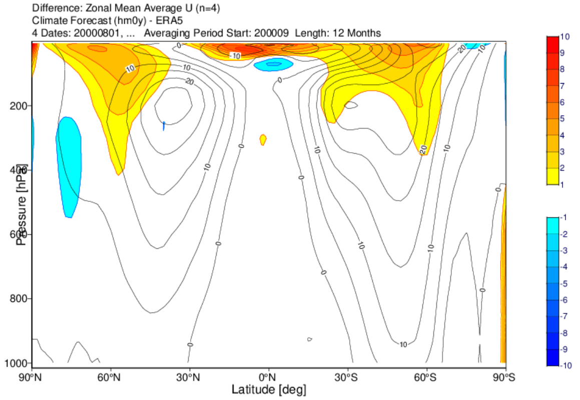


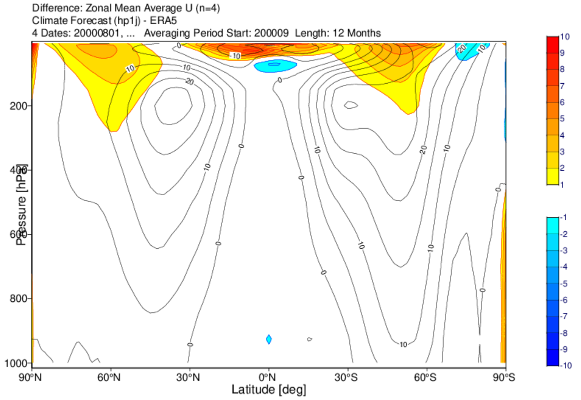


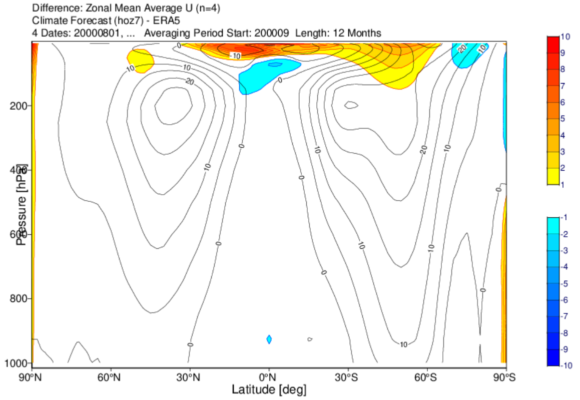


Temperature error almost eliminated

Eastward wind
Expt – ERA5







Jet wind errors reduced!

Spurious decrease of jet meander amplitude

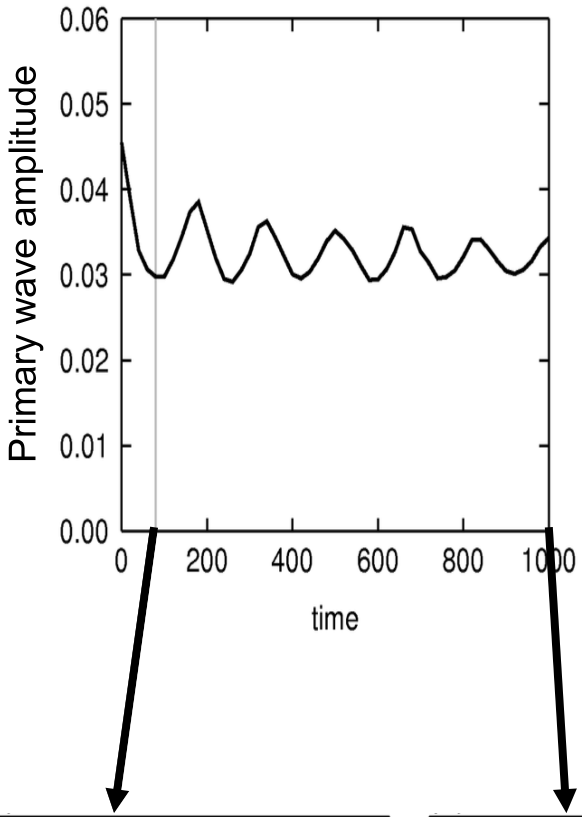
- Fast oscillation:

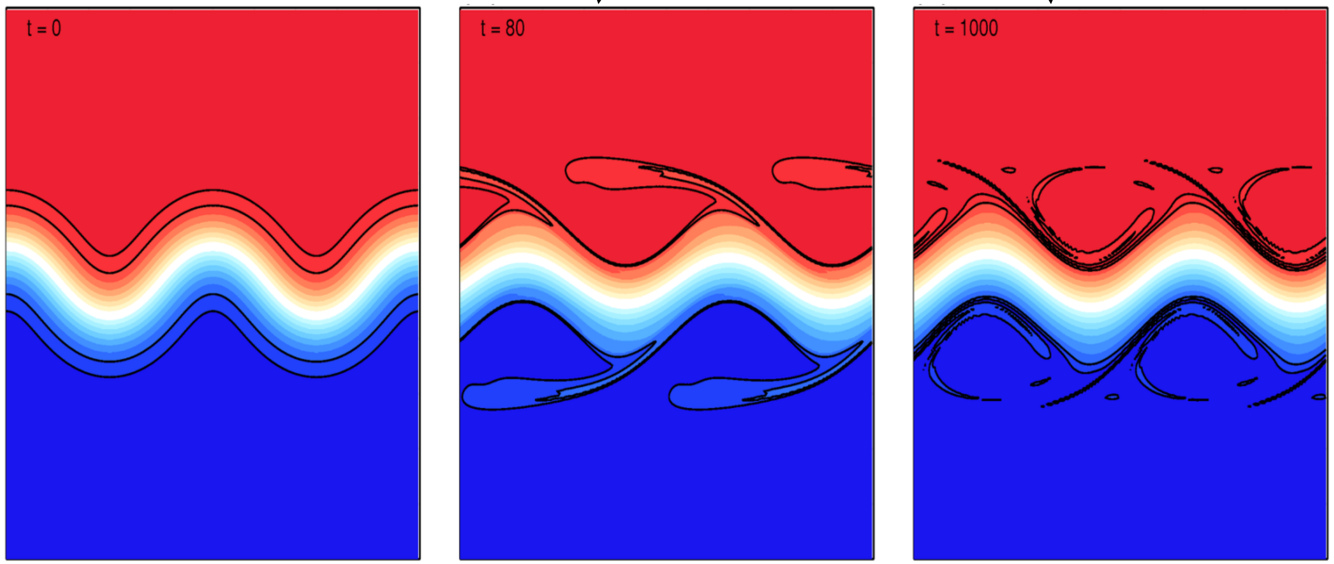
  through advection of PV filaments around the cat's eyes on jet flanks

- Gradual decrease:

  mixing of PV within the critical layer

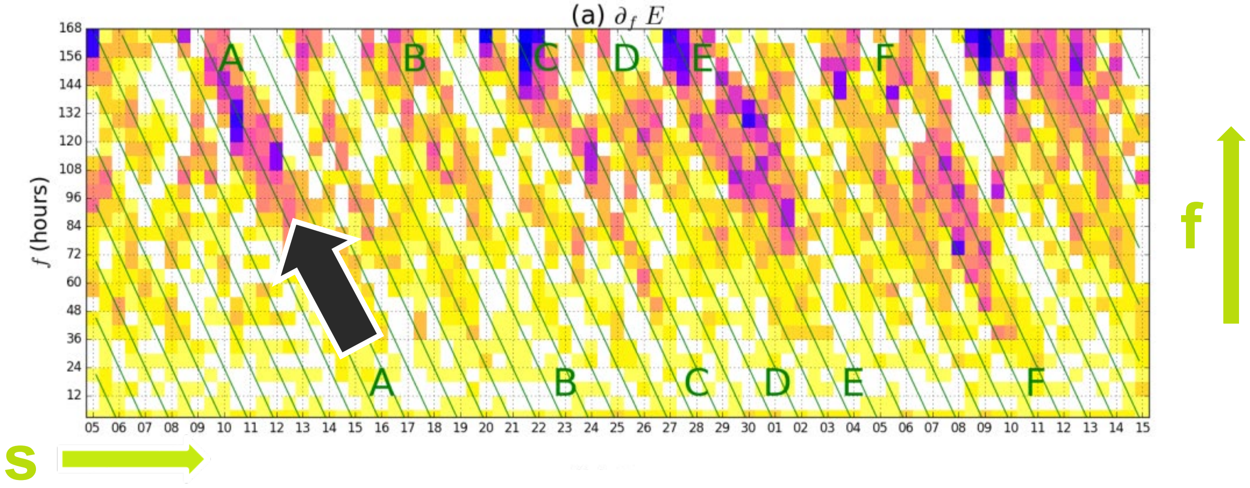
- Wave activity fluxes into jet flanks, but **global WA is conserved** ⇒ WA of jet meander must decrease.





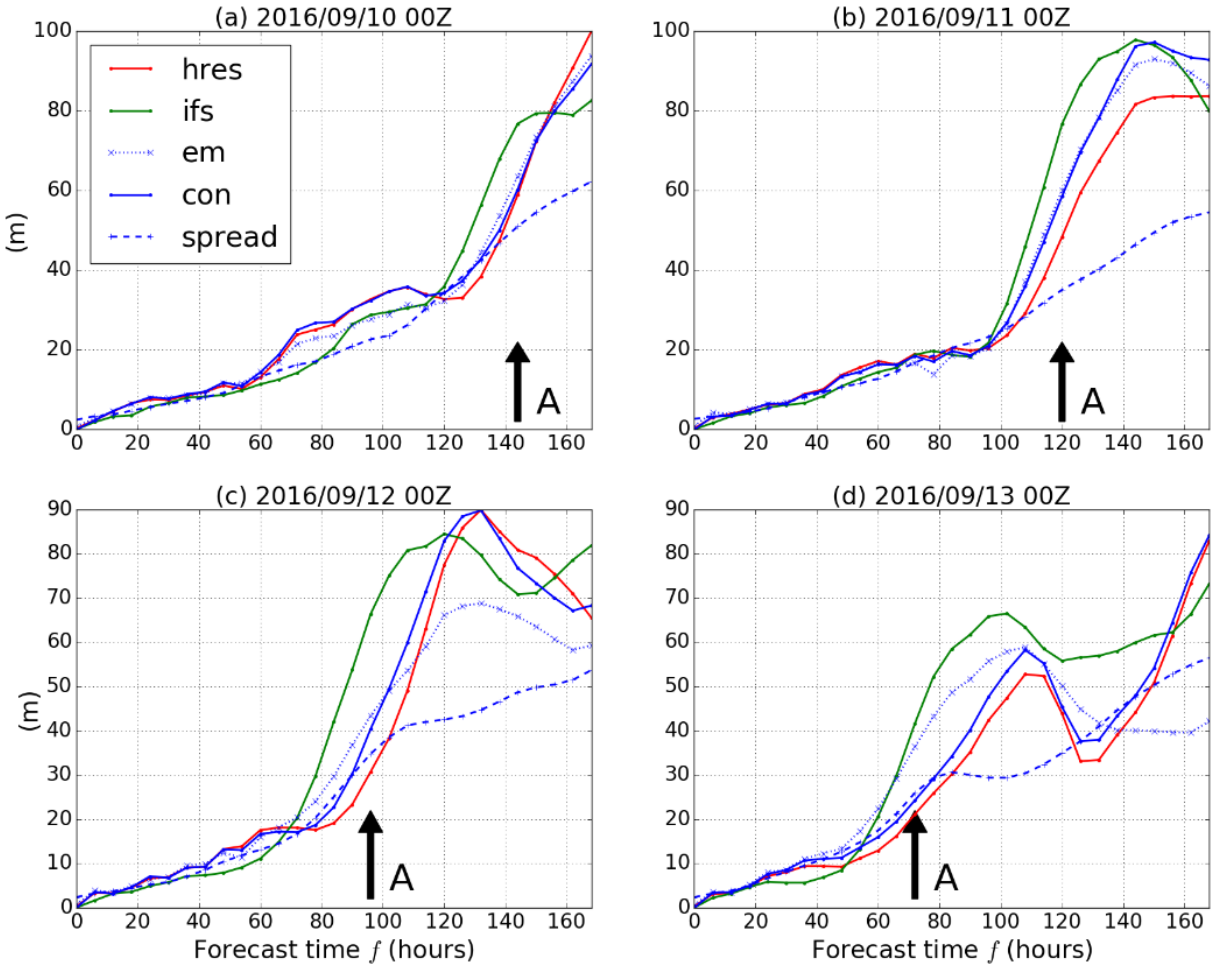
Harvey *et al*,
J. Atmos. Sci. (2018)

Predictability barriers (1)



Rate of change of RMSE in Z500 (∂E / ∂f) with **forecast lead time, *f*,** for all **forecast start dates, *s*,** *over* NAWDEX Period (15/9 to 15/10). **Validation time *t*** is constant along diagonals.

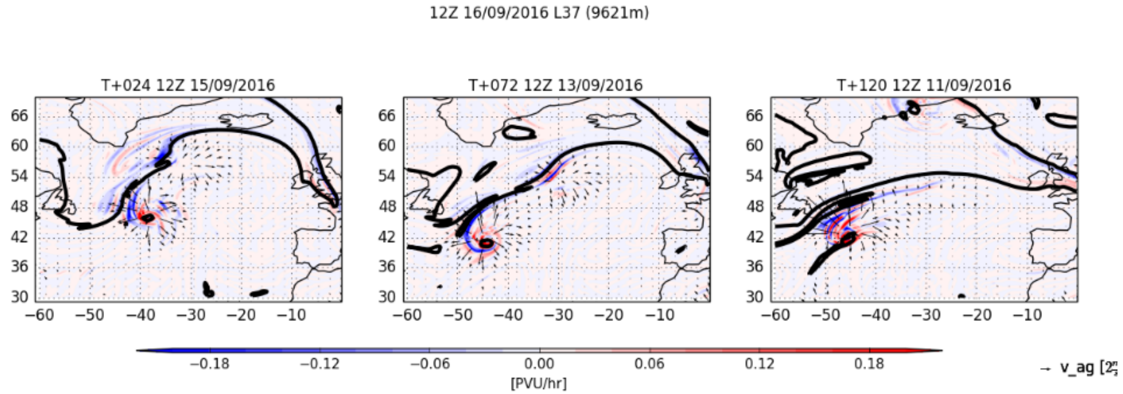
These are events where error grows rapidly (UM & IFS), occurring at the same ***t***

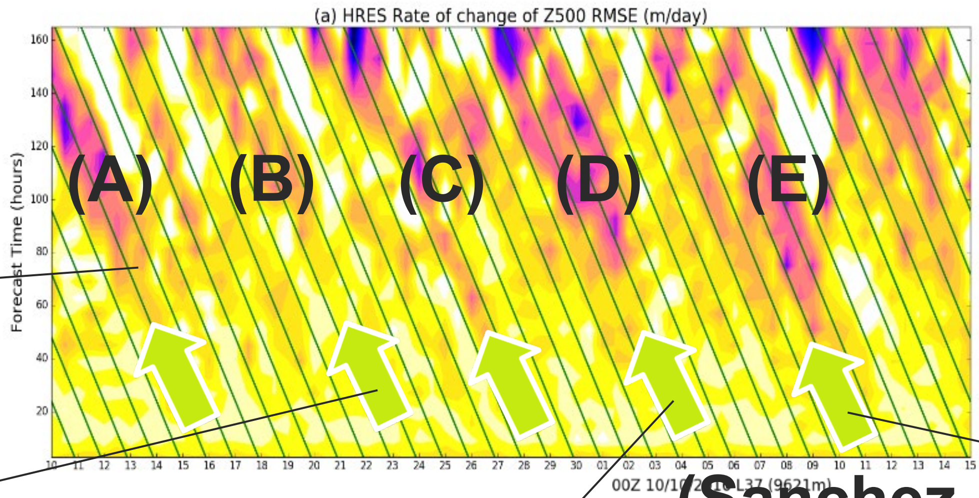


Rate of increase in MOGREPS ensemble spread (Z500) is not as marked

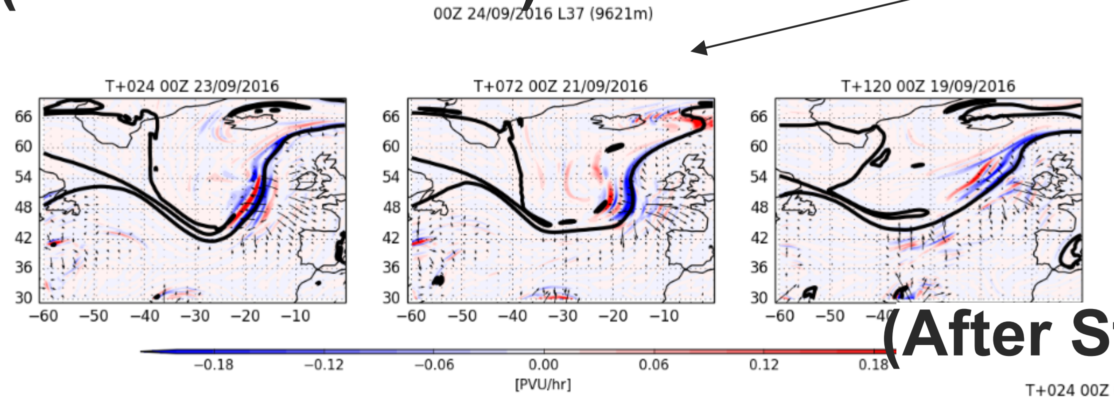
Diabatic outflow events associated with lower predictability

(Ian: 16 12Z)

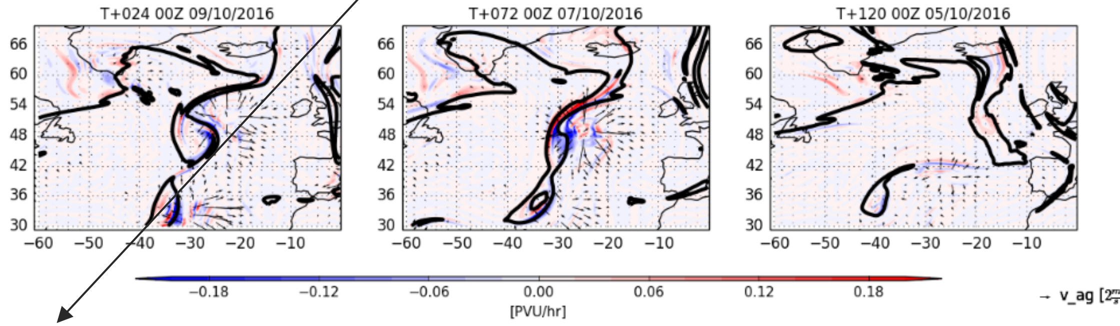




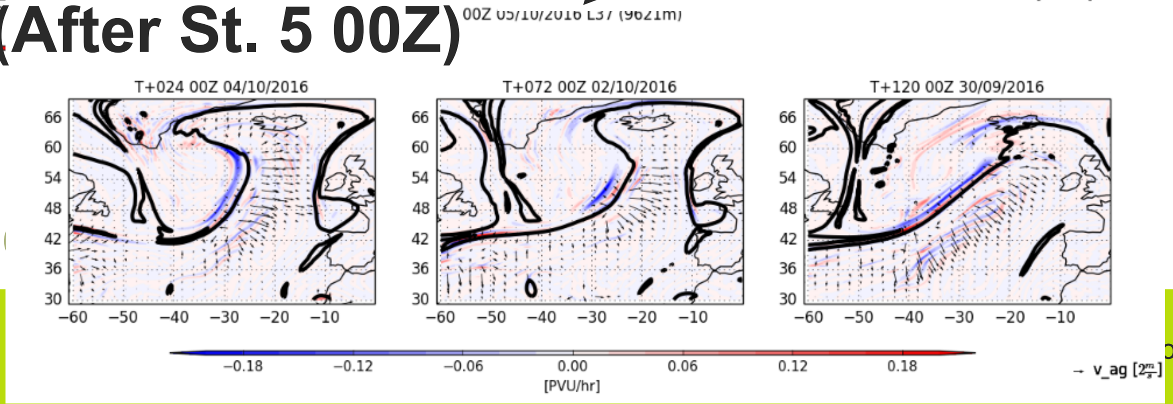
(Vladiana: 24 00Z)



(Sanchez. 10 00Z)



(After St. 5 00Z)



Sanchez, Methven, Cullen & Gray (2

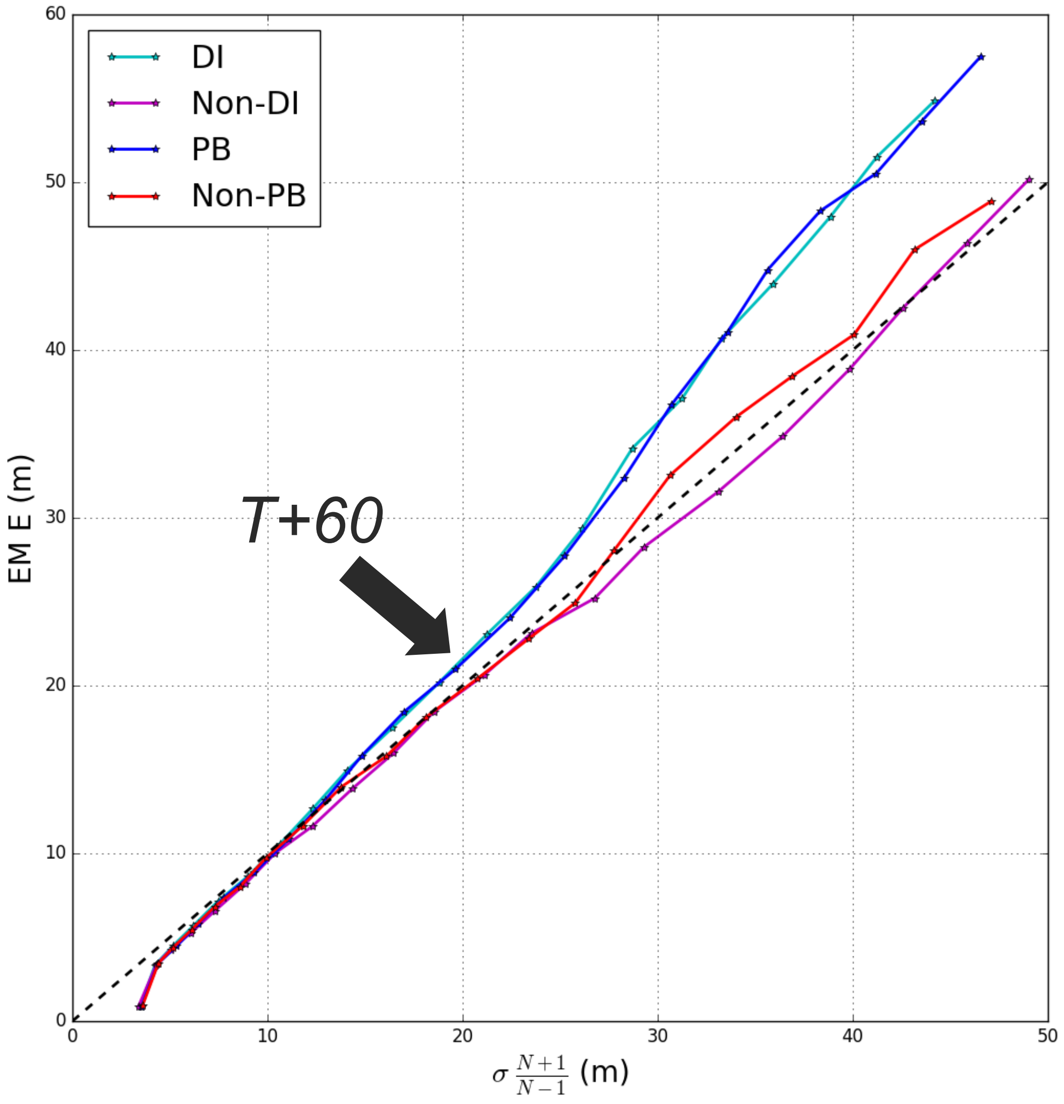
Heating and predictability barriers (PBs)

- Ensemble forecasts on days NOT associated with PBs are well calibrated.

- But, for PB events error grows faster than spread

- Same results obtained by compositing days with strong diabatic influence (DI) on tropopause advection

- **Conclude** – predictability is lower when diabatic processes influence tropopause
- *Model error - diabatic influence is too weak in medium-range forecasts?*

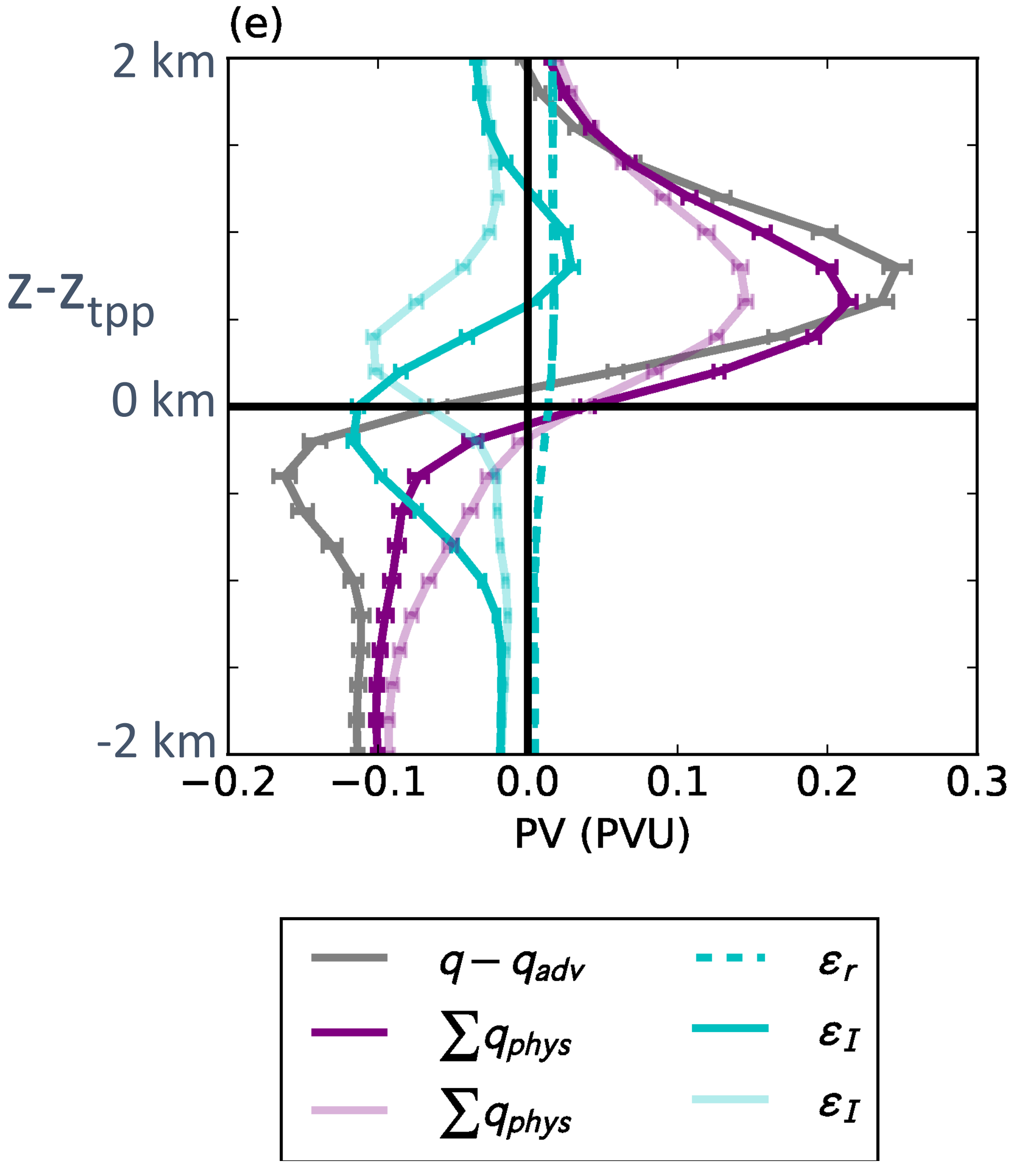


Sanchez, Methven, Cullen & Gray (2020), *QJRMS*

RMSE (E) vs spread (σ) on event-days and the complement. Event defined as upper threshold in PB or DI timeseries.

Composite of 92 forecasts

Relative to the tropopause in troughs



Troughs defined by locations where

$$\theta'(\lambda, \phi, PV2, t) < 0$$

Average on set of levels defined by vertical distance from the tropopause

Physics parameterisations reduce PV below tropopause (and increase it above)

Dynamical core of Met Office Unified Model reduces PV at tropopause

Saffin *et al* (2017), *JGR*

Effect on temperature in operational forecasts

Forecast – analysis