Modal view of atmospheric predictability

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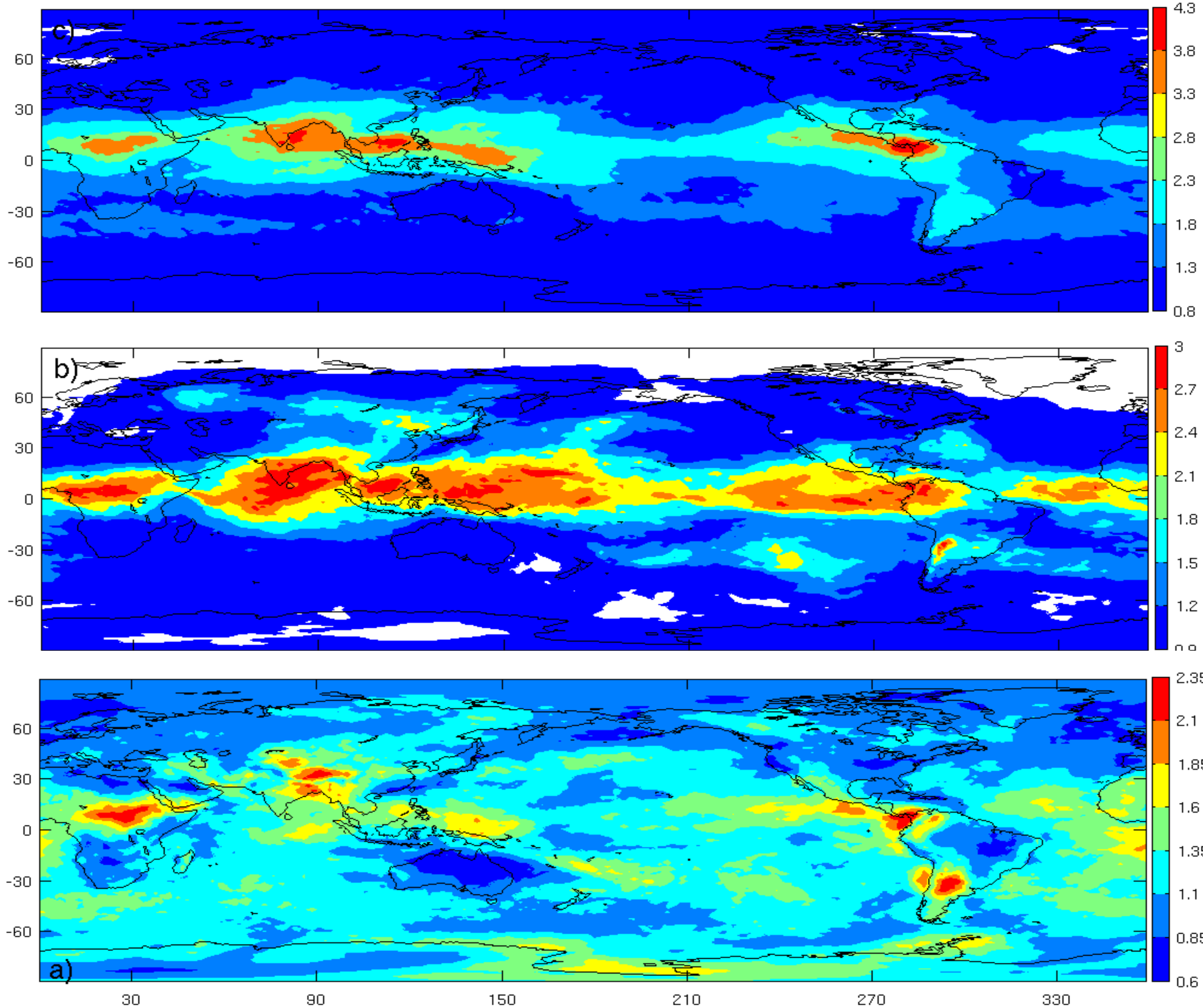
Based on Žagar, N., R. Buizza and J. Tribbia, J. Atmos. Sci., 2015, and Žagar, N., J. Anderson, N. Collins, T. Hoar, K. Raeder and J. Tribbia, to be submitted

The problem of data assimilation

level 38
96 hPa

level 49
199 hPa

level 76
826 hPa

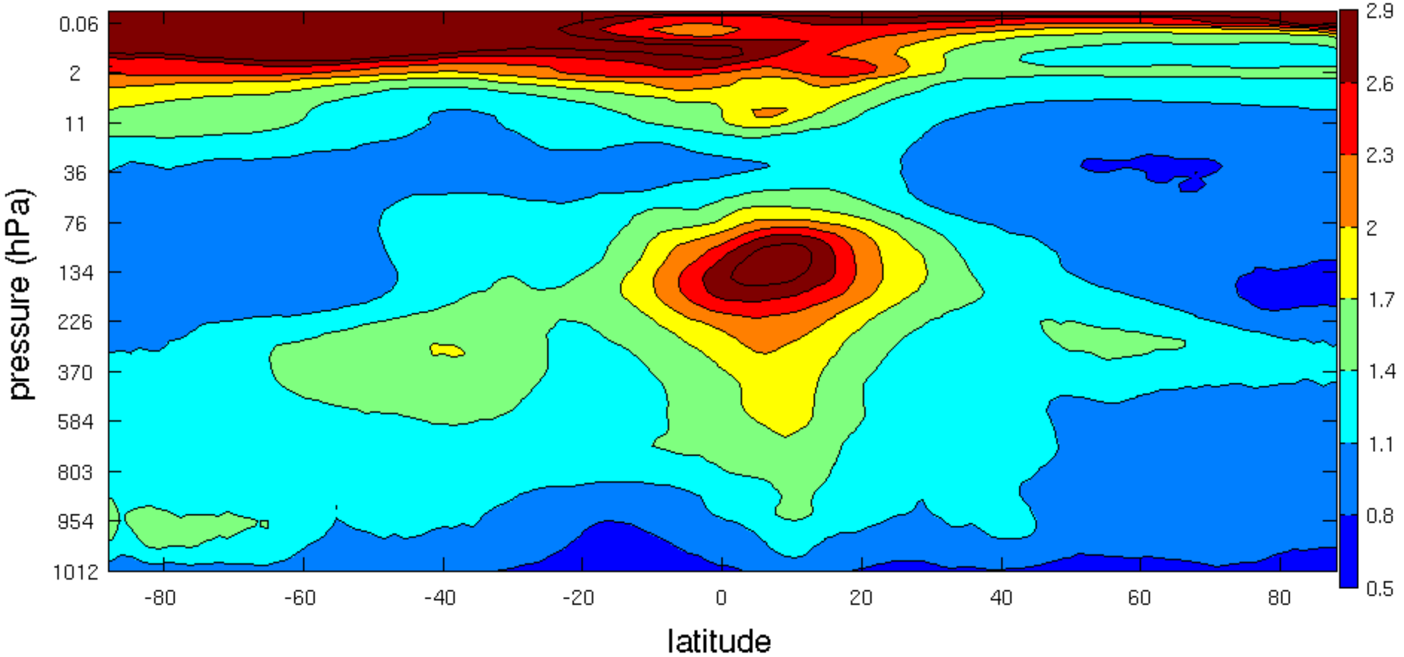


3-h fc errors in the zonal wind, derived from the ECMWF ensemble (cy32r3)

Zagar et al., 2013, QJRMS

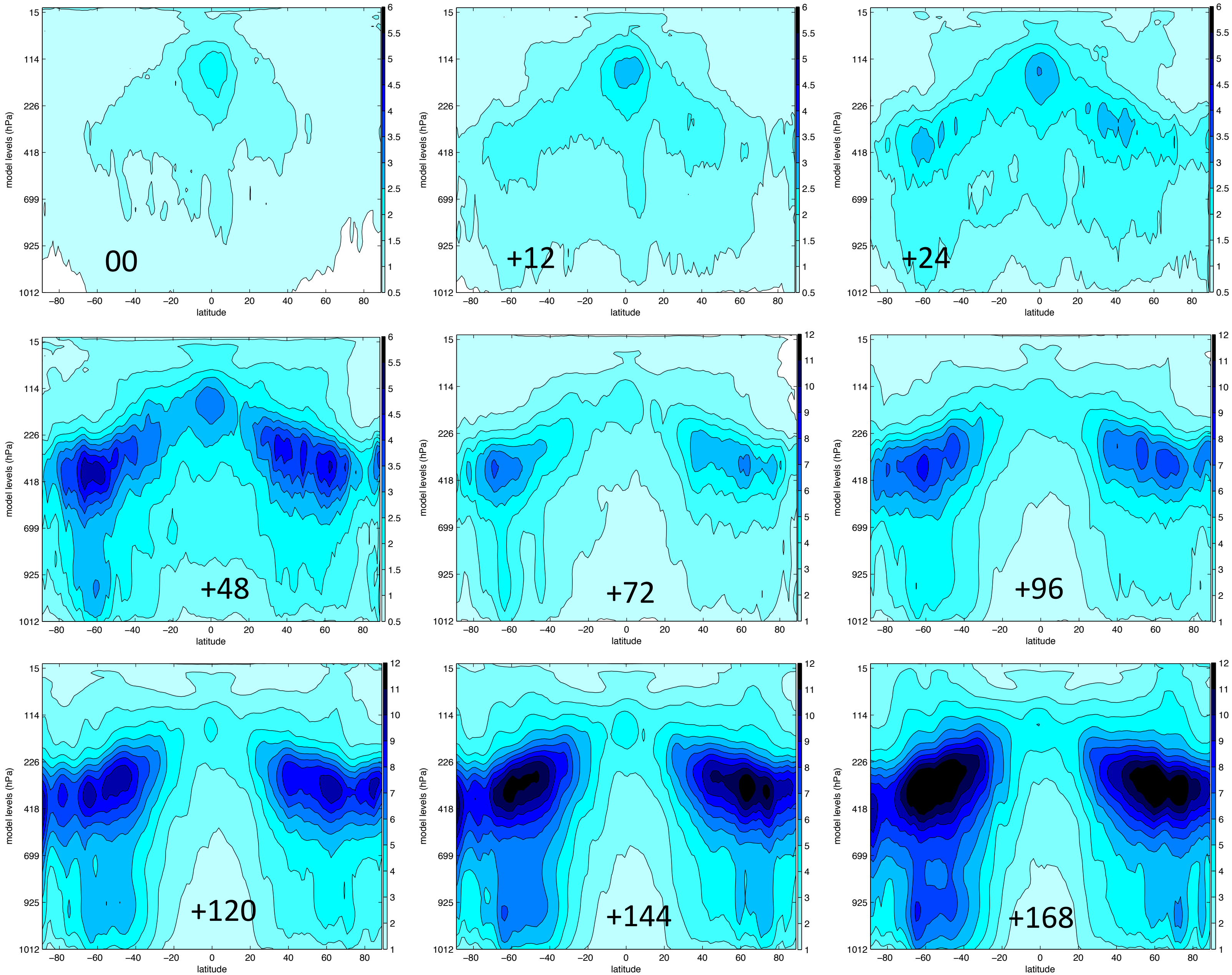
Short-range global forecast errors

Zonally-averaged global short-range forecast errors in the state-of-the-art NWP system are largest in the tropics



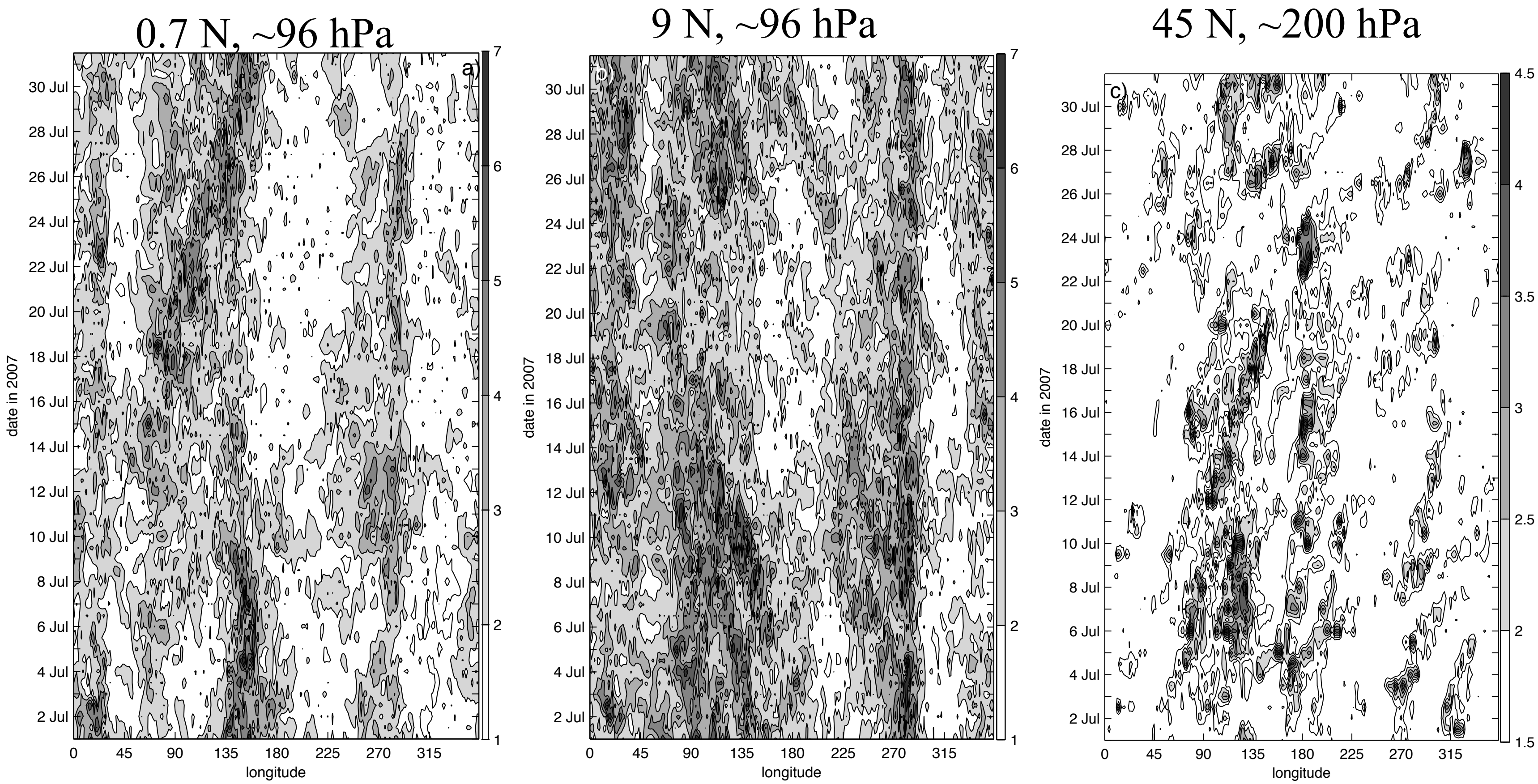
Zagar et al., 2013, QJRMS

Forecast error growth: an example from the ECMWF ENS



Growth of the ENS spread in zonal wind on 25 April 2014

Flow-dependency of the short-range forecast errors



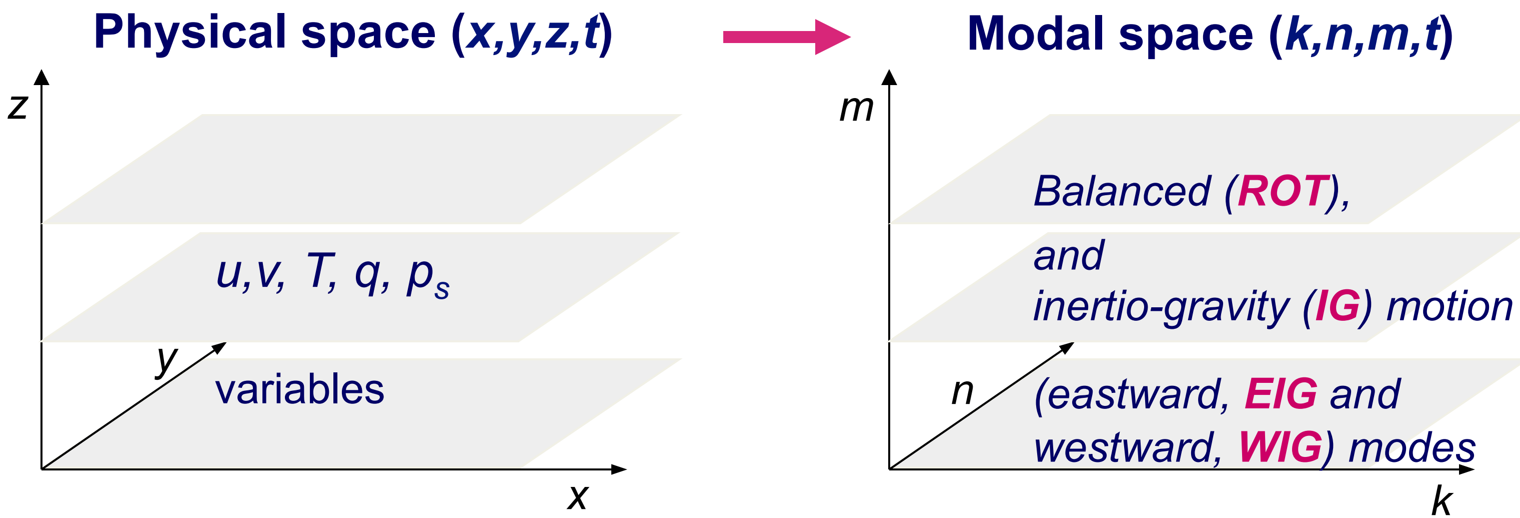
3-h fc errors in the zonal wind, derived from the ECMWF ensemble (cy32r3) during 1 month (July 2007)

Zagar et al., 2013, QJRMS

Outline

- Motivation
- Modal diagnosis of the analysis and forecast ensembles
- Scale-dependent balance analysis of the short-range forecast-error variances in the 4D-Var ensemble
- A modal diagnosis of ECMWF EPS
- Analysis of outputs from a perfect-model OSSE DART/CAM
- Conclusions

Methodology: NMF representation of the forecast errors



Balance: part of the forecast errors i.e. ensemble spread that is associated with the Rossby (quasi-geostrophic) type of solutions to the linearized primitive equations.

The unbalanced part projects onto the inertio-gravity solutions that propagate eastward (EIG) or westward (WIG).

Balanced and IG modes are produced by the normal-mode function expansion.

Ensemble spread in the modal space

If the input fields to the projection are differences between the ensemble members *n*=1,..,*N* and the ensemble mean, the total variance in the modal space is defined as

$$\sum_{k}\sum_{n}\sum_{m}\left[\Sigma_n^k(m)\right]^2$$

The specific modal variance Σ^2 is defined as

$$\left[\Sigma_n^k(m)\right]^2 = \frac{1}{P-1}\sum_{p=1}^{P} gD_m\left(\chi_n^k(m;p)\left[\chi_n^k(m;p)\right]^*\right)$$

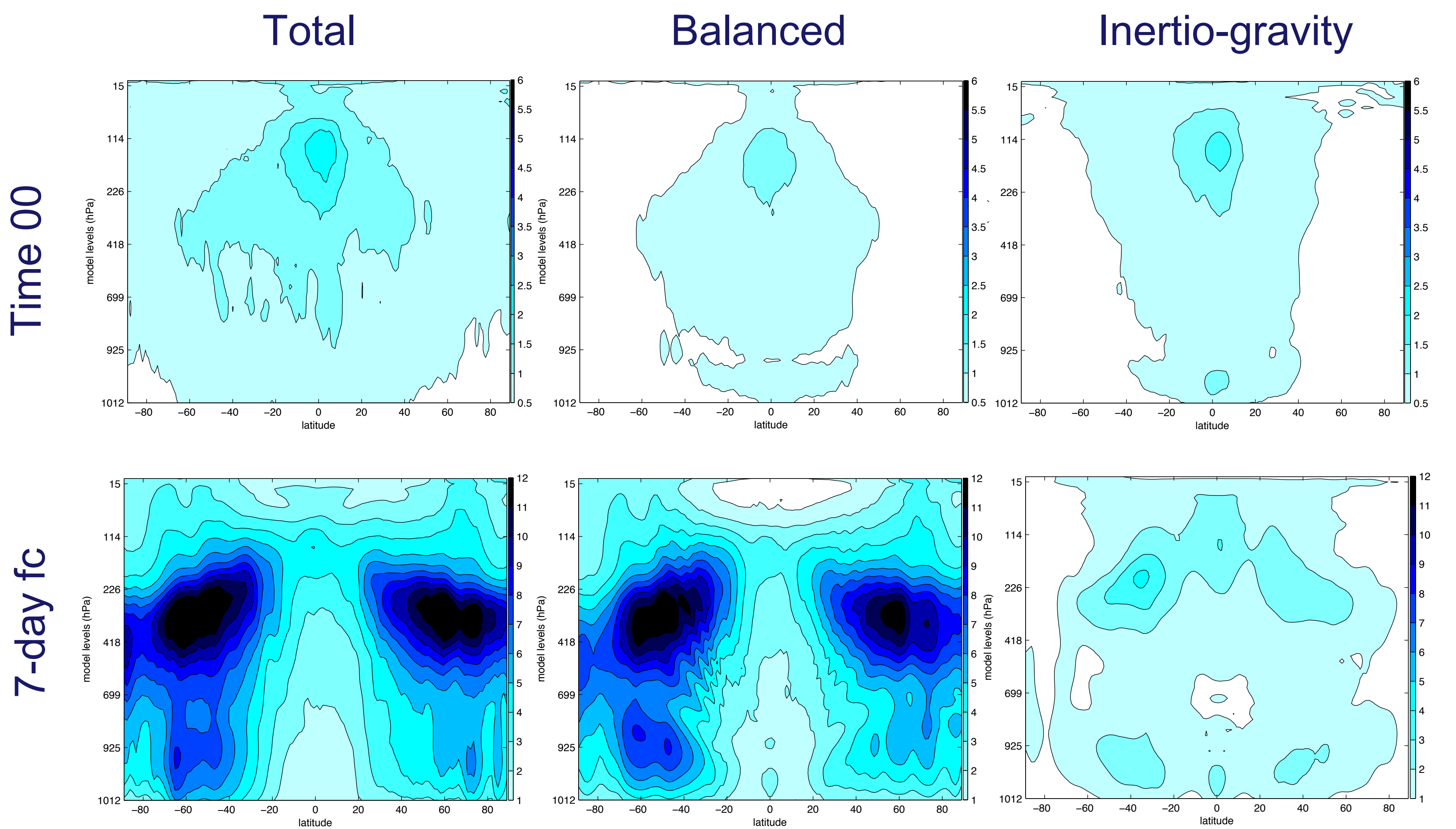
The modal-space variance defined by (5) is equivalent to the total variance in the physical space defined as

$$\sum_{i}\sum_{j}\sum_{m} S^2(\lambda_i,\varphi_j,m)$$

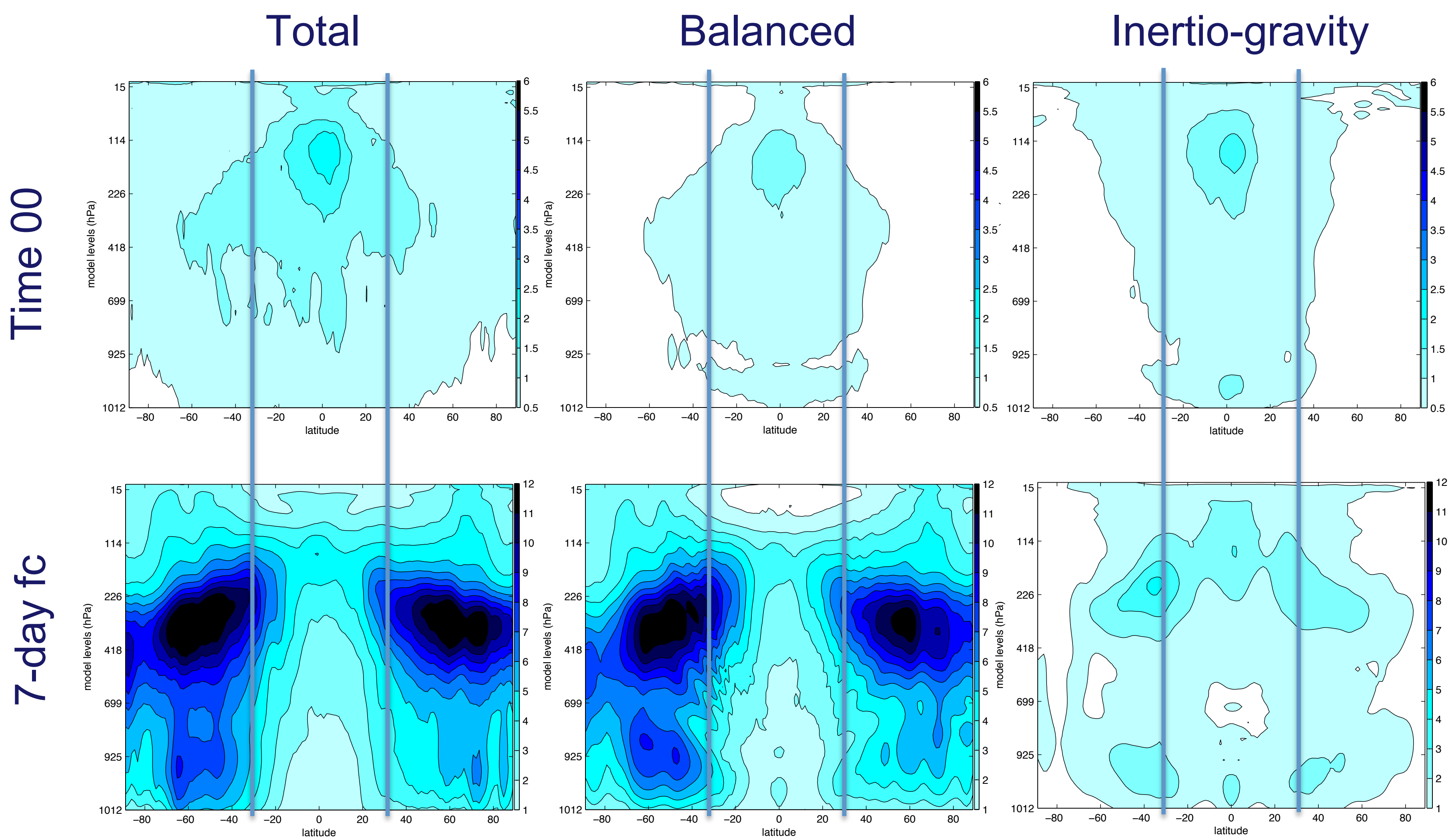
with the specific variance in physical space $\mathbf{S}^2$

$$S^2(\lambda_i,\varphi_j,m) = \frac{1}{P-1}\sum_{p=1}^{P}\left(u_p^2(\lambda_i,\varphi_j,m) + v_p^2(\lambda_i,\varphi_j,m) + \frac{g}{D_m}h_p^2(\lambda_i,\varphi_j,m)\right)$$

Separation of spread in balanced and inertio-gravity components



Separation of spread in balanced and inertio-gravity components



Large-scale structures dominate the spread

Level 43, time 00

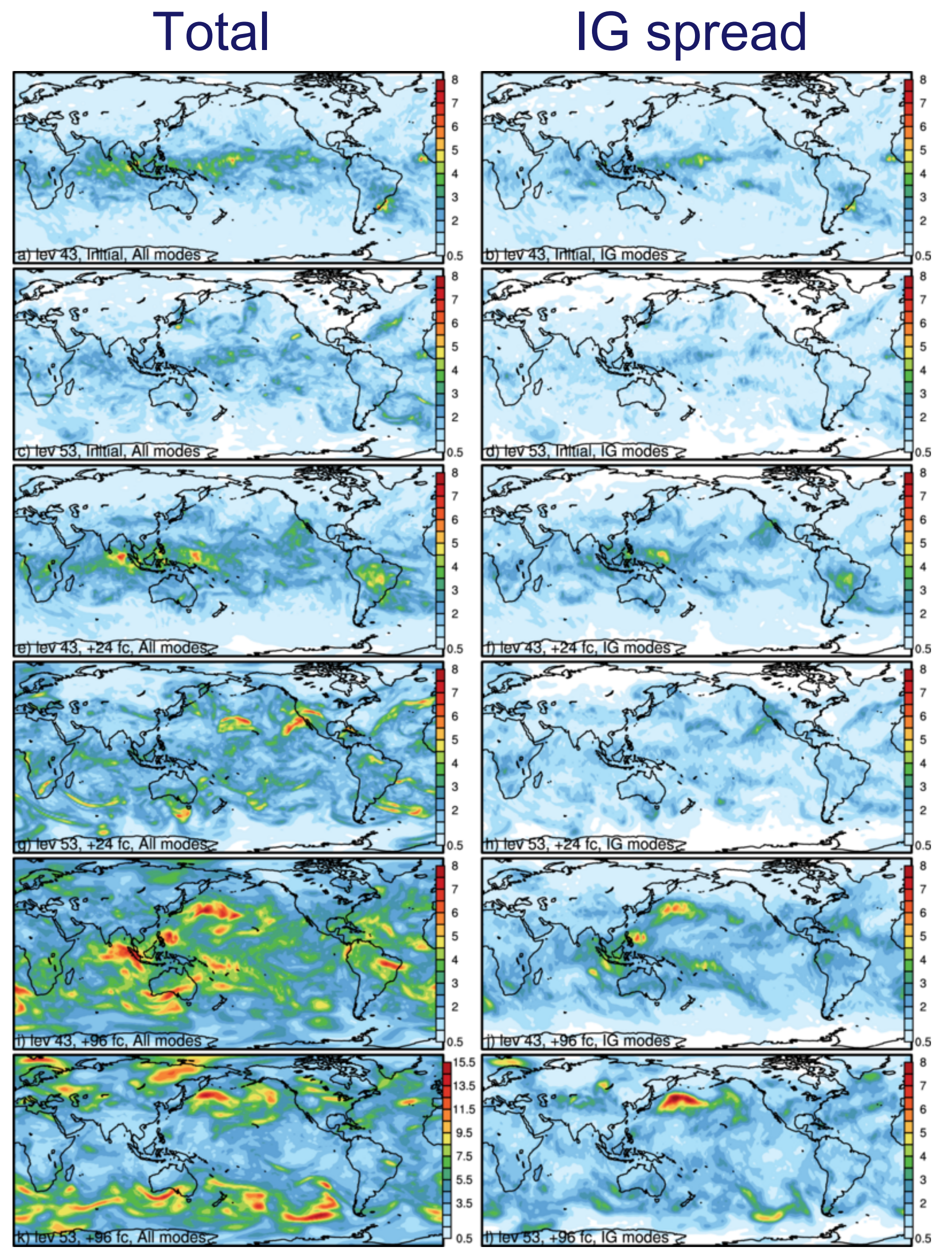
Level 53, time 00

Level 43, time +24

Level 53, time +24

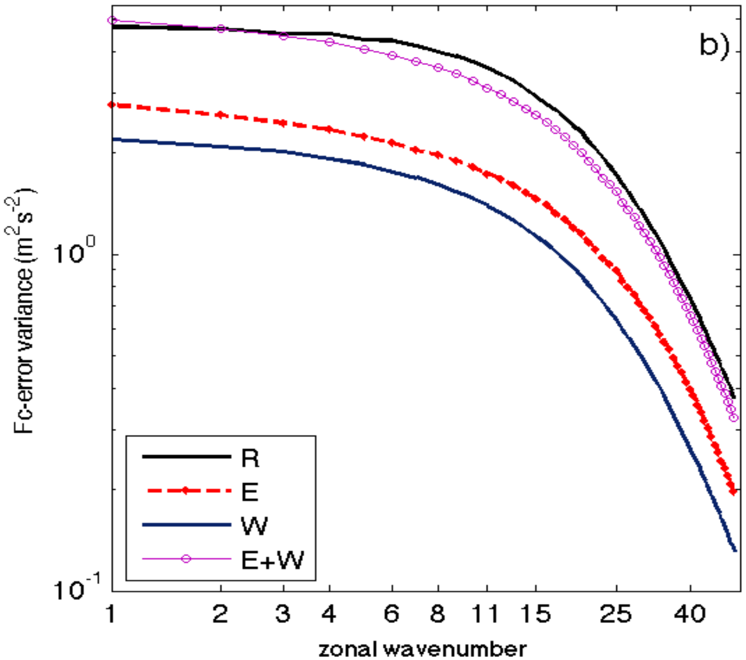
Level 43, time +96

Level 43, time +96

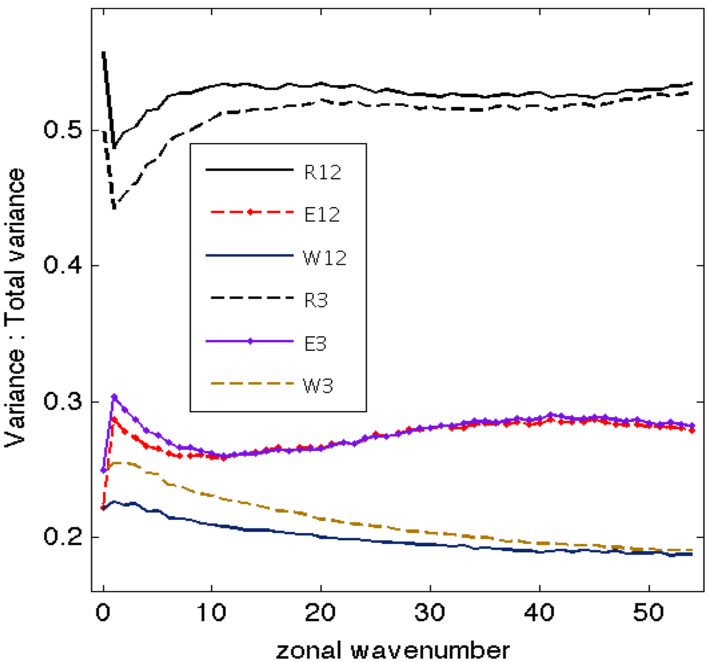


Short-range forecast errors, ECMWF system

12-hr fc range



3-hr versus 12-hr fc range



ROT	EIG	WIG
~52%	~27%	~21%

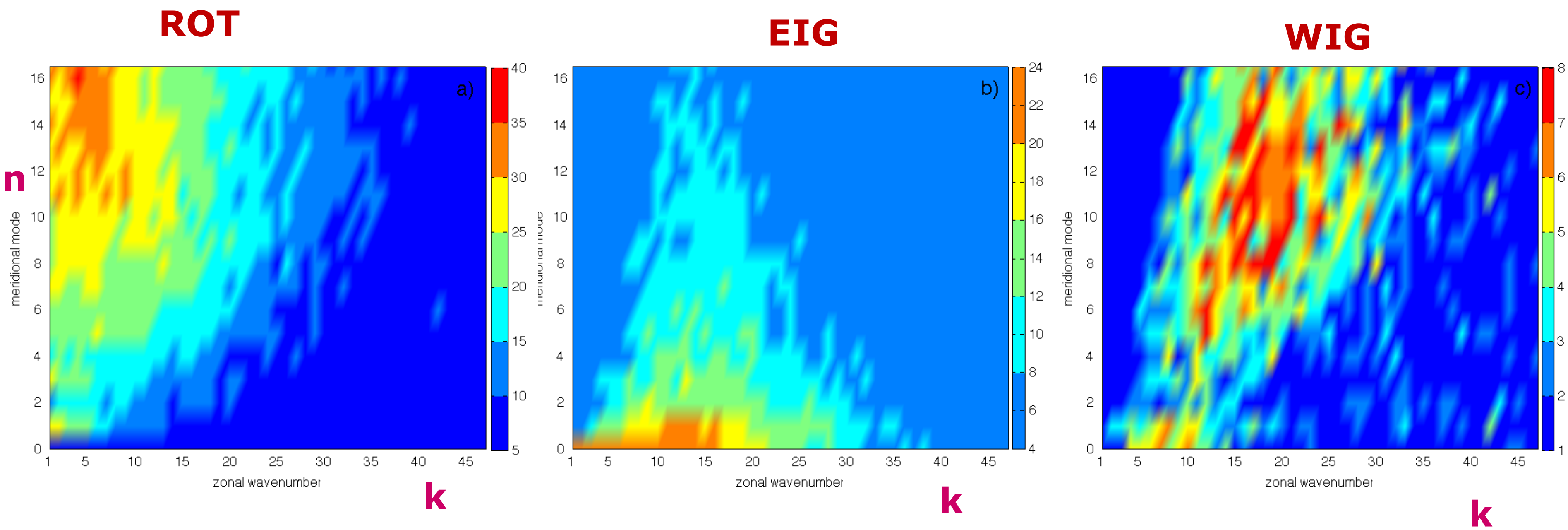
Almost half of the variance of the short-term forecast errors is associated with the inertio-gravity modes

The EIG variance dominates over the WIG variance on all scales

Zagar et al., 2013, QJRMS

Forecast-error variance growth from 3-h to 12-h

[Variance(12) – Variance(3)] / Variance(3)*100%



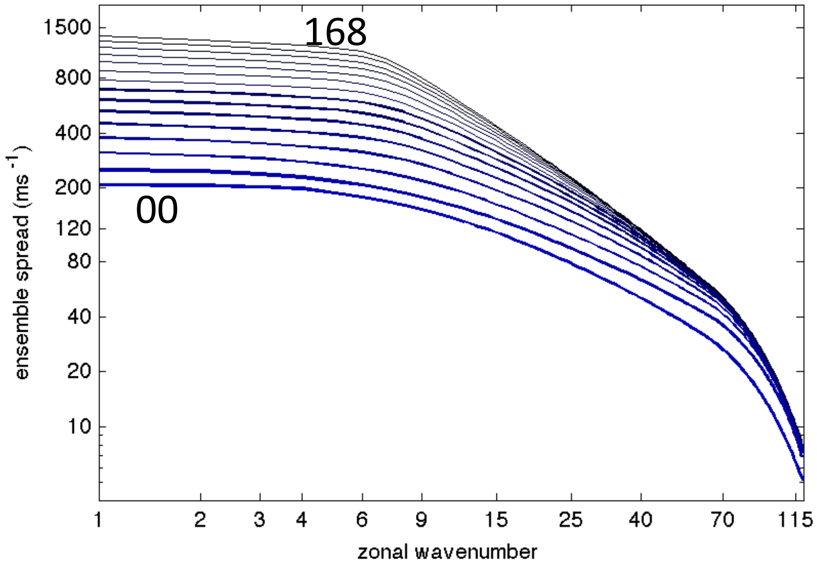
Substantially different forecast-error variance growth in different modes and scales
In the tropics, the short-range growth is largest in the Kelvin mode
A part of the growth of variance in WIG modes is accompanying the balanced variance growth in the midlatitudes

Zagar et al., 2013, QJRMS

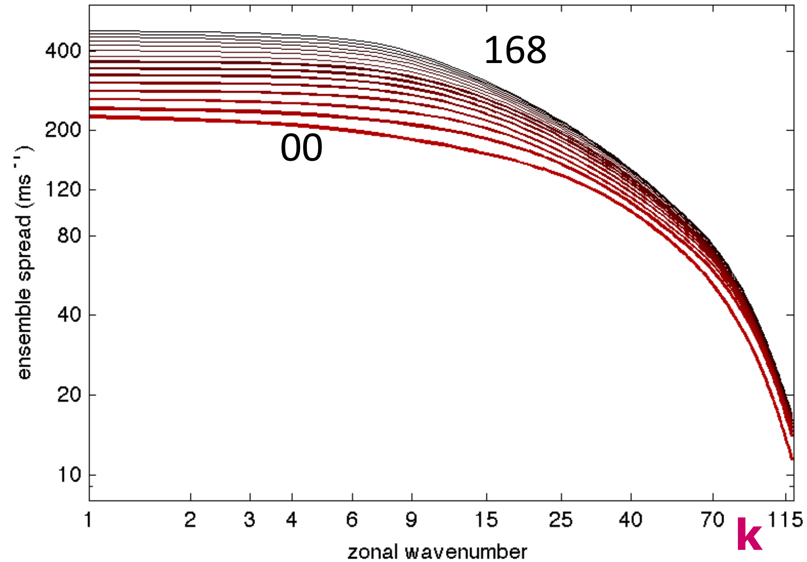
Modal view of the growth of ensemble spread

Based on 1 month of model-level data from the operational ECMWF ENS L91 during Dec 2014

Balanced spread



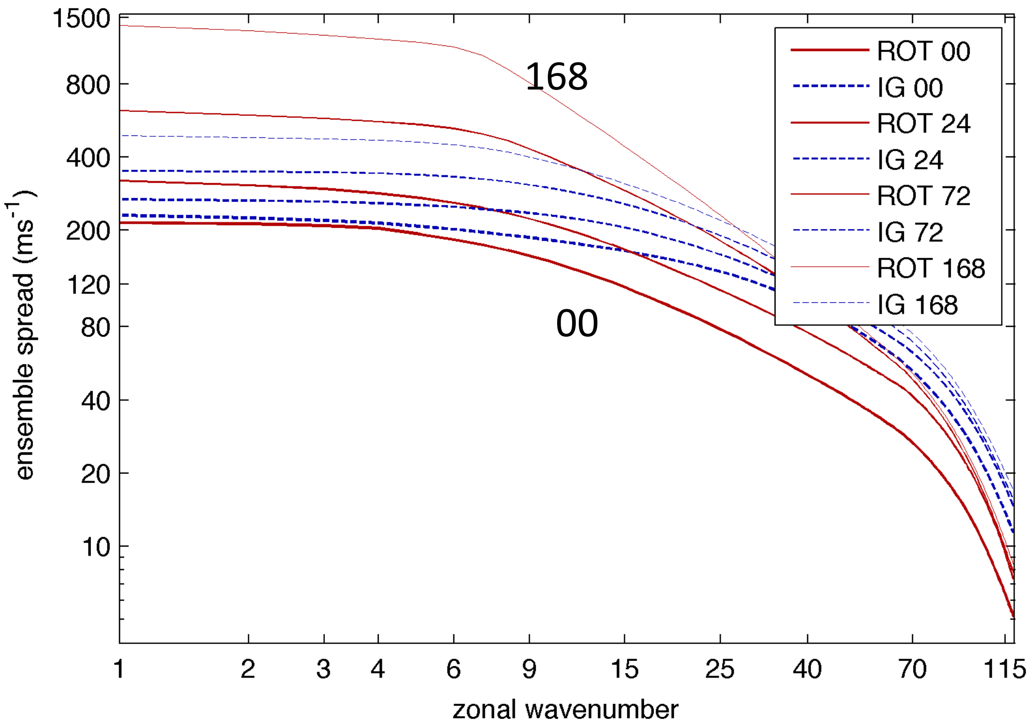
IG spread



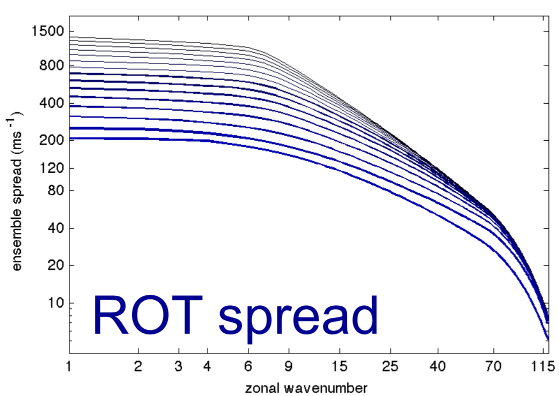
Meridionally and vertically integrated ensemble spread as a function of the zonal wavenumber

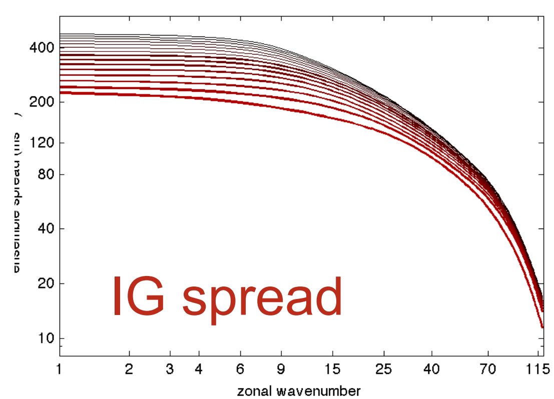
Initially, about half of the ensemble spread is associated with the inertio-gravity modes. Lateron, balanced spread growth dominates

Modal view of the growth of ensemble spread



Initially the IG spread dominates on all scales, especially on synoptic and subsynoptic scales.
In 7-day forecasts it is dominant on the subsynoptic scales (under ~1000 km).

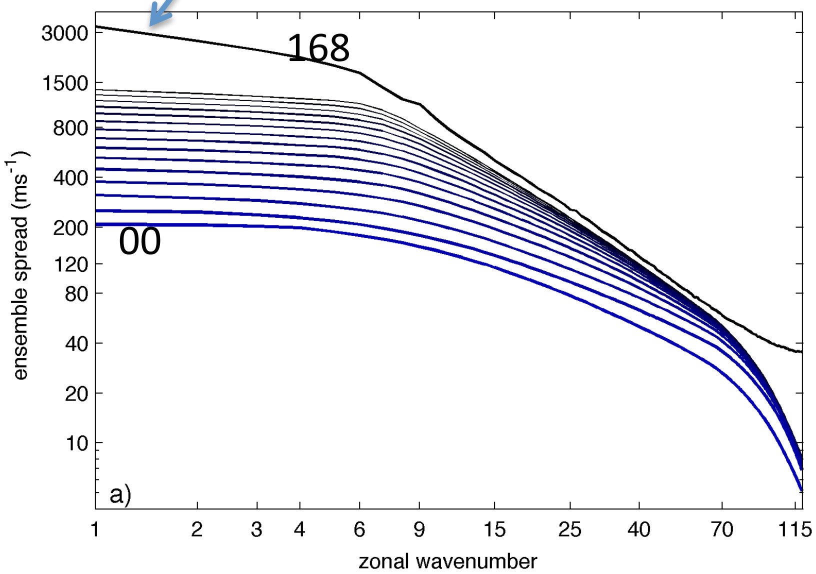




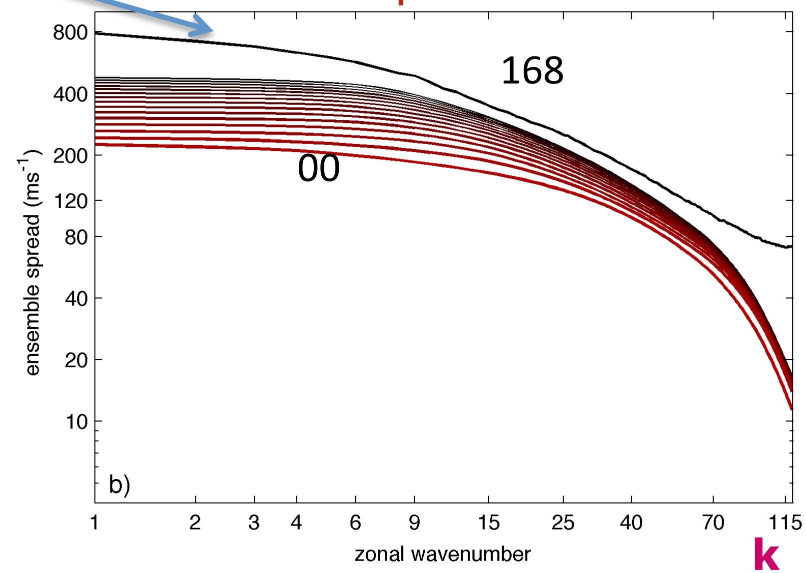
ECMWF EPS ensemble spread: asymptotic curve

Asymptotic curve obtained from non-correlated analyses

Balanced spread



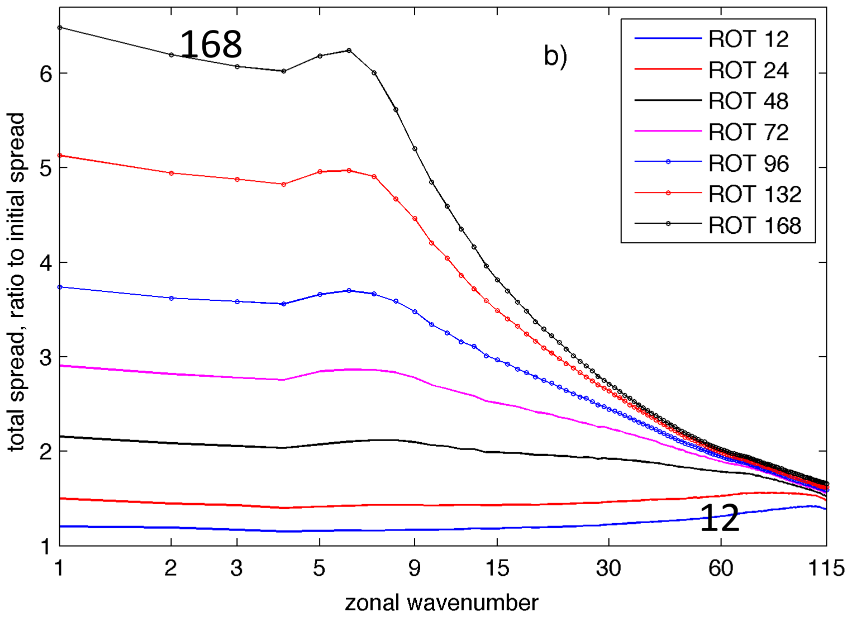
IG spread



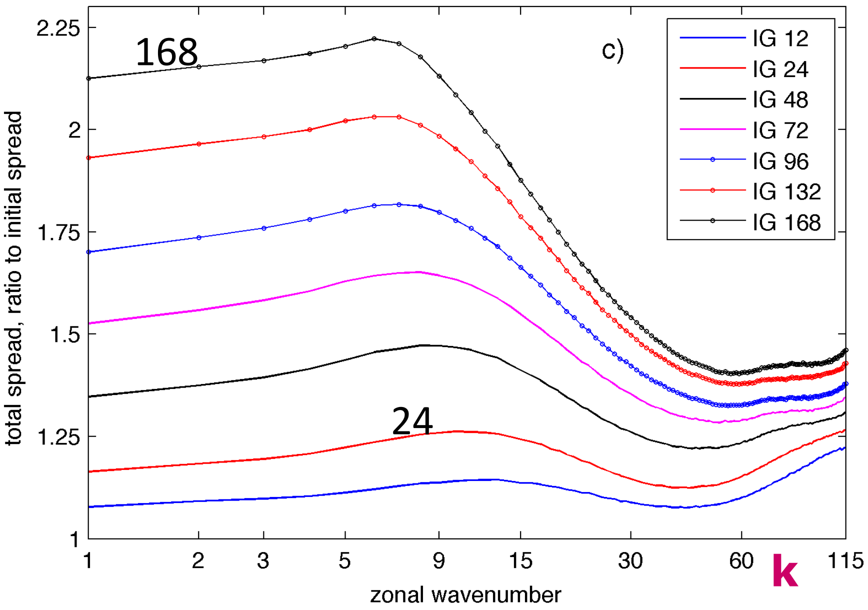
7-day fc range is still far from the limiting curve, especially for IG range

Growth of the spread wrt initial spread

Balanced spread



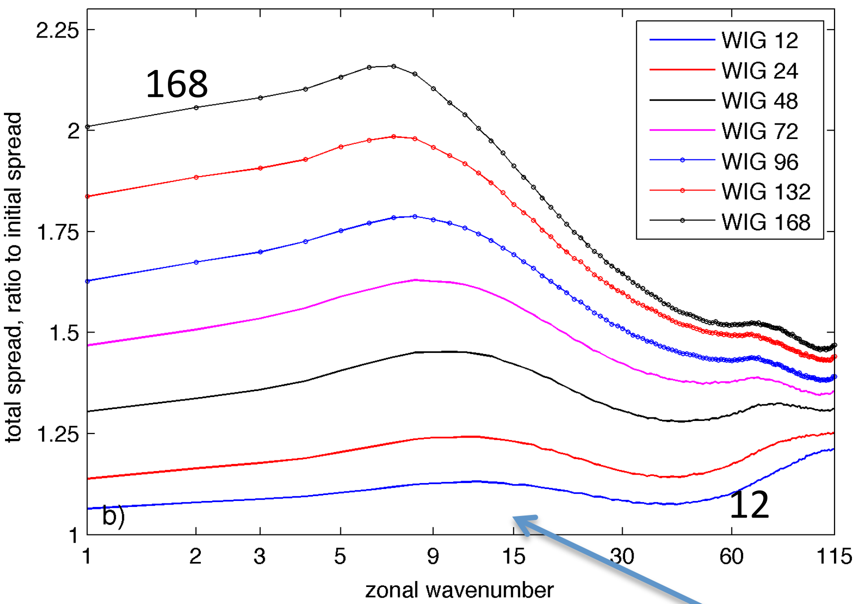
IG spread



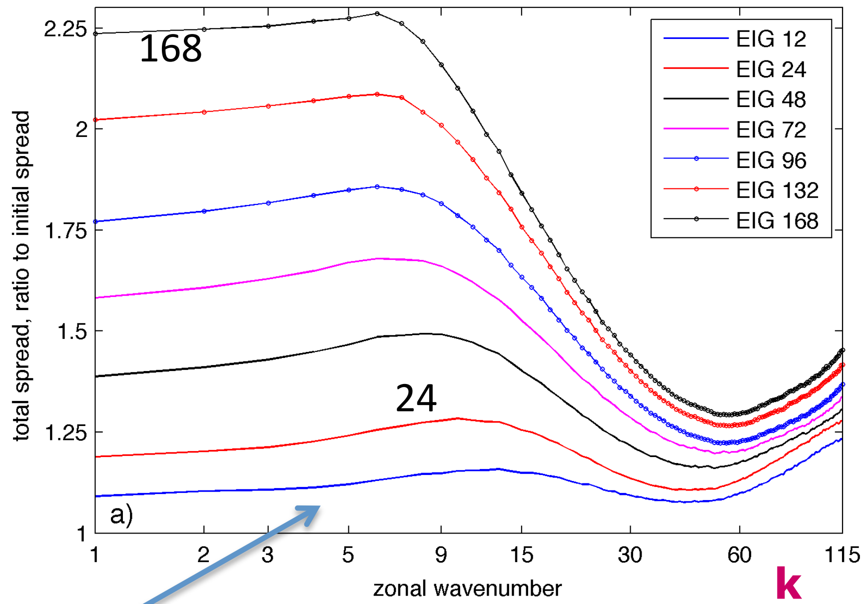
Initially, spread growth is largest in the smallest scales and the synoptic scales of the IG modes (tropics)

Growth of the IG spread wrt initial spread

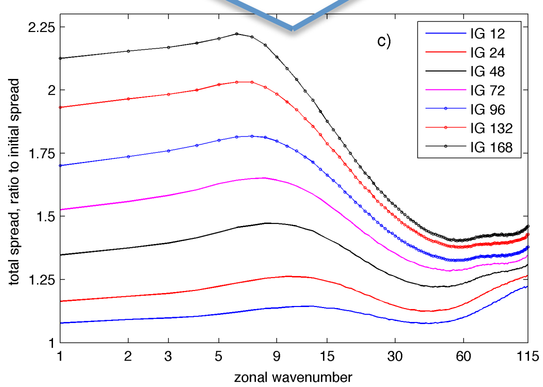
WIG spread



EIG spread

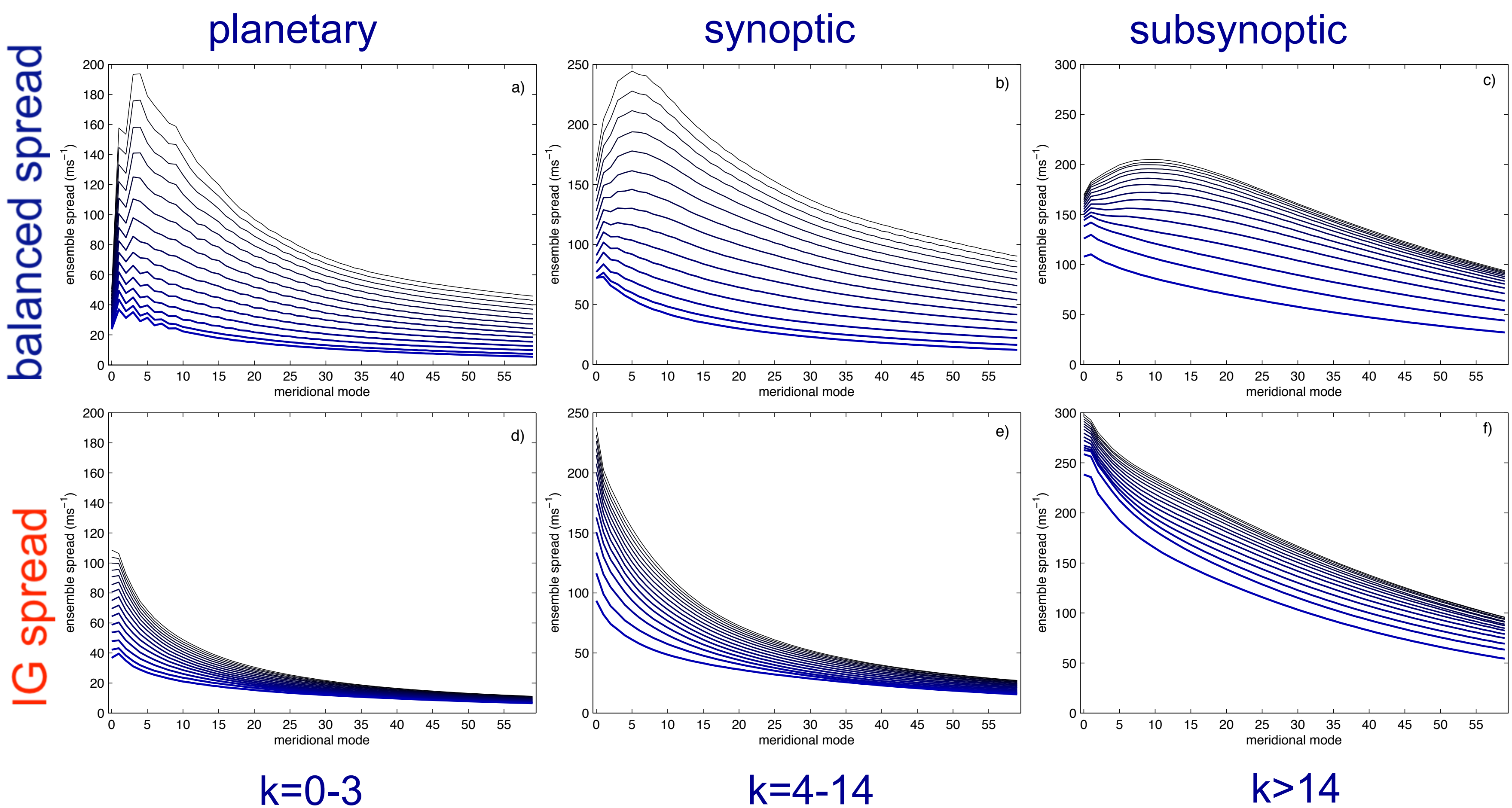


IG spread



Scale-dependent view of the spread growth

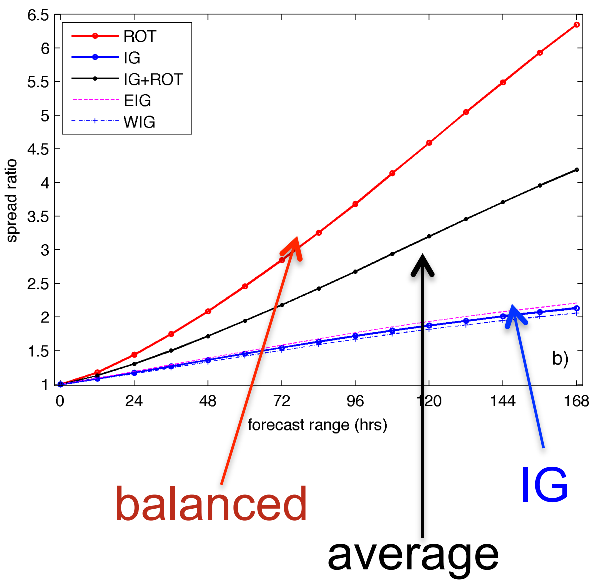
Zonally and vertically integrated ensemble spread as a function of the meridional mode and forecast range



Globally integrated growth curves

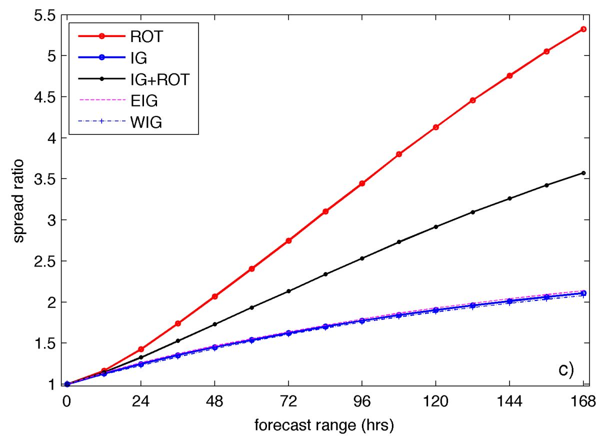
3D integrated ensemble spread normalized with its initial value as a function of the forecast range

k=0-3
planetary



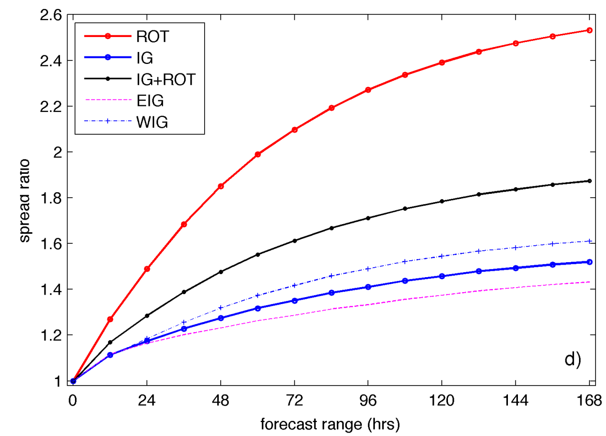
Largest growth of spread is in planetary scales

k=4-14
synoptic



Initially nearly linear growth slows down after day 3

k>14
subsynoptic

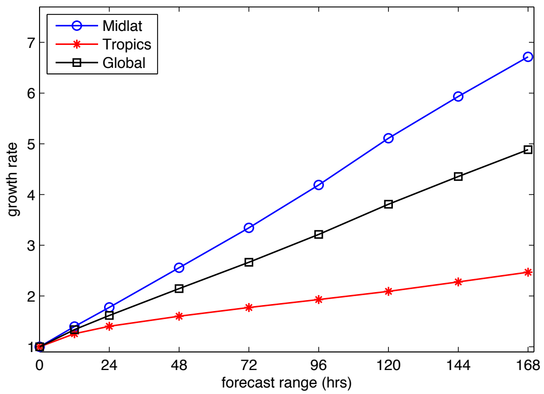


Growth after the first 24 hours slows down in both IG and balanced modes

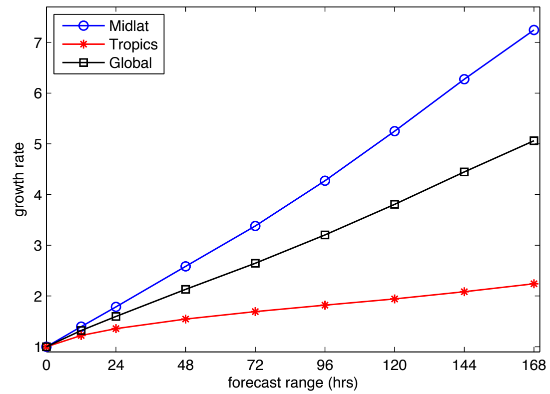
Comparison of the modal and physical space

physical space

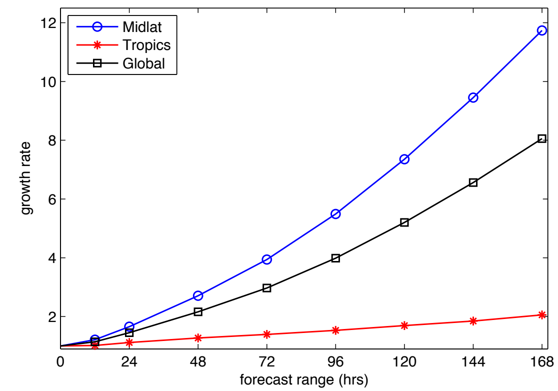
u wind



v wind

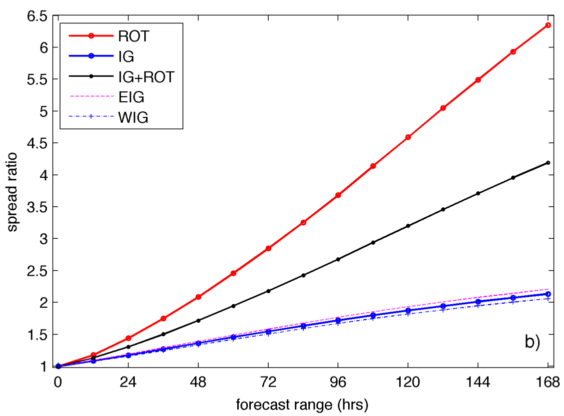


geo. height

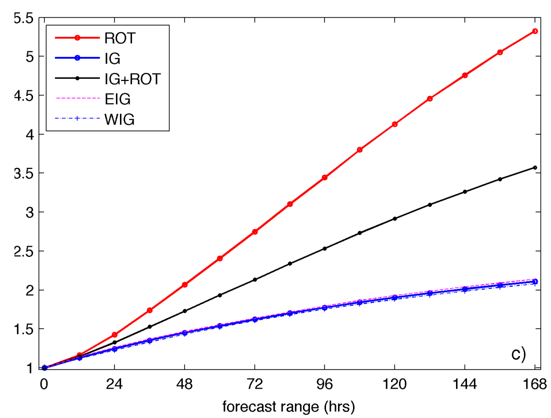


modal space

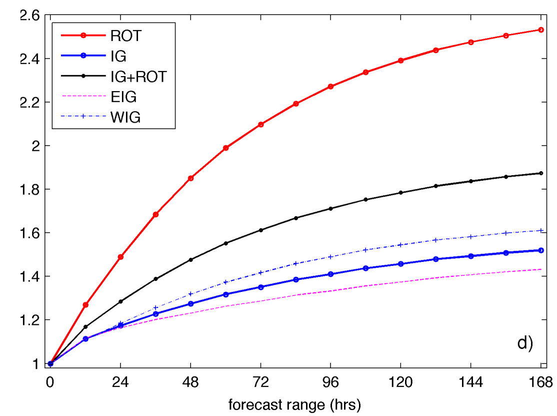
planetary



synoptic



subsynoptic



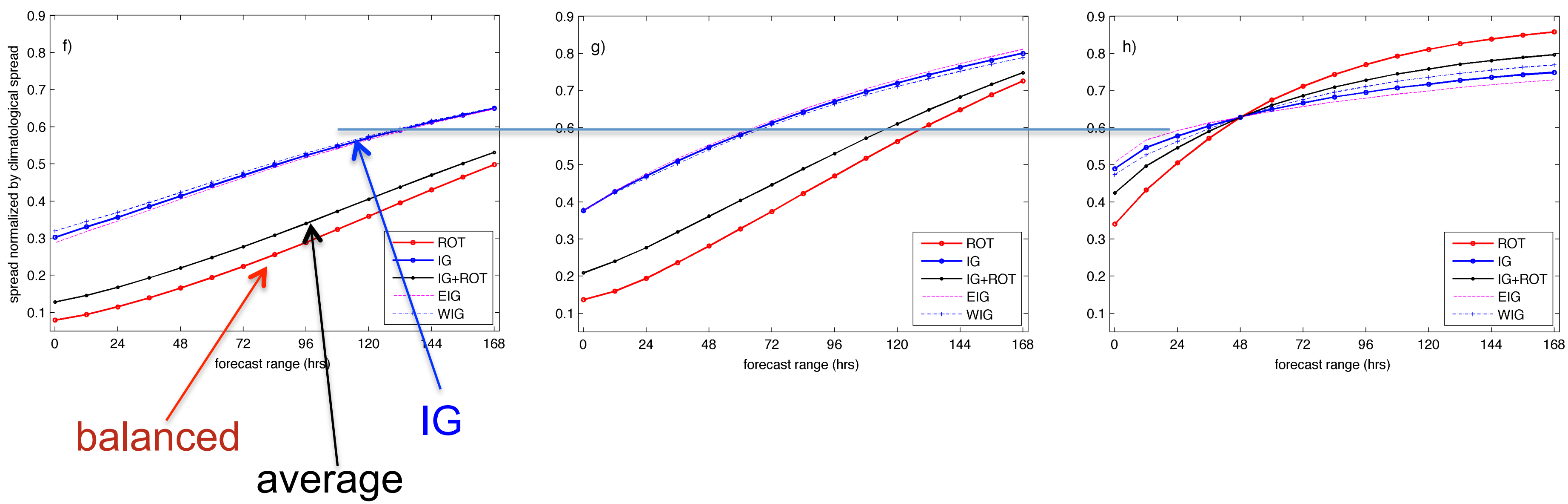
Growth curves and asymptotic curves

3D integrated ensemble spread normalized with climatological spread

k=0-3
planetary

k=4-14
synoptic

k>14
subsynoptic



In 2-day forecast range, the global IG spread reaches 60% of its asymptotic value while the same percentage of the global balanced spread is reached after 5 days of forecasts.

Ensemble reliability in modal space

The control member, not used in the computation of spread, is used as a verifying analysis for the comparison with the ensemble mean forecast.
The computed root-mean-square error (rmse Δ) is compared with the ensemble spread Σ.
The computation of rmse Δ is performed in the modal space as

$$\left[\Delta_n^k(m,t)\right]^2 = \left\langle gD_m \left(\chi_n^k(m,0) - \overline{\chi_n^k(m,t)}\right)\left(\chi_n^k(m,0) - \overline{\chi_n^k(m,t)}\right)^* \right\rangle$$

control member at initial time ($\chi_n^k(m,0)$)

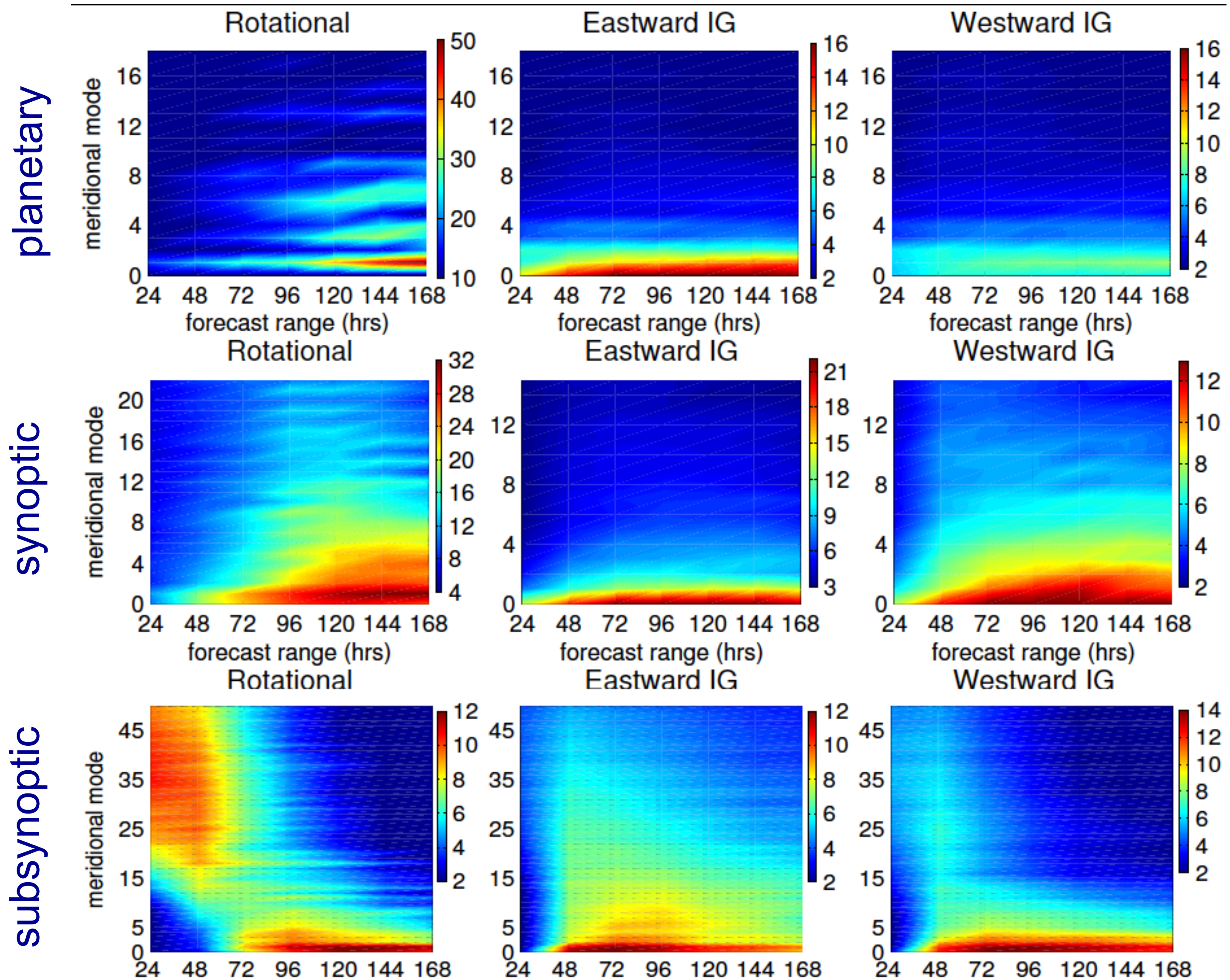
ensemble mean at forecast range t ($\overline{\chi_n^k(m,t)}$)

For a reliable ensemble, the ensemble variance should approximate the mean square error of the ensemble mean, i.e.

$$\left[\Delta_n^k(m)\right]^2 \approx \left[\Sigma_n^k(m)\right]^2$$

Reliability of the ECMWF ENS

A small lack of variability is initially seen in subsynoptic balanced scales, and lateron in tropical IG modes, primarily the Kelvin mode



What if the model were perfect?

Perfect-model assimilation experiment with DART/CAM ("PM")

Data Assimilation Research Testbed (DART), by Jeff Anderson and collaborators, *http://www.image.ucar.edu/DAReS/DART/*

Spectral T85 Community Atmosphere Model, CAM 4 physics

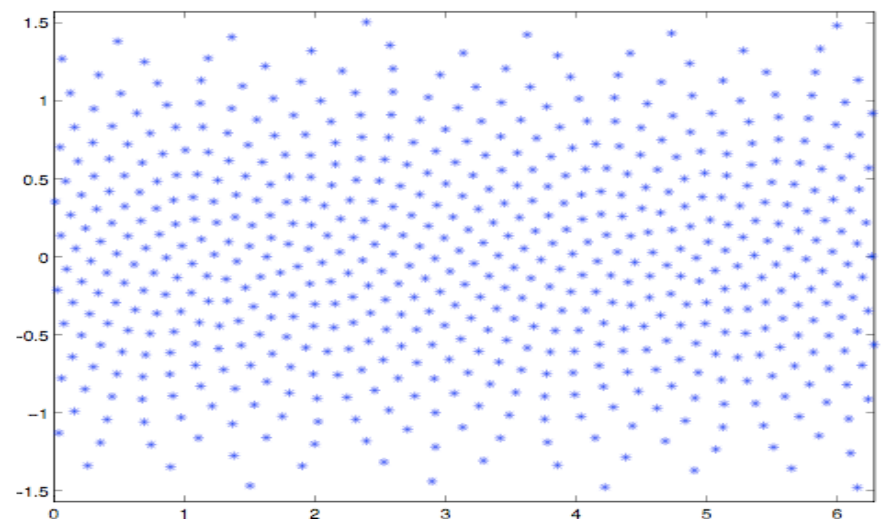
Long spin-up (from 1 Jan 2008) with the observed SST to reproduce nature run ('truth')

Preparation of the observations from the nature run

Preparation of the homogeneous observing network (Δ~920 km)

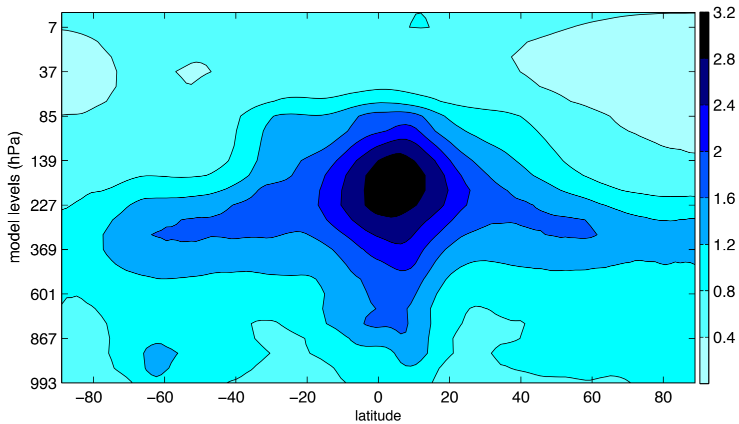
Assimilation cycle during three months (Aug-Oct) in 2008

No inflation



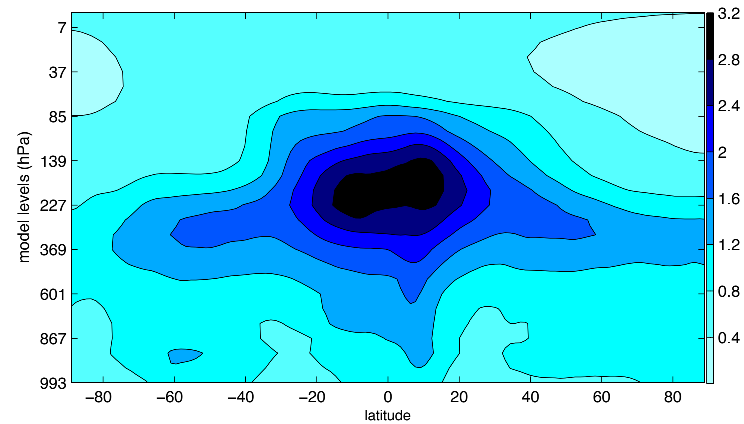
Short-range global forecast errors in the perfect-model EnKF framework

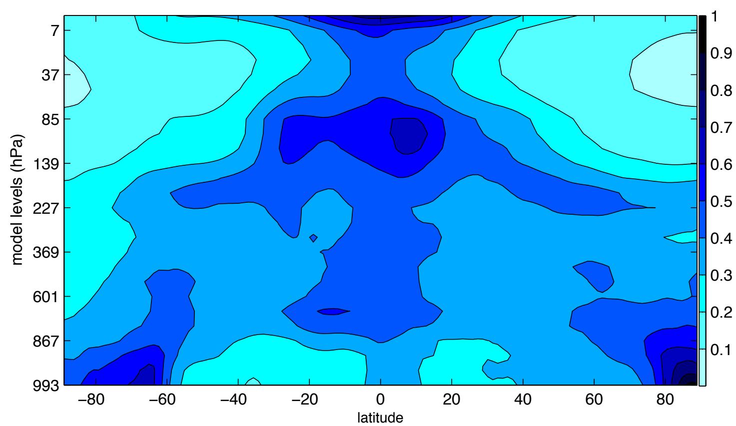
Zonally-averaged global short-range forecast errors in all variables are largest in the tropics



Zonal wind

meridional wind

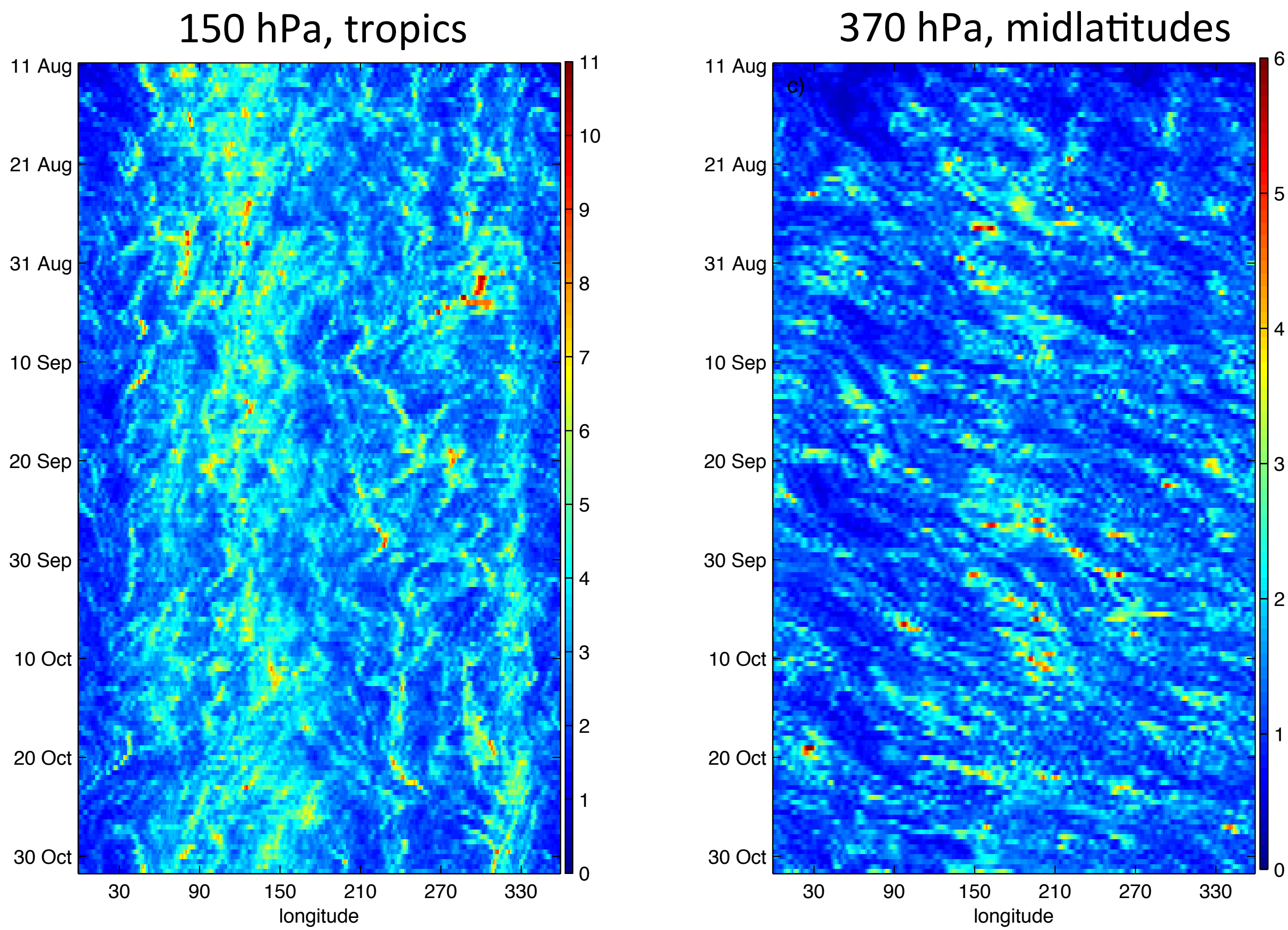




temperature

Flow dependency of forecast errors in the perfect-model EnKF framework

Ensemble spread in zonal wind, 12-hour forecast ensemble



Summary

- Projection of the forecast-error fields on the normal modes of the N-S equations offers a physically attractive approach to the quantification of errors and understanding of their dynamical properties during the forecast.

- The QG theory (balance) has been the backbone of the variational data assimilation modelling for the global NWP. However, it is not the optimal way to improve the data assimilation modelling in the tropics, where the short-range forecast errors are largest. An approach aware of the IG balances may be needed.

- About half of the global forecast-error variances in short range in the NWP model ECMWF is unbalanced. The perfect-model (PM) assimilation experiment with the EnKF and DART/CAM system provides similar results.

- The growth of spread in the ECMWF EPS system is dominated by the increase of balanced spread in planetary scales. Overall the system is found to be somewhat underdispersive in the tropics, associated primarily with the Kelvin wave in all scales.

Thank you for your attention!