Diagnosis of analysis and forecast ensembles by using normal modes

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Questions

- How large part of the global atmospheric forecast errors pertains to the divergent motion i.e. inertio-gravity (IG) waves?
- How is the analysis uncertainty split between the balanced (ROT) and IG motion? How is it dependent on the assimilation system and the assimilation methodology (4D-Var versus the ensemble Kalman filter (EnKF)?
- How important are the large-scale tropical waves for the global data assimilation? How are the tropical forecast errors in the IG motion spread across the scales, time and motion types?
- What is the real potential of the EnKF due to flow-dependent background-error covariances in comparison to 4D-Var, especially in the tropics?

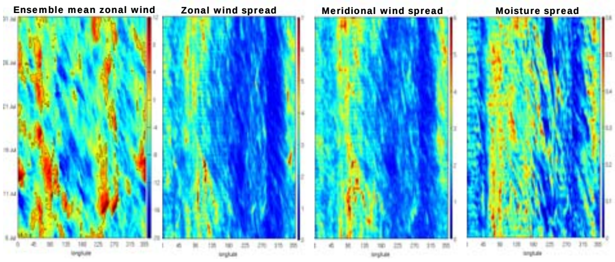
Datasets

Two ensembles of global analyses and forecasts for July 2007:

- NCAR EnKF system DART/CAM (http://www.image.ucar.edu/DAReS/DART/): 80-member CAM ensemble on the horizontal resolution T85, 26 vertical levels up to 3.5 hPa. Limited number of observations (conventional observations and AMVs). The covariance localization and a time constant, spatially varying covariance inflation are applied. No moisture observation assimilated.
- ECMWF 4D-Var ensemble: 21-member ensemble with 12 hour 4D-Var and model cycle 32r3. It uses operational 91 levels up to 0.01 hPa (80 km) and a new physical parameterization which resulted in increased spread.

Both datasets interpolated to N64 grid horizontally on all model vertical levels.

Flow dependency of uncertainties (analysis ensemble spread) in the DART/CAM system at 370 hPa along 5ºN



Normal mode expansion

3D orthogonal modes of Kasahara and Puri (MWR, 1981). Basic idea is to select the subset of modes which provides the optimal fit to the input vector **X** for each ensemble member. Differences between the ensemble members are analyzed in the space of modes (*k*,*n*,*m*).

N_m – number of vertical modes, index *m*
N_n – number of meridional modes per wave type, index *n*
N_k – number of zonal waves, index *k*

$$\mathbf{X}(\lambda,\varphi,z,t)=\sum_{m=1}^{N_m}\sum_{n_l=0}^{N_n-1}\sum_{k=-N_k}^{N_k}\chi_{knm}(t)\mathbf{S_m}\Pi_{knm}(\lambda,\varphi,z)$$

3D normal mode functions; input data vector; common expansion coefficient; normalization matrix

$$\mathbf{X}=(u,v,P/g)^T\,,\quad P=gz+RT_o\ln(p_s)$$

$$\Pi_{knm}(\lambda,\varphi,z)=\Phi_m(z)\cdot\mathrm{H}_{knm}$$

Hough functions; vertical normal modes

Summary

- Application of normal modes offers a physically attractive approach to quantification of uncertainties in analyses and forecasts. It can point out the scales and motion types most affected by the inflation, localization, observations and model biases.
- Two very different ensembles show an increased uncertainty in mid-July 2007. Its exact origin and implications to be studied.
- Among various IG motion, the greatest uncertainty is found in the Kelvin wave in both systems.
- The fact that there is more IG motion in the increment fields than in the prior ensemble spread in the DART/CAM system is possibly an indication of the noise introduced by the assimilation step.

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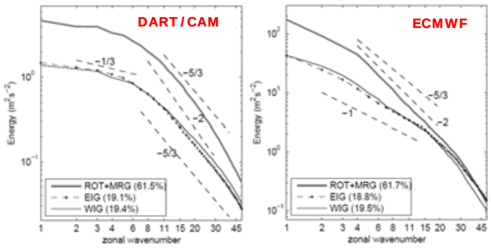
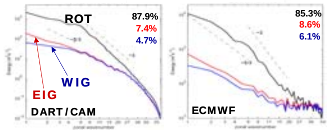
Analysis increments average spectra

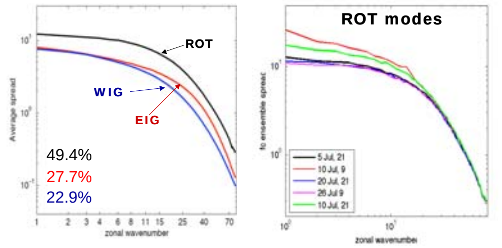


Average analysis spectra

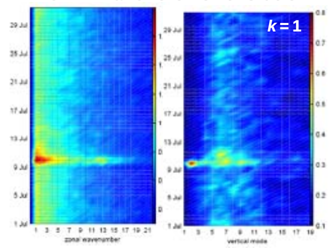


The increment fields contain about 60% of their energy in the balanced (ROT) motion i.e. there is about 2-3 relatively more energy in the IG motion in increment fields than in the full analysis fields (wave part).

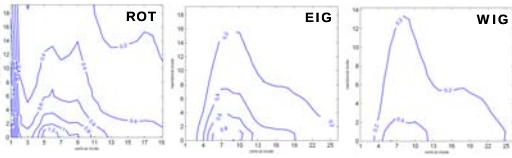
ECMWF 3-h fc ensemble: average spread vs. its variability



Kelvin wave fc-error evolution



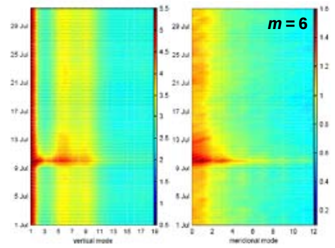
ECMWF: average 3-h fc spread in (m,n) space

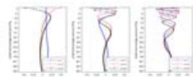


Half of the 3-hour forecast ensemble spread is associated with the IG motion. Long scales dominate; *k*=1 Kelvin wave (*n*=0) for the eastward IG (EIG) motion and *k*=0, *n*=1 for the westward IG (WIG) motions. The error amplitude variability is large, factor 2-3 in the balanced (ROT) modes.

The origin of the the large error increase on 9-10 July 2007 and its importance for the initialization still unclear.

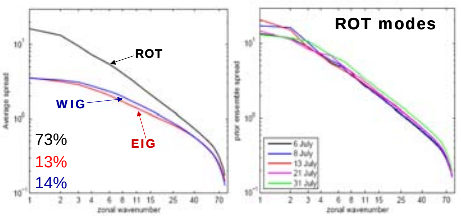
ROT modes fc-error evolution



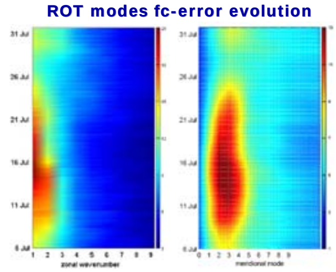


Structure of the first nine vertical modes when the 10 top model levels are excluded

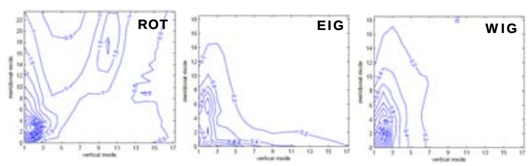
DART/CAM 6-h forecast ensemble: average spread vs. spread variability



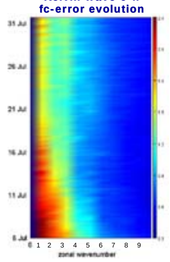
ROT modes fc-error evolution



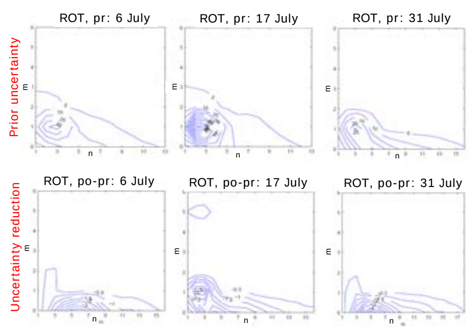
DART/CAM: average 6-h fc spread in (m,n) space



Kelvin wave 6-h fc-error evolution



DART/CAM: Uncertainty reduction in time



The ensemble spread is related to the impact of inflated covariances, the observation coverage and flow properties.

The reduction of uncertainties does not necessarily coincide with the structure of the forecast ensemble spread.

Uncertainties reduce where the observations exist.

Little observation available in the tropics => the Kelvin wave spread cannot be maintained.