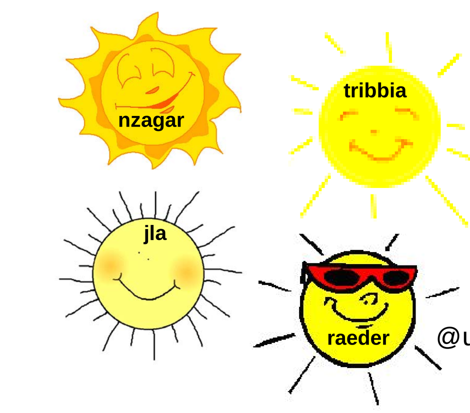
Diagnosis of model biases by using DART

N. Žagar, J. Tribbia, J. Anderson and K. Raeder, National Center for Atmospheric Research, Boulder, CO

NCAR

Contact information



@ucar.edu

Summary

The normal mode expansion is applied to the ensembles of analyses and forecasts produced by using the CAM 3.1 T85 model and the ensemble adjustment Kalman filter (Data Assimilation Research Testbed system - DART). The selection of normal modes accounts for over 90% of the flow variance in the free atmosphere. Of particular interest are large-scale inertio-gravity waves. Result show that about 12% of the wave energy is associated with the inertio-gravity motions, and that the difference between the eastward and westward propagating waves is due to Kelvin waves.

Large scale flow in CAM/DART analyses compares well with other existing analysis datasets, i.e. NCEP-NCAR and ECMWF analyses. Comparison of three datasets illustrates the uncertainties in the description of the large-scale tropical circulation. Tropics are also the area with largest biases in three studied datasets. It is proposed that the "perfect model" assimilation experiment be utilized as a diagnosis tool for understanding model biases in terms of various motions types and scales.

Motivation

- Divergent tropical circulations crucial for understanding the climate but unreliable from present (re)analysis
- Unclear how large part of the global atmospheric energetics pertains to the divergent motion i.e. inertio-gravity waves.
- Large-scale equatorial waves in recent years diagnosed from different mass-field observations and models, but exact quantification of their variance and dynamical relevance not completely understood.

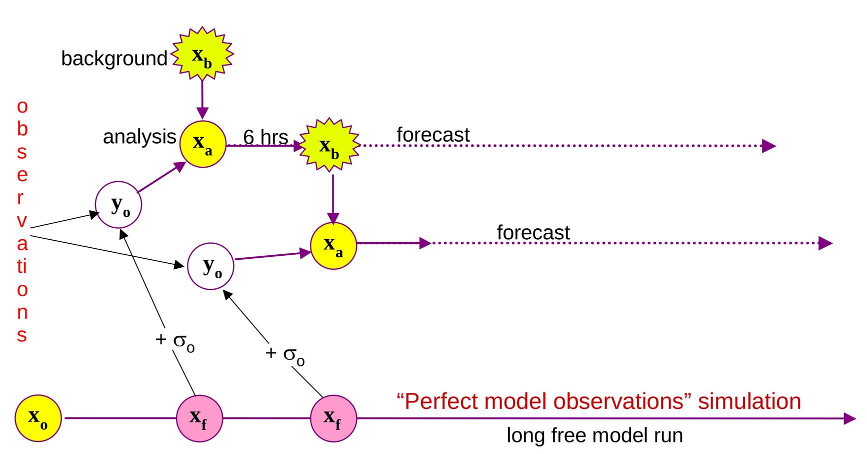
Objectives

- Apply normal mode functions (NMFs) to the analysis and forecast fields to quantify percentage of energy contained in balanced (Rossby) and inertio-gravity (IG) motions.
- Estimate energy spectra for the Community Atmospheric Model (CAM), with emphasis on the large-scale divergent motions (tropics).
- Compare analyses produced using CAM 3.1 T85 and the Data Assimilation Research Testbad (DART) system with other analysis datasets
- Analyze model biases by carrying out the "perfect model" experiment

Tropics: Questions

- How much of the large-scale tropical circulation is made up by the Kelvin wave, mixed Rossby-gravity wave, other inertio-gravity waves?
- How is this dependent on the model resolution, physics, biases?
- What are the spectra of forecast errors in the tropics like? How are the tropical forecast errors spread across the scales and motion types?
- What modes do the biases project onto?
- How important are Kelvin, mixed Rossby-gravity and other large-scale IG for tropical and global the data assimilation?

Analysis-forecast cycle

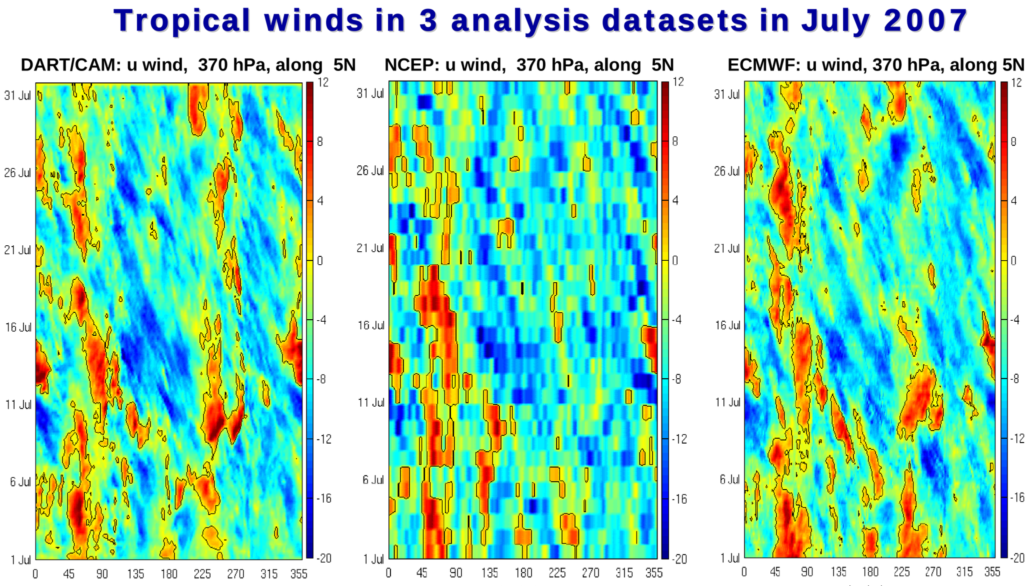


Datasets

Three analysis datasets for July 2007, global fields every 6 hours

- DART/CAM: ensemble mean of an 80-member ensemble produced by the DART system. For details see http://www.image.ucar.edu/DAReS/DART/. The CAM version is 3.1, horizontal resolution T85, 26 vertical levels up to 3.5 hPa.
- ECMWF operational analyses: 12-hour 4D-Var system, Cycle 32r2, T799 interpolated to N64 grid, 91 vertical level up to 1 Pa.
- NCEP-NCAR reanalyses: 3D-Var system, T46 horizontal resolution, 28 vertical levels up to 2.7 hPa. An old system compared to the operational NCEP data.

Tropical winds in 3 analysis datasets in July 2007



Normal mode expansion

Applied set of orthogonal modes was derived by A. Kasahara (Kasahara and Puri, MWR, 1981). Basic idea in the present application is to select the subset of modes which provides the best fit (best correlation and variance fit to the input grid-point fields) ⇔ tuning of the truncation parameters N_k, N_n, 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

$$\mathbf{X}(\lambda,\varphi,z,t)=\sum_{m=1}^{N_m}\sum_{n_{i=1,2,3}=0}^{N_n-1}\sum_{k=-N_k}^{N_k}\chi_{knm}(t)\mathbf{S_m}\Pi_{knm}(\lambda,\varphi,z)$$

input data vector ($\mathbf{X}$); common expansion coefficient (χ_{knm}); normalization matrix ($\mathbf{S_m}$); 3D normal mode functions (Π_{knm})

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

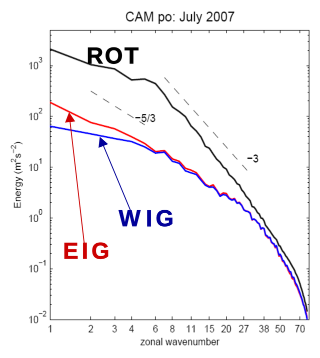
$$\Pi_{knm}(\lambda,\varphi,z)=\Phi_m(z)\cdot \mathrm{H}_{knm}$$

vertical normal modes (Φ_m); Hough functions (H_{knm})

$$\mathbf{S_m}=\begin{pmatrix}(gH_{eq})^{1/2} & 0 & 0\\ 0 & (gH_{eq})^{1/2} & 0\\ 0 & 0 & H_{eq}\end{pmatrix}$$

$$\langle\Pi_{knm},\Pi_{k'n'm'}\rangle=\delta_{kk'}\delta_{nn'}\delta_{mm'}$$ orthogonal 3D expansion basis

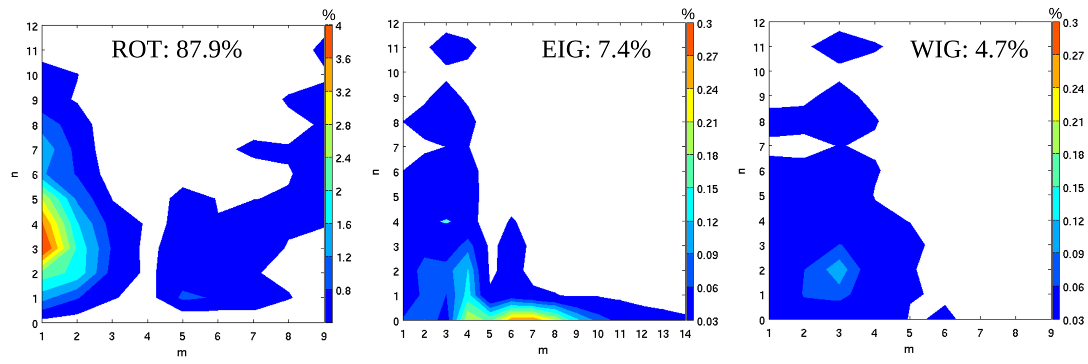
Energy distribution in CAM

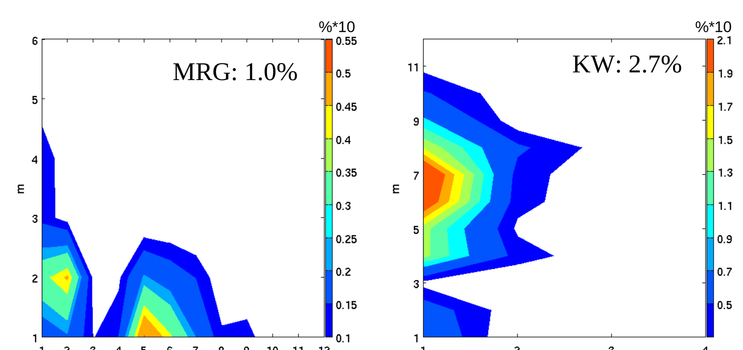


25-day period average: 6-31 July 2007

$$\sum_k\sum_n\sum_m gH_{eq}|\chi_{knm}|^2$$ Zonally averaged state (k=0) is not included.

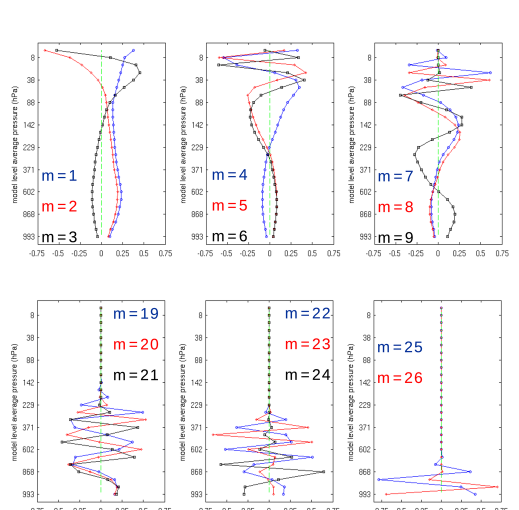
ROT- non-divergent (Rossby)
EIG - eastward inertio-gravity
WIG – westward inertio-gravity





Energy in each mode is normalized by total energy in all waves. In July 2007, ~12% of energy in IG motion. Percentage values pertain to the integrated energy across all scales (except k=0). Difference between EIG and WIG almost completely due to Kelvin waves (KW).

Vertical eigenstructures for CAM



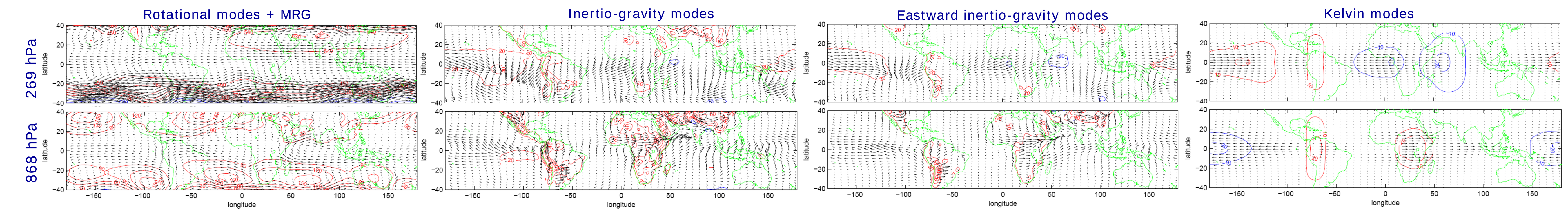
Input information: vertical discretization, vertical mean temperature (T_0) and stability profiles

H_{eq}- separation constant for vertical and horizontal structure ("equivalent depth")

H_{eq} in range from 10 km to 0.3 m: 10 km, 6.2 km, 2.2 km, 985 m, 572 m, 379 m, 250 m, 162 m, 107 m. Modes 10-26 have H_{eq} below 100 m

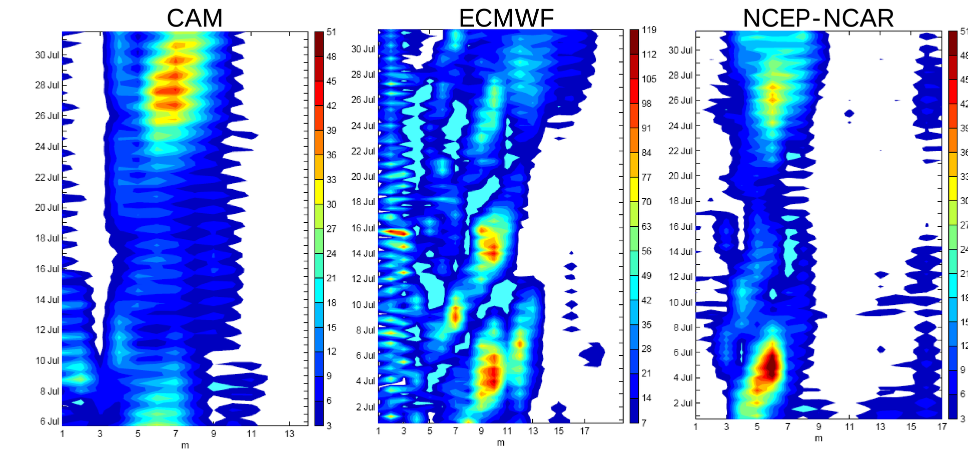
- Truncation parameters selected for CAM are: N_k = 80, N_n = 25, N_m = 25.
- Verification of the expansion into NMFs performed by comparing input fields to those obtained after projection and its inverse.
- On average, expansion accounts for over 90% of the variance above 900 hPa which allows reliable quantification of the percentage of energy contained in various motions.
- Correlation coefficients are between 0.9 and 1.

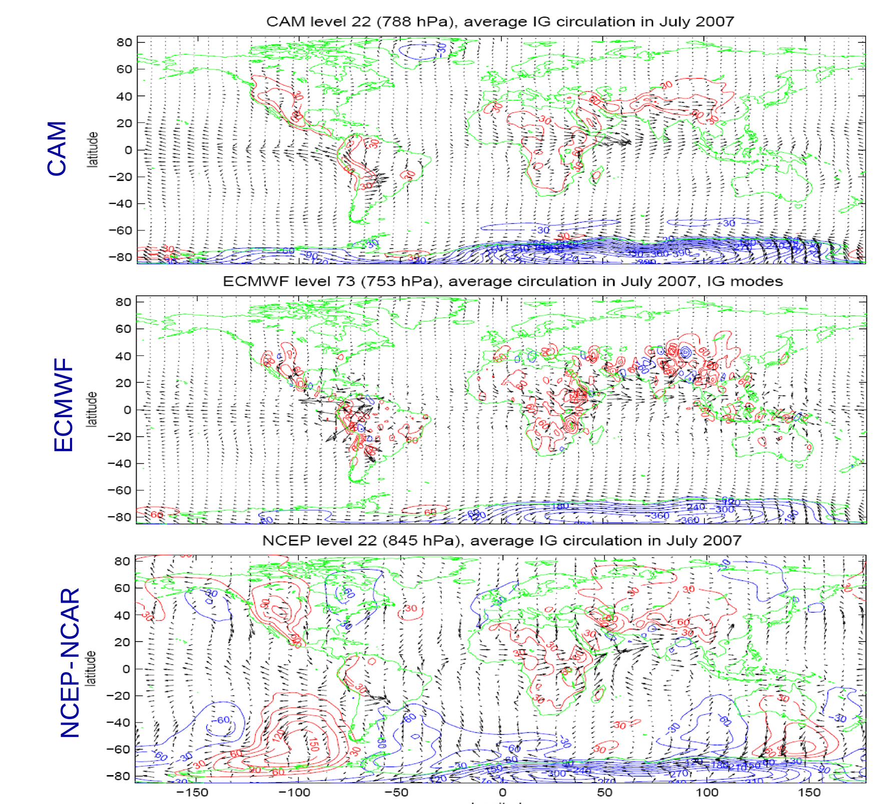
Tropics as envisaged by A. Gill (1980): CAM / DART analyses



Inter-comparison of divergent tropical motion in 3 analysis datasets

Temporal evolution of the KW, k=1 signal

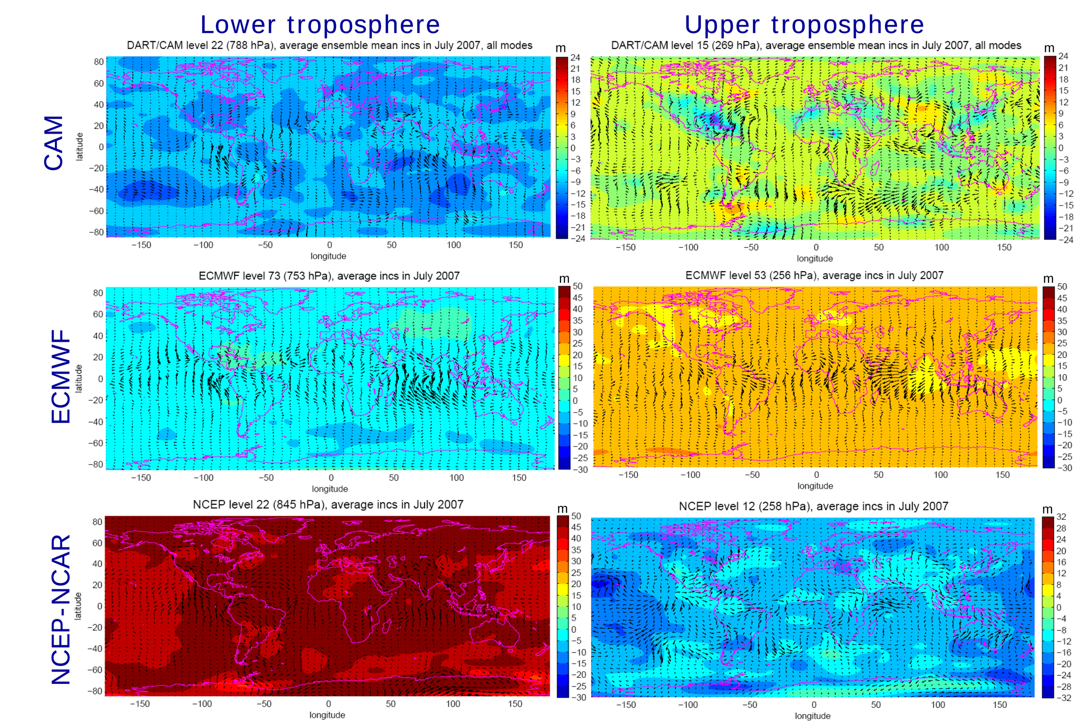




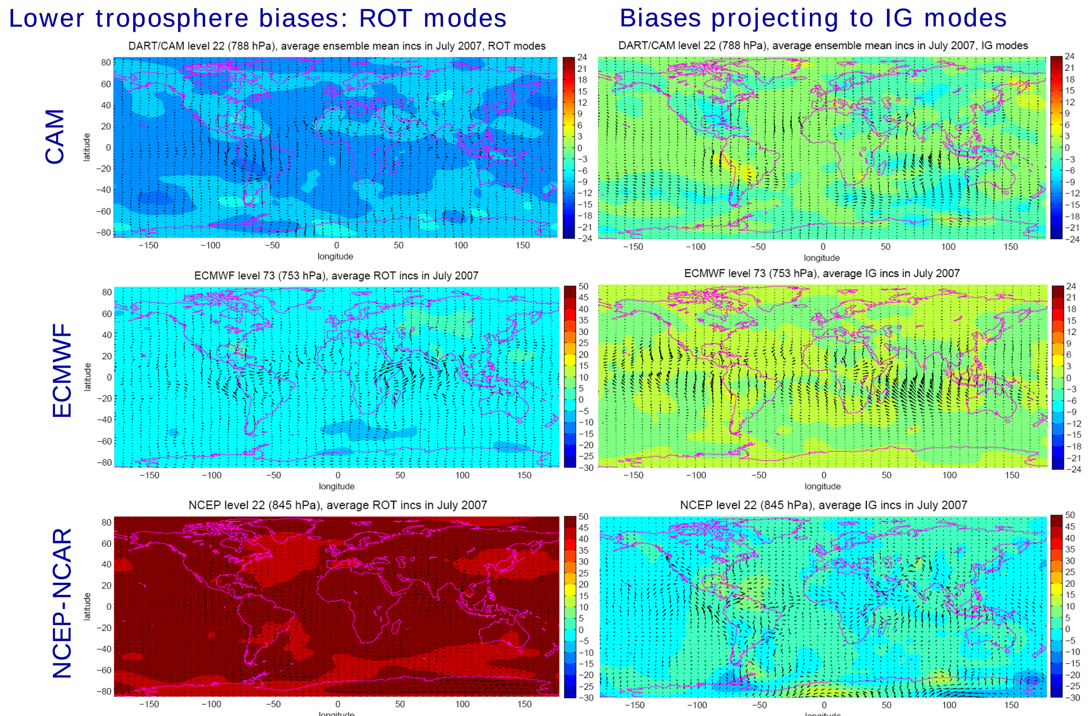
- On average, divergent flow in the lower and upper troposphere is reversed, i.e. easterlies fond over the Pacific in the lower troposphere and westerlies in the lower troposphere.
- Kelvin mode an important contributor to the zonal winds over the Pacific and the equatorial Africa. (Length of the wind vectors for ROT modes three times larger than for IG modes.)
- Most of divergent circulation is in the tropics, except for NCEP-NCAR reanalysis.
- Analyses agree to some extent about the divergent component of the zonal tropical circulation. But significant differences exist for example in the Indian ocean, related to the monsoon circulation.
- Antarctic circulation divergent in all analyses.

Total biases in 3 analysis systems

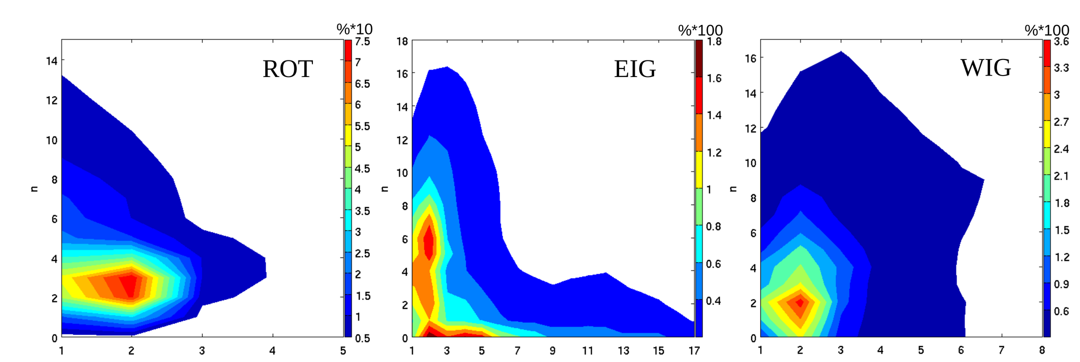
- Monthly-averaged analysis increments are used as a proxy for analysis bias (model biases + observation biases).
- Most of bias is in the tropical wind field, especially in cross-equatorial winds



- Tropical wind biases are largely in the divergent component and especially in the meridional wind in the Indian ocean. This is consistent in all 3 analysis systems.



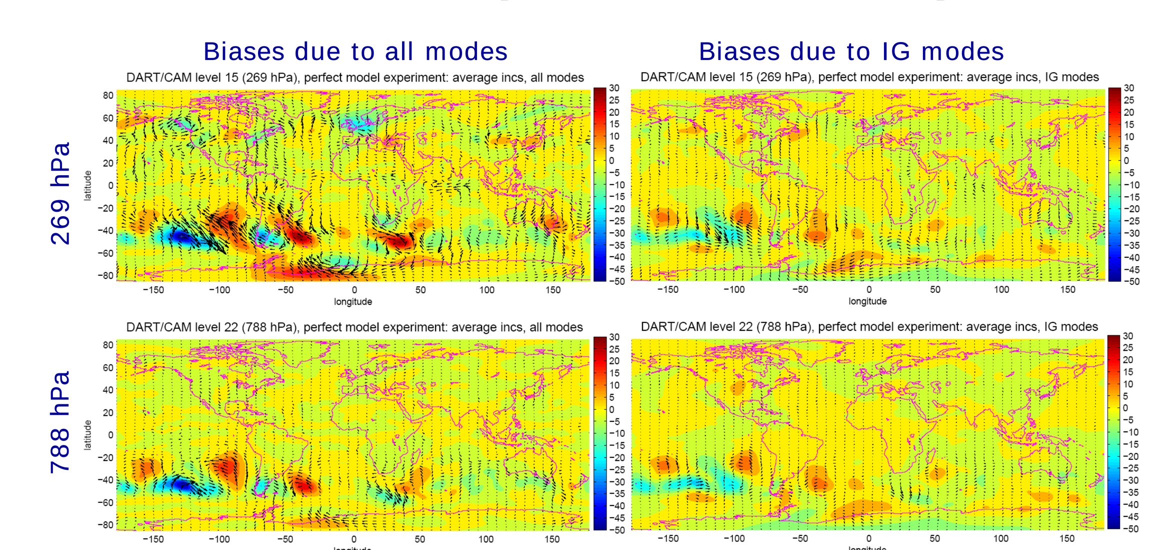
Uncertainty of analysis solution as estimated from the CAM / DART 80-member ensemble



Energy spread in each mode is normalized by total average wave energy in the ensemble mean.

Areas of the modal space with largest uncertainties do not coincide with the scales containing most of the energetic flow.

CAM 3.1 T85 perfect model experiment: biases



In perfect model experiment, the impact of model errors is removed provided good observation coverage. Present experiment used conventional observation; thus, the southern hemisphere poorly observed ⇒ here, model errors establish in time-averaged analysis increments.

Most of these extra-tropical biases reside in balanced motions.

Conclusions

- Large-scale flow in CAM/DART analyses compares well to other existing analysis datasets.
- Tropics are areas with largest uncertainties in existing analysis datasets. Tropics are also the area with largest biases in three studies data assimilation systems.
- Normal mode expansion allows to quantify energy in various motions and to modify traditional view of inertio-gravity motions as junk. With normal modes it is possible to quantify variance in various tropical divergent motions and its relevance for data assimilation.
- Application of normal modes offers a physically attractive approach to quantification of uncertainties in analyses and forecasts. Uncertainties vary in time and space, thus an argument for a flow-dependent estimates of the forecast errors, i.e. the ensemble data assimilation. The normal mode application may also help to address modeling aspects such as model-error covariances and initialization.