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Development of a 4DVAR version of GSI at NCEP

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Content

- Development of a 4DVAR version of GSI
- A single observation test
- Example of a single analysis
- Improving efficiency of the perturbation model
- Other developments and future work

1. Development of a 4DVAR version of GSI at NCEP

- Contemporary observations of the atmosphere (such as those coming from the geostationary, polar orbiting and GPS satellites) are spread through the analysis window

- In the classical 3DVAR we knowingly introduce error in the estimation of the innovation vector (observation minus background) by comparing observations with the background at the analysis time

- **FGAT** (First Guess at Appropriate Time) 3DVAR improves this situation to some extend, by introducing more then one background field

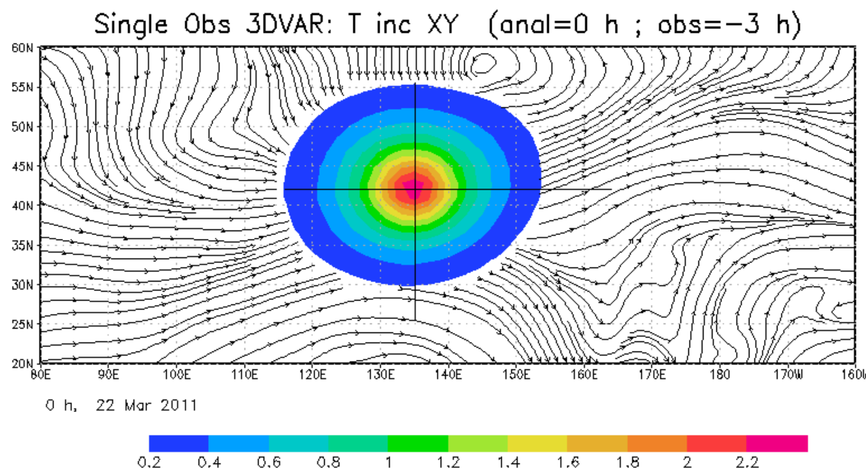
- At NCEP, we tried to increase a “temporal awareness” of our data assimilation system GSI (Grid-point Statistical Interpolation) by a simple method **FOTO** (First Order interpolations To Observations)

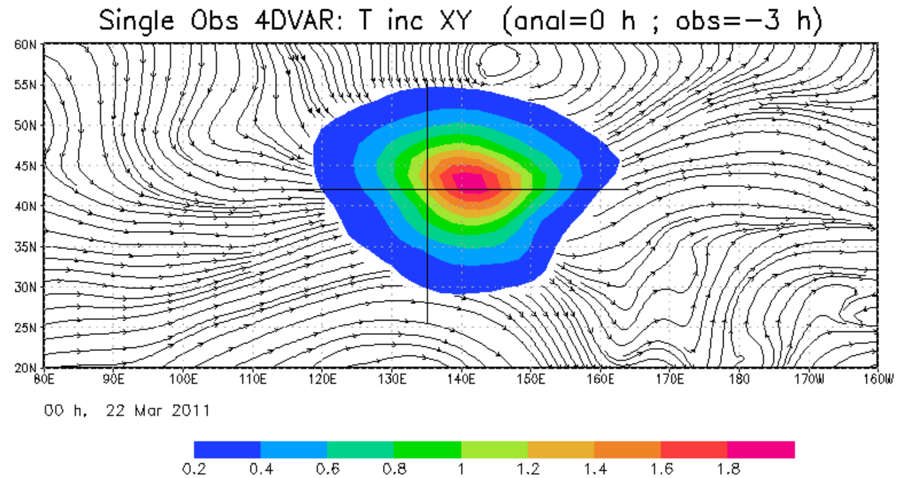
- An **ensemble based 4-dimensional** data assimilation method has been recently finished, which prescribes the time evolution through ensemble perturbations

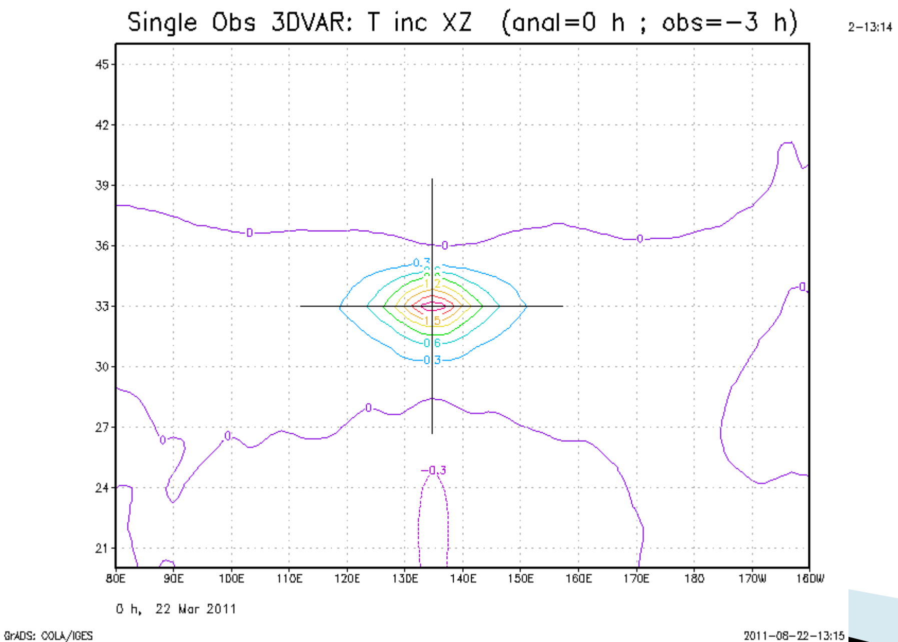
- A **classical**, weak constraint **4DVAR**, where innovation is propagated in time using a tangent linear model, **M** (TLM), and its adjoint, $\mathbf{M}^T$ (ADM), is arguably still capable to satisfy most criteria (a full rank method, long assimilation window, inclusion of model error, etc.)

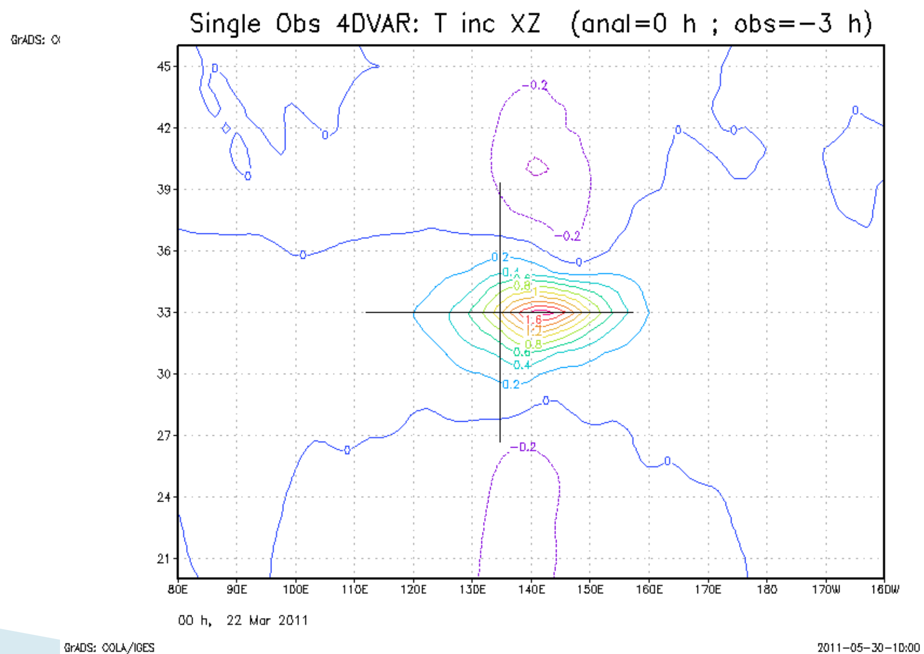
- The **model based 4DVAR** has been recently **merged with the Hybrid EnKF** within GSI, which we expect to further advance the realism of the analysis
- **A 4DVAR option**, with several appropriate minimization and preconditioning algorithms (Lanczos, sqrtB, etc.), has been introduced in GSI through **collaboration with GMAO/NASA**
- **Perturbation model** for driving 4DVAR has been derived by readjusting a pre-existing tendency model, used in 3DVAR for formulation of the dynamical constraints
- It maintains **the same vertical structure as GFS** (Global Forecasting System – Global model at NCEP), but horizontal gradients are derived using high-order compact differencing

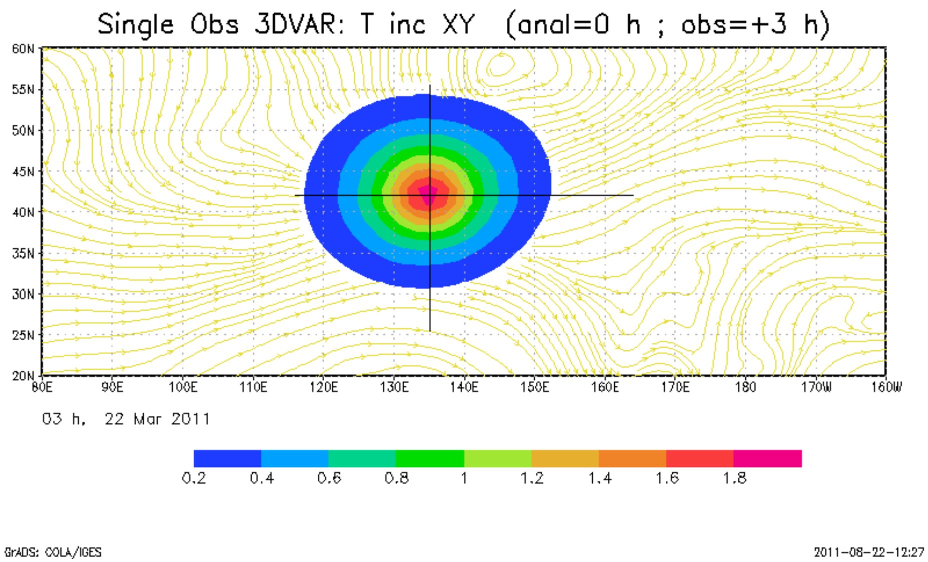
2. Single Observation Tests

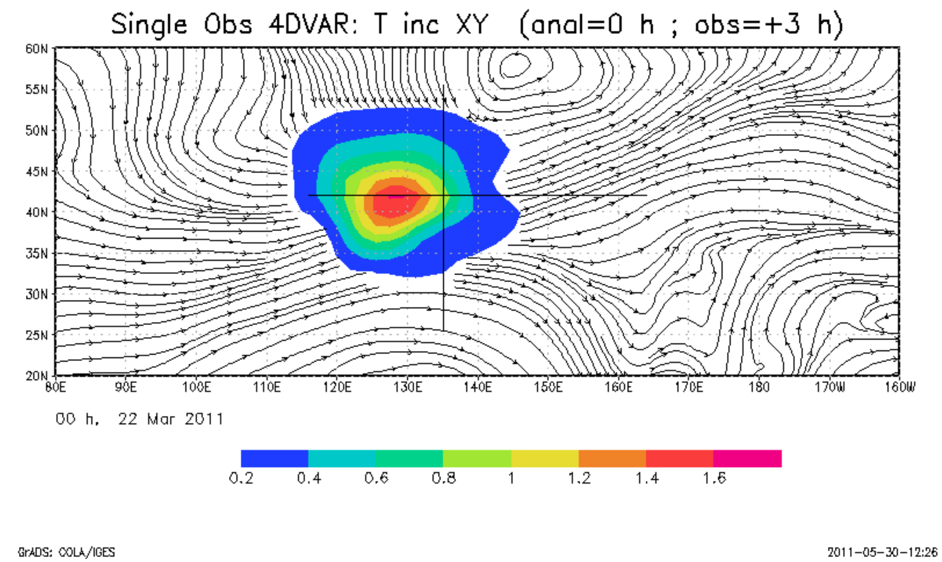









Single Obs 3DVAR: T inc XY (anal=0 h ; obs=+3 h)
60N 55N 50N 45N 40N 35N 30N 25N 20N
80E 90E 100E 110E 120E 130E 140E 150E 160E 170E 180 170W 160W
03 h, 22 Mar 2011
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8
GrADS: COLA/IGES
2011-08-22-12:27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60N 55N 50N 45N 40N 35N 30N 25N 20N
80E 90E 100E 110E 120E 130E 140E 150E 160E 170E 180 170W 160W
00 h, 22 Mar 2011
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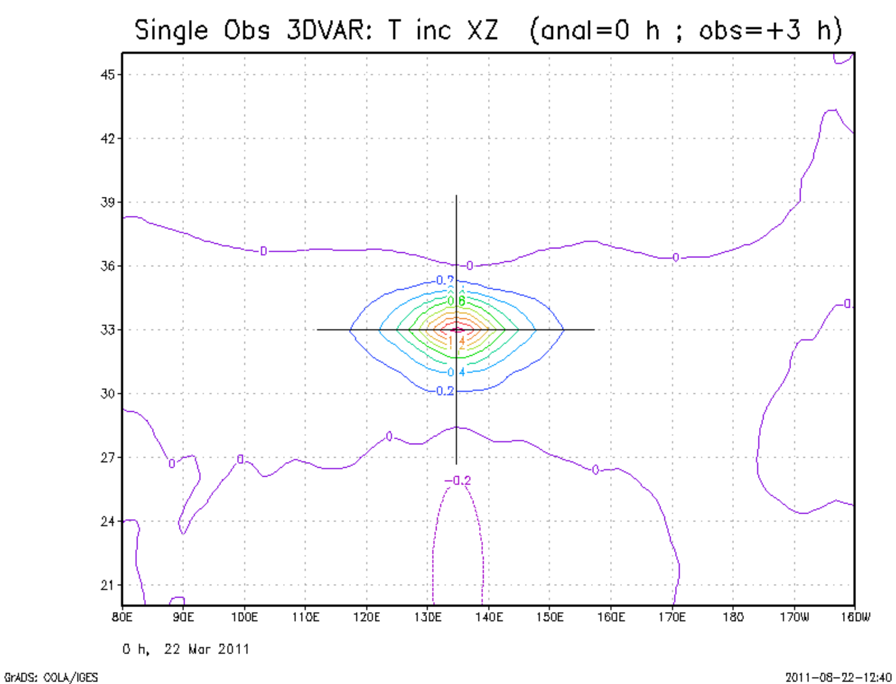
Single Obs 3DVAR: T inc XZ (anal=0 h ; obs=+3 h)
45 42 39 36 33 30 27 24 21
80E 90E 100E 110E 120E 130E 140E 150E 160E 170E 180 170W 160W
0 h, 22 Mar 2011
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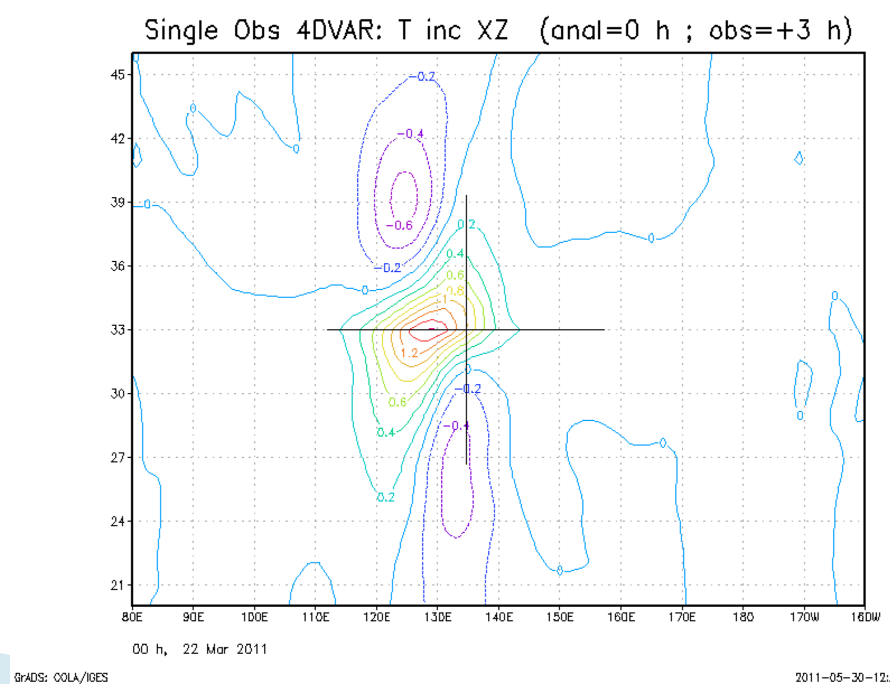
Single Obs 4DVAR: T inc XZ (anal=0 h ; obs=+3 h)
45 42 39 36 33 30 27 24 21
80E 90E 100E 110E 120E 130E 140E 150E 160E 170E 180 170W 160W
00 h, 22 Mar 2011
GrADS: COLA/IGES
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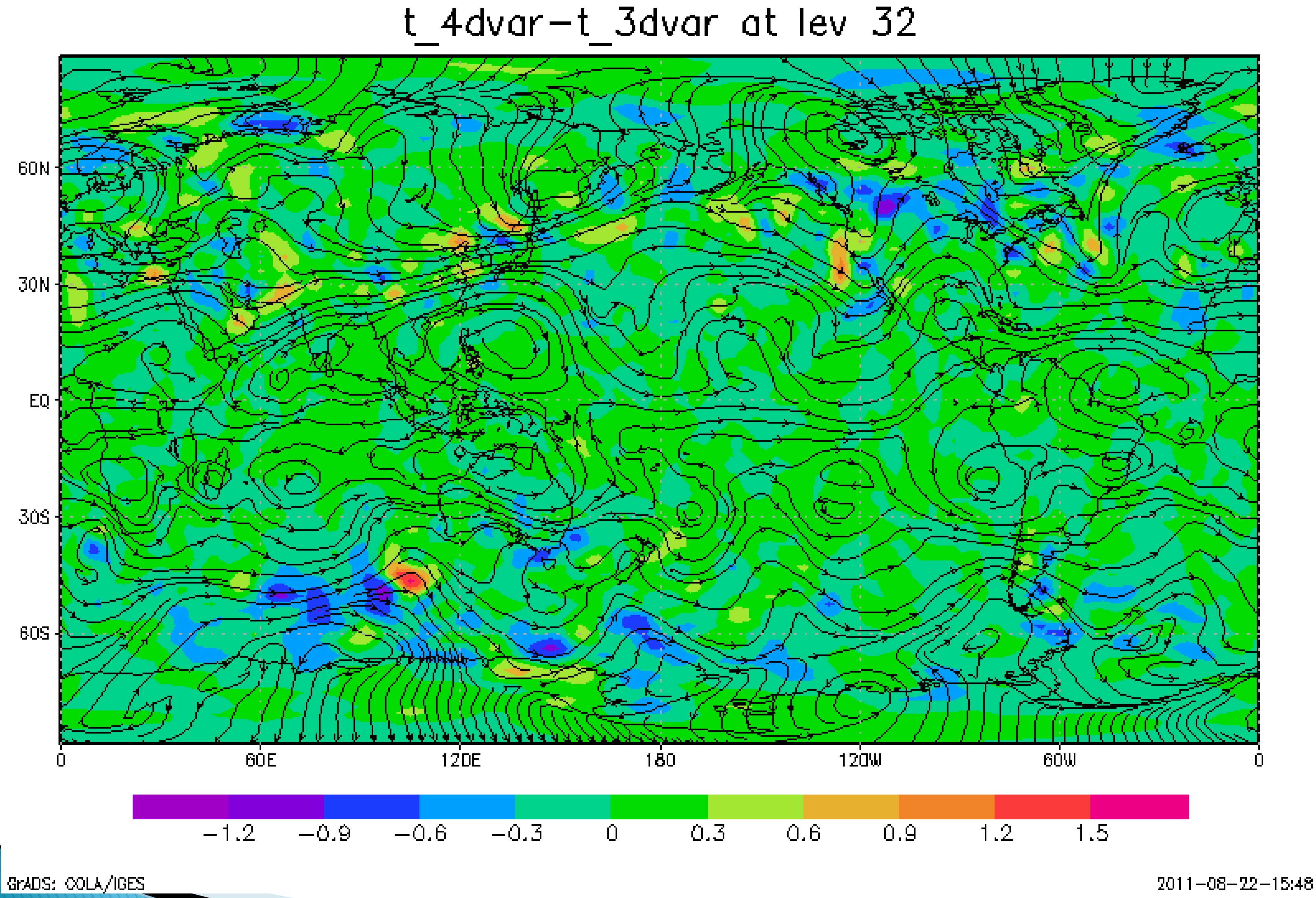
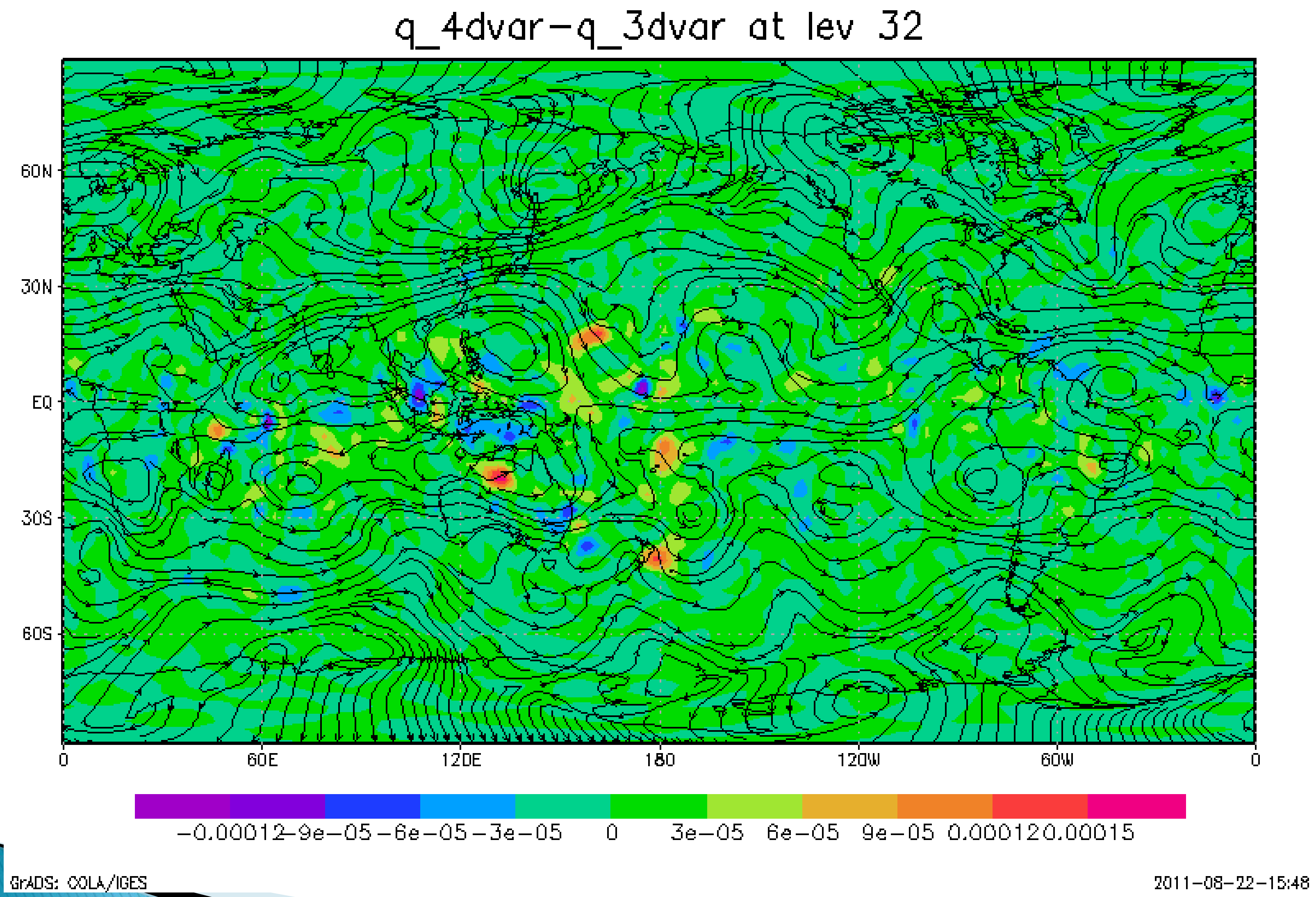
3. Example of a single analysis

- T62 Gaussian grid
- Nonlinear fields are read in **1 hour intervals**
- **Analysis window is 6 hours** long, with the analysis time in the middle
- Analysis for March 22, 2011 at 0 h
- Code is organized in such a way that we run separately the '**observer**' and the **minimization**


t_4dvar−t_3dvar at lev 32
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
0
−1.2
−0.9
−0.6
−0.3
0
0.3
0.6
0.9
1.2
1.5
GrADS: COLA/IGES
2011−08−22−15:48


q_4dvar-q_3dvar at lev 32
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
0
-0.00012
-9e-05
-6e-05
-3e-05
0
3e-05
6e-05
9e-05
0.00012
0.00015
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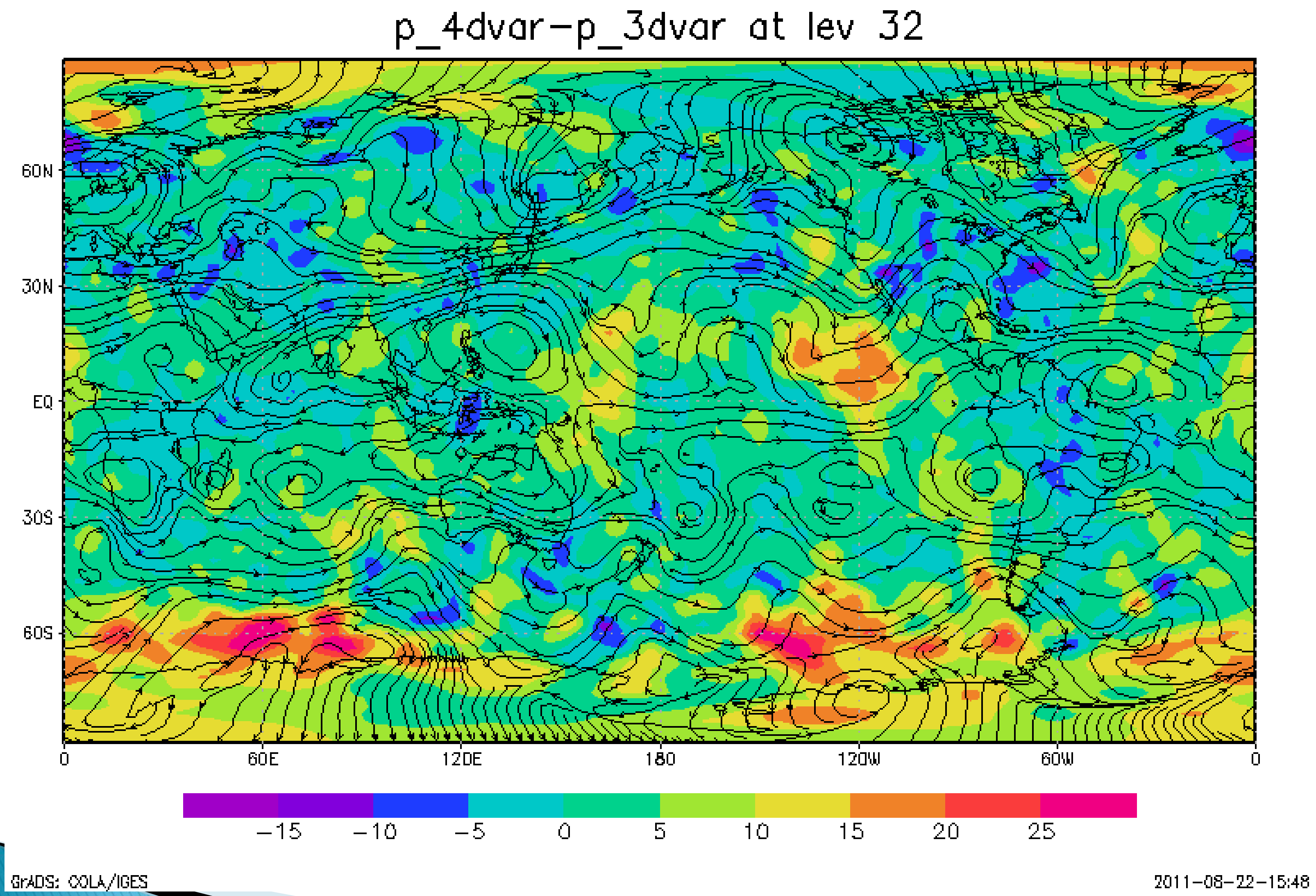
p_4dvar-p_3dvar at lev 32
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
0
-15
-10
-5
0
5
10
15
20
25
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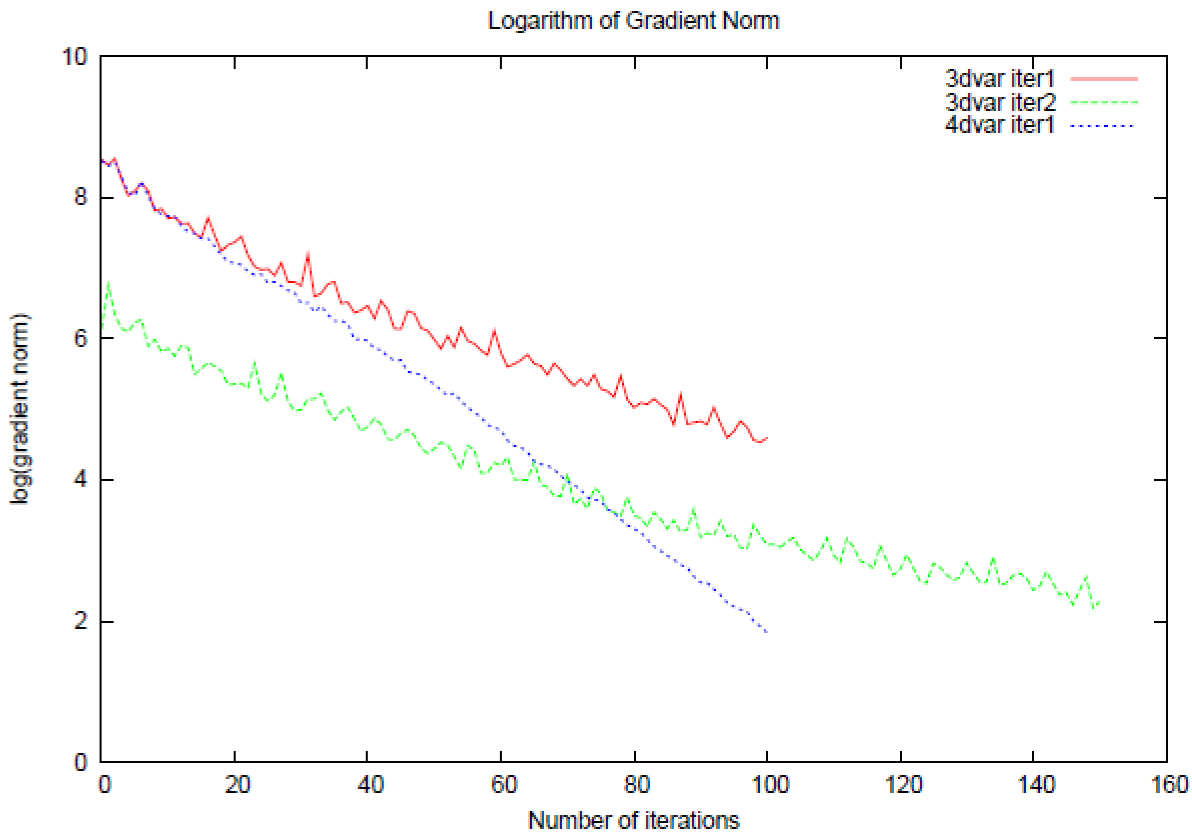
2011-08-22-15:48

Logarithm of the Gradient Norm

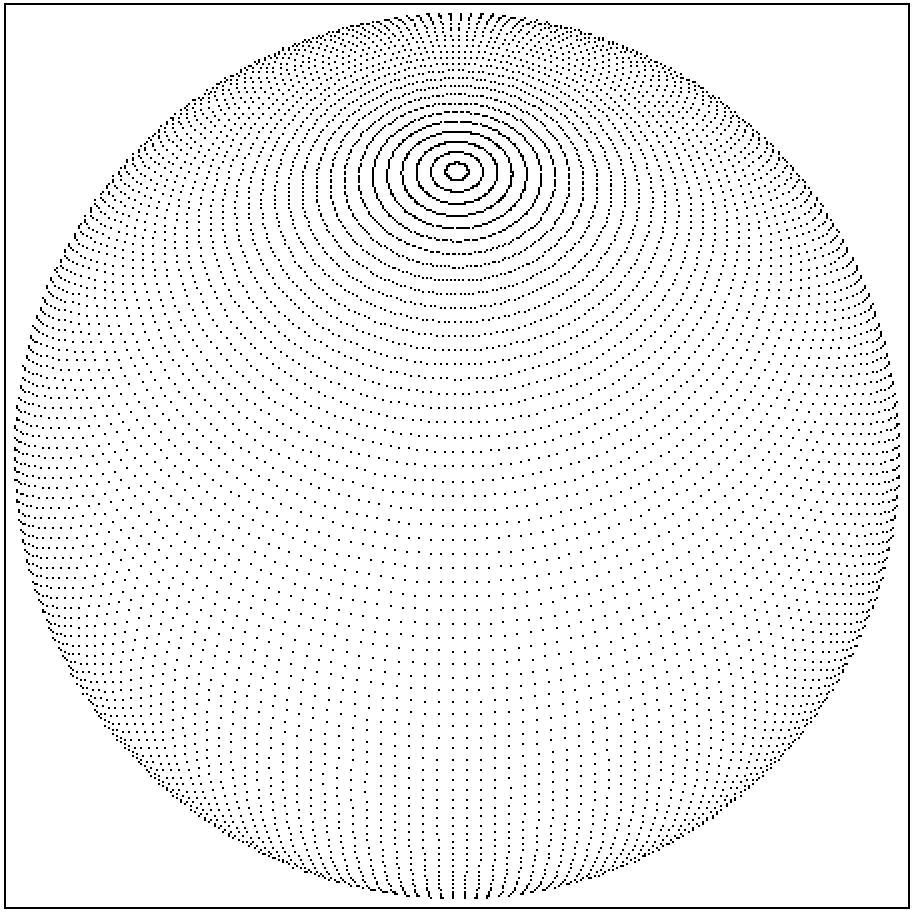


Computational Efficiency

- 3DVAR spends 654.966 s, using preconditioned conjugate gradient for minimization, using 32 PE of NCEP's IBM supercomputer
- 4DVAR spends 238.940 s for observer, and 4769.815 s for minimization, using Lanczos algorithm for minimization with 100 inner iterations (~7.6 times more)
- With typical 2 outer loops, first with 100, followed by another with 150 inner iterations, 4DVAR is at this stage about ~**16-20 time more expensive** than 3DVAR

4. Improving efficiency of the perturbation model

- The major consumer of computational time is **perturbation model**, primarily due to a very small time step on the Gaussian grid (3 min onT62 resolution!!)



Several strategies for improving efficiency are investigated

- Further **simplifications** of the model
- Application of a **cylindrical** longitude-latitude grid
- Applying a new concept of polar filtering through **zonal averaging** of tendencies
- Running model on a **reduced grid**
- Reformulating model using a **quasi-uniform grid**

Cylindrical grid (Sadourny 1975)

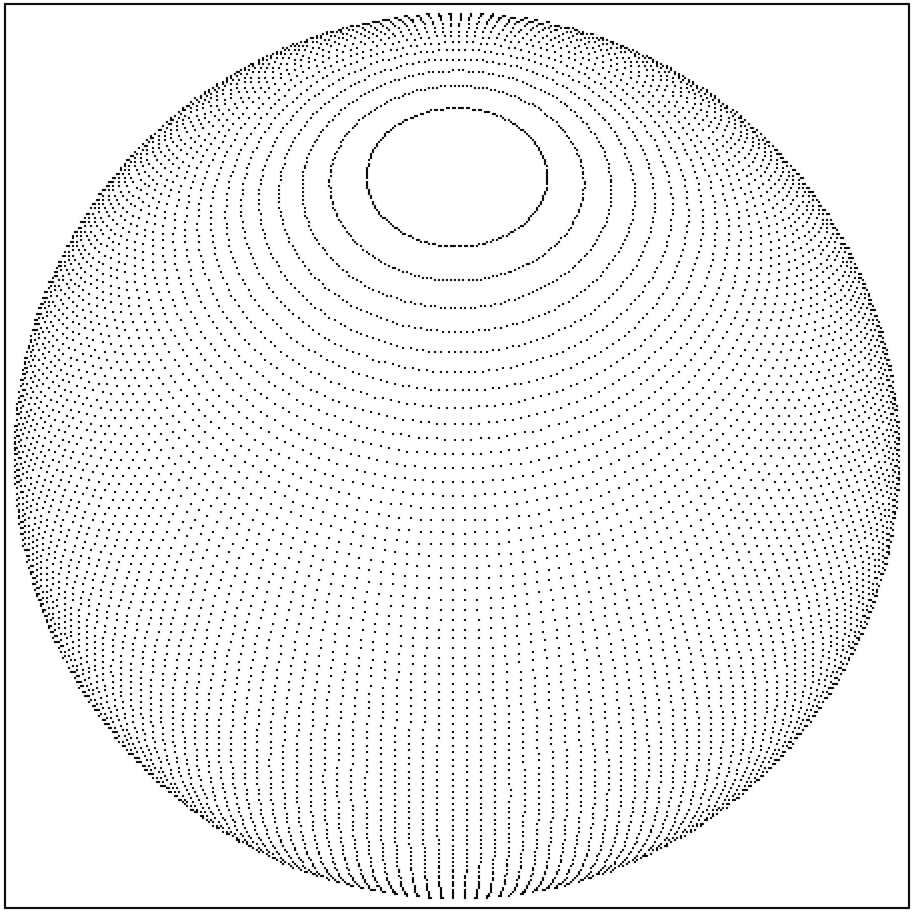
- Cylindrical grid is defined by assuming spherical coordinates as

$$x = \lambda$$

$$y = \sin \varphi$$

- **Equal grid boxes** and a larger time-step

- No meridional structure close to the poles

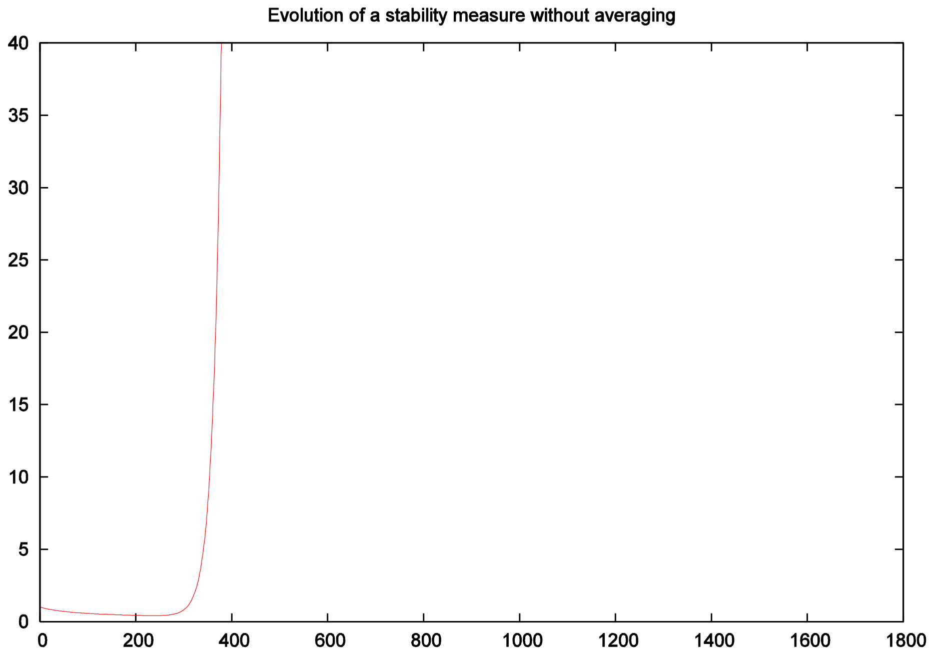


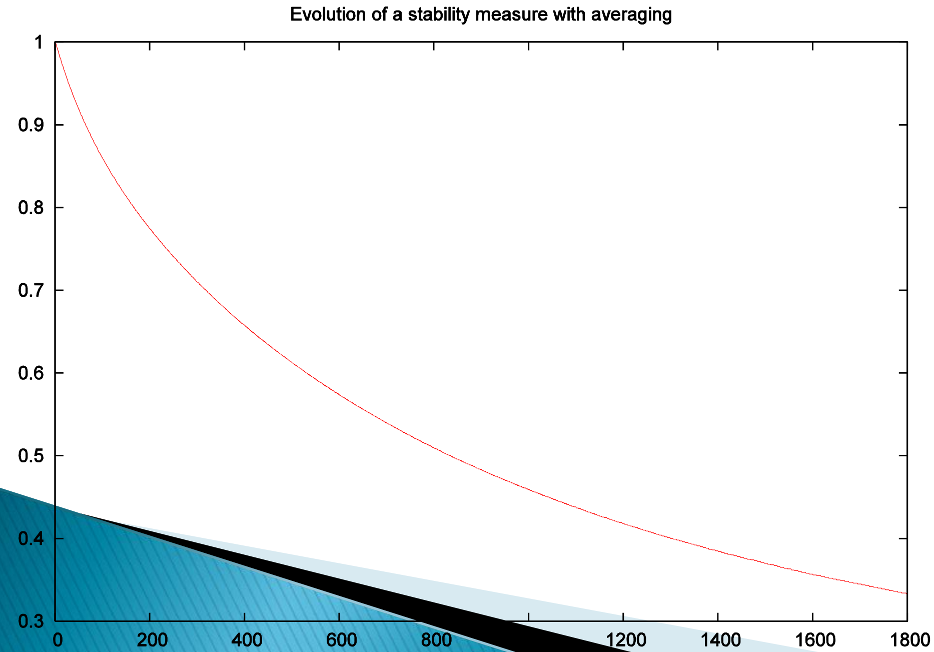
Polar averaging

- Polar filtering through **zonal averaging** is an innovative and presumable a more efficient alternative to standard Fourier polar filtering

- The averaging as the method to increase time-step of a numerical scheme was originally suggested by Konor and Arakawa (2007)

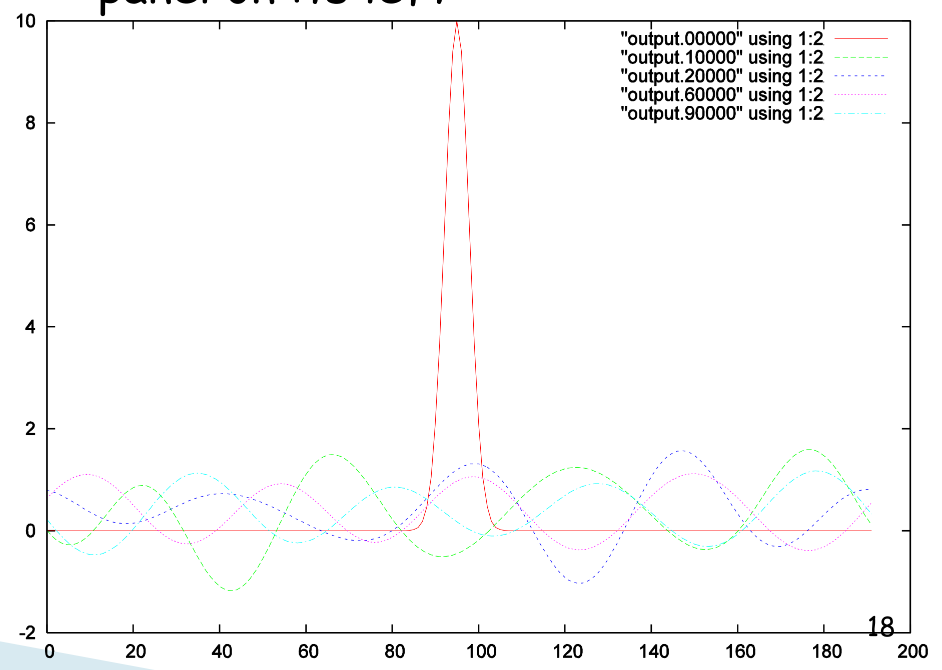
- **Averaging coefficients** are derived by requiring that the dispersion relation for the propagation of gravity waves at a high latitude has the same stability properties as at some lower, reference latitude





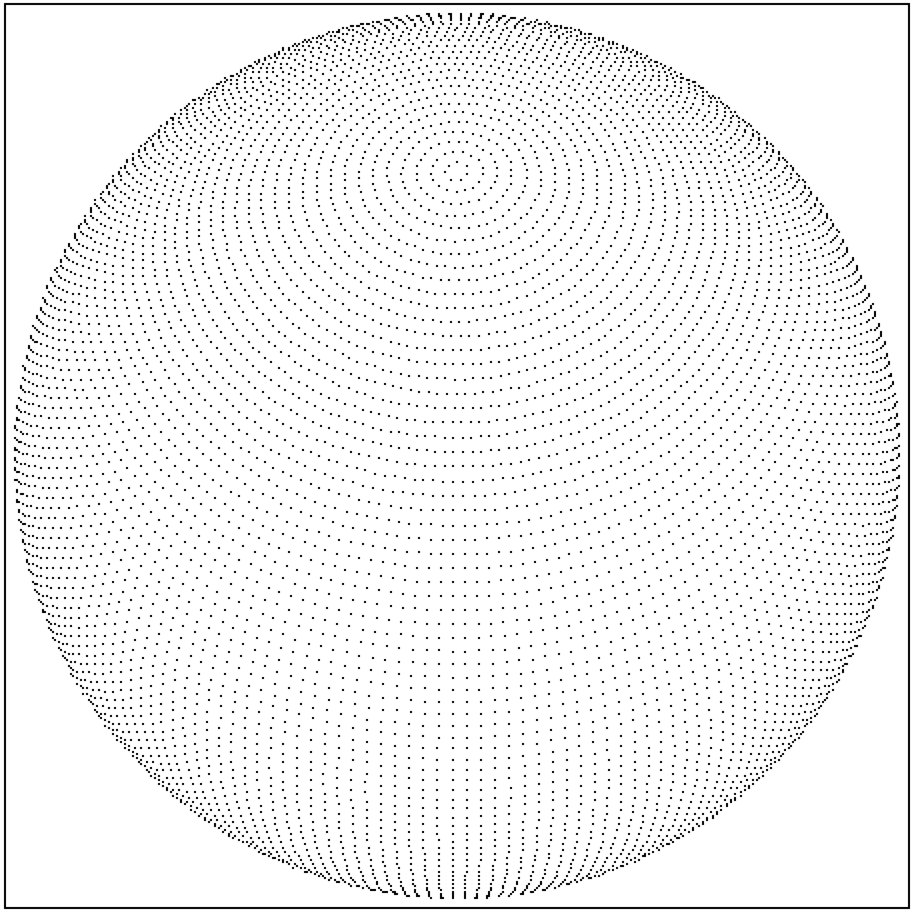
Left panels show evolution of a stability measure at a latitude 84.76 deg at the Gaussian T62 grid without (upper) and with (lower) polar averaging in the test of propagation of 1D gravity wave

Figure in the **right lower corner** shows propagation of the gravity wave from the panel on its left

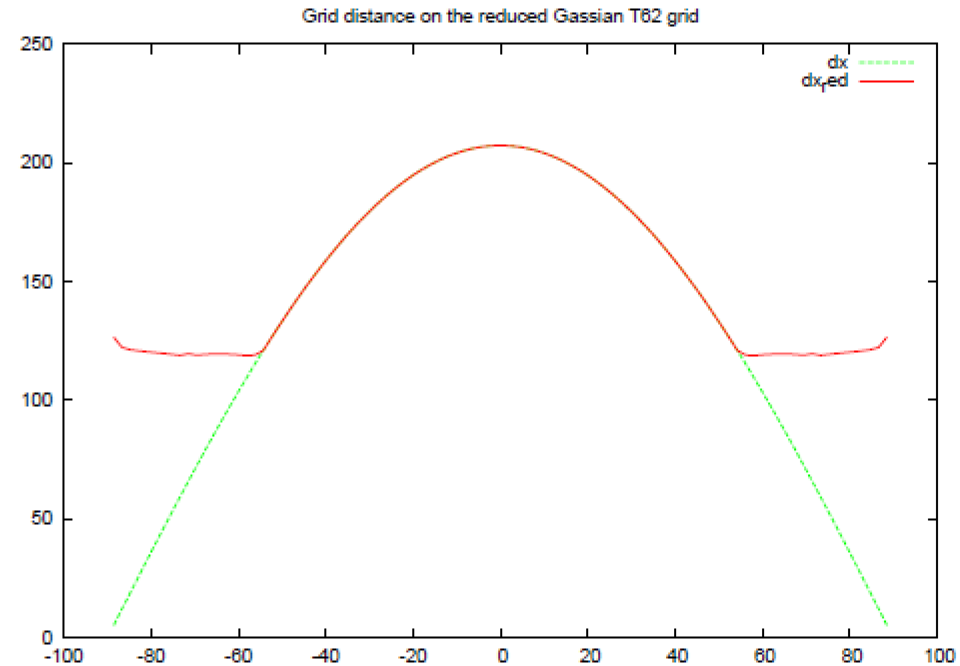


Reduced Gaussian Grid

- Reduced grid is not used in weather prediction models because of the problems related to formulation of the **gradients in the meridional direction**
- In the short integrations of TLM and ADM **in data assimilation** we are not too concerned with the lack of formal conservation, and the reduced grid **is an acceptable and a promising choice**

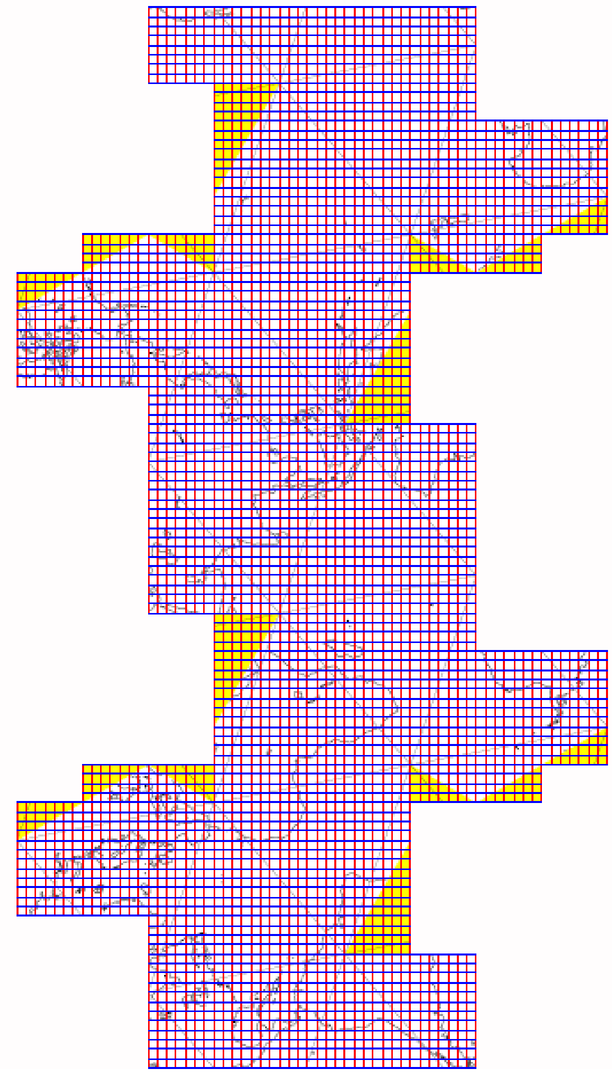


- The reduced grid has about **20% less grid points** than a full Gaussian grid
- ***Aspect ratio*** of the smallest to the largest time step is **0.630** on the particular grid shown on the previous slide

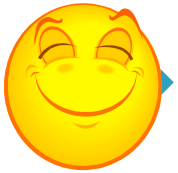


Application of a quasi-uniform grid

- The idea is to cover surface of the earth **with a series of orthogonal rectangular grids** with a similar resolution, allowing a small overlapping at the edges
- This is achieved by a **modification of the mappings** between various **regular polyhedra and the sphere**
- Figure shows as an example **a regular icoshedron mapped** to the surface of the Earth using the new method



Possible advantages of the quasi-uniform grid approach



- **Smaller number number of used grid points** than on the reduced grid
- **Larger time step**, that is, aspect ratio between the smallest and the largest time step is closer to 1
- An original **conformal mapping** (very soon)
- More extra work !!!

5. Other developments …

- **GMAO** is using the same 4DVAR algorithm as NCEP but with a perturbation model derived by the linearization of their own atmospheric model
  - At this stage, the efficiency of GMAO's TLM and ADM of dry core appears to need further optimization
    - 7500 s for 100 iterations in the inner loop at 24 PEs
    - TLM runs about 2 times longer than NLM and ADM even 4 times on 24 PEs

- A **4-dimensional ensemble-variational method** is less affected with the efficiency problem – it is just twice as expensive as the 3D Hybrid EnKF

… and future work

- **Improve efficiency** and start testing 4DVAR in the cycling experiments
- **Extend physics** of the perturbation model (moist physics, more comprehensive PBL and surface exchange)
- Include capability to use **arbitrary nonlinear model** (GFS, a global NMMB – Nonhyrdrostatic Multiscale Model on B-grid)
- Develop a parameterized **model error** targeting a **weak 4DVAR**
- Investigate how a more realistic treatment of time dimension affects overall **performance of GSI**
- Include 4DVAR in **the regional analysis**

Acknowledgements

- 4DVAR development at NCEP has been done through collaboration with **GMAO/NASA**, with a significant participation of **Yannick Trémolet** on the leave from **ECMWF**

- A 4-dimensional ensemble-variational method is being developed through collaboration with **Xuguang Wang** from **The University of Oklahoma**

- Overlapping quasi-uniform grids are investigated jointly with **Jim Purser** (NCEP Office Note 467 at http://www.emc.ncep.noaa.gov/officenotes/FullTOC.html)