Applying an incremental normal mode operator to improve balance in variational data assimilation

Weather-Chaos Group Meeting – 12 November 2009

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3DVAR

\[ J = (x-x_b)^T B^{-1} (x-x_b) + (H(x)-y)^T (E+F)^{-1} (H(x)-y) \]

\[ J = \text{Fit to background} + \text{Fit to observations} \]

- \( x \) = Analysis
- \( x_b \) = Background
- \( B \) = Background error covariance
- \( H \) = Forward model (Observation operator)
- \( y \) = Observations
- \( E+F \) = \( R \) = Instrument error + Representativeness error
Gridpoint Statistical Interpolation (GSI)

- 3DVAR assimilation based on the SSI / Eta 3DVAR
  - Formulated in gridpoint space
  - Analysis (Control) Variables:
    - $\psi$, $\chi$, $T_u$, “q”, $P_{su}$, $O_3$ (not $\zeta$, $\delta$)
    - Multivariate relation differs (non-trivial to use things like full nonlinear balance equation on a grid)
  - Grid point definition of background error
    - Spectrally defined horizontal background errors replaced with recursive filters
    - Vertical EOFs replaced with recursive filters
    - Background error statistics are a function of height and latitude
  - Improved efficiency*, coding, and documentation
Increase in Ps Tendency found in GSI analyses

Zonal-average surface pressure tendency for background (green), unconstrained GSI analysis (red), and GSI analysis with TLNMC (purple).

Substantial increase without constraint
Is “noise” important for data assimilation and NWP?

- Fast gravity waves are generally NOT important, but can rather be considered a nuisance.
- Fast waves in the NWP system require unnecessary short time steps: inefficient use of computer time.
- Gravity waves add high frequency noise to the assimilation system resulting in:
  - rejection of correct observations
  - poor use of observations
  - e.g. deriving wind field properly from satellite radiance observations
  - noisy forecasts (e.g. unrealistic precipitation)
  - Spin-up and Spin-down

- Solution: Set tendencies of gravity waves to zero in initial fields – **Nonlinear Normal Mode Initialization**
Potential Corrections for Noise / Imbalance

- **Noise in the background (first guess/model forecast)**
  - Digital filters
  - Initialization (Nonlinear Normal Mode Initialization)
    - Analysis draws to data, Initialization pushes away from observations

- **Noise in the analysis increment**
  - Improved multivariate variable definition
  - Dynamic weak constraint
    - This was our first attempt but:
      - Poor convergence / ill-conditioned
      - Scale selectivity was an issue
      - Significant degradation in analysis fits to the data, similar to full field initialization
  - *Incremental normal mode initialization*
Tangent Linear Normal Mode Constraint

\[ J = (x-x_b)^TB^{-1}(x-x_b) + (H(w)-y)^T(E+F)^{-1}(H(w)-y) \]

\[ w = C(x-x_b) \]

- analysis state vector after incremental NNMI
- C = Correction from Incremental nonlinear normal mode initialization (NNMI)
- represents correction to analysis increment that filters out the unwanted “noise”

Based on:


* Similar idea developed and pursued independently by Fillion et al. (2007)
Tangent Linear Normal Mode Constraint

Practical Consideration:
- $C$ is operating on $x-x_b$ only, and is the tangent linear of NNMI operator
- Only need one iteration in practice for good results

Procedure:
- Compute incremental tendency $x_t$
  - Implemented dry, adiabatic, generalized coordinate tendency model (TL and AD)
- Project $x_t$ onto vertical modes
- Project vertical modes to gravity modes
- Obtain adjustment $\Delta x$ to zero out incremental gravity tendencies
- Transform $\Delta x$ back to physical space
- Update analysis increment with $\Delta x$

Single observation test

- Magnitude of TLNMC correction is small
- TLNMC adds flow dependence even when using same isotropic $B$

500 hPa temperature increment (right) and analysis difference (left, along with background geopotential height) valid at 12Z 09 October 2007 for a single 500 hPa temperature observation (1K O-F and observation error)
Single observation test

Cross section of zonal wind increment (and analysis difference) valid at 12Z 09 October 2007 for a single 500 hPa *temperature* observation (1K O-F and observation error)
Surface Pressure Tendency Revisited

Zonal-average surface pressure tendency for background (green), unconstrained GSI analysis (red), and GSI analysis with TLNMC (purple).

Zonally Ave. RMS Sfc Pres Tendency
Vertical velocity

Zonal Mean Difference of the RMS (TLNMC-No Constraint) of the derived vertical velocity increment for the analysis valid at 12Z 09 October 2007
Balance Diagnostic

- Compute RMS sum of incremental tendencies in spectral space (for vertical modes kept in TLNMC)
  - Unfiltered: $S_{uf}$ (all) and $S_{uf\_g}$ (projected onto gravity modes)
  - Filtered: $S_f$ (all) and $S_{f\_g}$ (projected onto gravity modes)
  - Normalized Ratio:
    - $R_f = \frac{S_{f\_g}}{S_f - S_{f\_g}}$
    - $R_{uf} = \frac{S_{uf\_g}}{S_{uf} - S_{uf\_g}}$

<table>
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<th></th>
<th>$S_{uf}$</th>
<th>$S_{uf_g}$</th>
<th>$R_{uf}$</th>
<th>$S_f$</th>
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<td>NoJC</td>
<td>1.45x10^{-7}</td>
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<td>1.41x10^{-7}</td>
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<td>TLNMC</td>
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<td>0.419</td>
<td>1.70x10^{-8}</td>
<td>3.85x10^{-9}</td>
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Little Impact on Minimization

Norm of gradient (left) and total penalty (right) for each iteration for analysis at 12Z 09 October 2007

No Constraint (orange) versus TLNMC (green)
Fits of Surface Pressure Data in Cycled Experiment
Impact of TLNMC on 500 hPa AC Scores

500 hPa Geo. Height AC Scores for period 01 Dec. 2006 to 14 Jan. 2007

No Constraint (control, black) versus TLNMC (red)
Tropical Wind Vector RMS Error

No Constraint (control, black) versus TLNMC (red)

200 hPa & 850 hPa Tropical Vector Wind RMS Error for period 01 Dec. 2006 to 14 Jan. 2007
A scale-selective dynamic constraint has been developed based upon the ideas of NNMI

- Successful implementation of TLNMC into global version of GSI at NCEP and GMAO
- Incremental, does not force analysis (much) away from the observations compared to an unconstrained analysis
- Improved analyses and subsequent forecast skill, particularly in extratropical mass fields

Work is ongoing to apply TLNMC to regional applications & domains (Dave Parrish – NCEP)

  - Adequate for small domains: success with assimilation of radar radial velocities
  - Apparent issues with larger domains: variation of map factor/Coriolis

Work is ongoing to improve tendency model (i.e. add physics)

- Should improve tropics

TLNMC applicable to EnKF analysis perturbations?
More Recent & Future Work (mostly unrelated)

- Extension of tendency model to be used to extend GSI to 4DVAR
- Background error for high resolution GFS and CFSRR
- Data impact studies
- Moisture analysis
  - Control variable, background error, constraints
- Tropical cyclone initialization within GFS
  - Assimilation of pseudo-MSLP observations
- Flow-dependent background error variances
- EnKF with GFS*
- Hybrid Var/EnKF (alpha control variable)
New flow-dependent adjusted background error standard deviation

“As is” 500 hPa streamfunction (1e6) background error standard deviation

Valid: 2007110600
Surface pressure background error standard deviation fields

- a) with flow dependent re-scaling
- b) without re-scaling

Valid: 2007110600
TCs are often much too weak in GFS

Observed: 956 hPa ; 105 kts  
GFS: 1008 hPa ; 30 kts
Impact on Ike Analysis (Cycled)

**OPS MSLP/SfcWind(kts) IKE - 2008090400 Anl**

Contour Interval 1 mb

**GFS:** 1008 hPa; 30 kts

**ParaGFS:** 987 hPa; 48 kts

**Observed:** 956 hPa; 105 kts
GFS Phase1 Tropical Cyclone Average Track Errors (NM)
2008 Atlantic Season (1 July - 10 Nov)

- Includes all four daily cycles (00, 06, 12 and 18 UTC)
- GFS/GSI phase1 tropical cyclone track error reduced through 120h hours
- The 120h track error reduced by 8% (117 cases)
Operational GFS

GFS Phase 1 Tropical Cyclone Average Track Errors (NM) 2008 Eastern Pacific Season (1 July – 10 Nov)

- Includes all four daily cycles (00, 06, 12 and 18 UTC)
- GFS/GSI phase 1 tropical cyclone track error reduced through 120h hours
- The 96h track error reduced by 24% (62 cases)
- The 120h track error reduced by 28% (32 cases)