A Three-Dimensional Variational (3DVAR) Data Assimilation System For The WRF Community

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Presented by Yong-Run Guo on 28 June 2004

Acknowledge:Yong-Run Guo, Wei Huang, Mi-Seon Lee, Syed Rizvi, Qingnong Xiao and many others……..

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Outline Of Talk

1. Motivation.
2. Observations
3. The WRF VAR Algorithm.
4. Tuning Of Background Error Statistics.
5. Computational Efficiency.
6. Preliminary WRF 3D-Var/WRF verification
7. WRF 3D-Var Releases.

1. Motivation

Goals For 3DVAR Project

a) MM5 version **operational** in Taiwan (CAA) and US (AFWA) in 2002, and Semi-operation in KMA(2002).

b) Computationally **efficient** and **robust**.

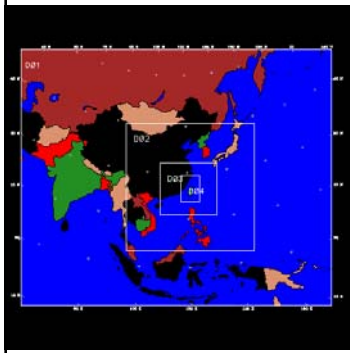
c) **Flexible** to expansion e.g. new observations, flow-dependent background errors, 4DVAR, etc.

d) **Portable** to a wide variety of platforms.

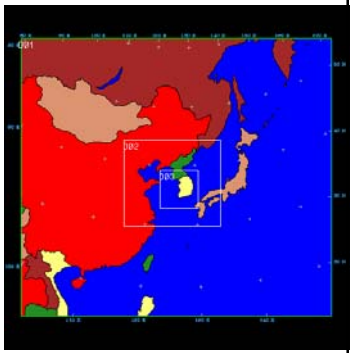
e) Well documented and supported by NCAR/MMM Division.

3DVAR East-Asia Real-Time Applications

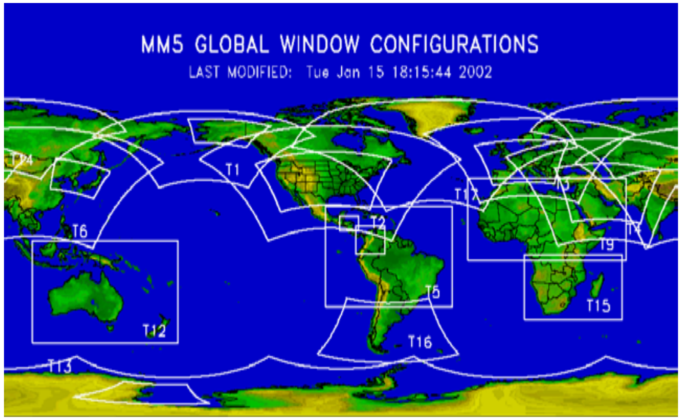
135/45/15/5km Taiwan CAA



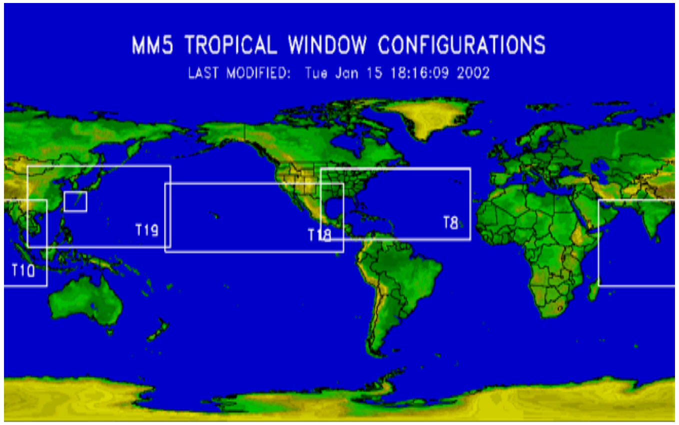
30/10/5 km Korean Met. Admin.



US Air Force Weather Agency (AFWA) Theaters



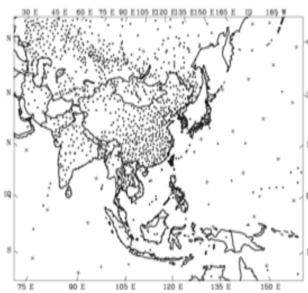
3DVAR AFWA Tropical Theaters



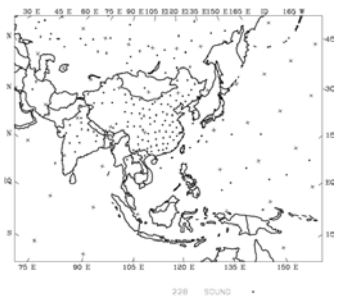
2. Observations

1998/05/30 Case-Study: Observation distribution

Surface Observations

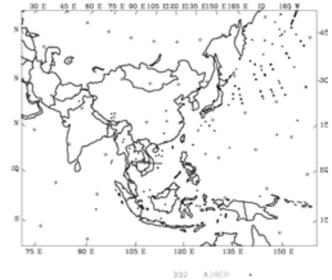


Radiosonde Observations

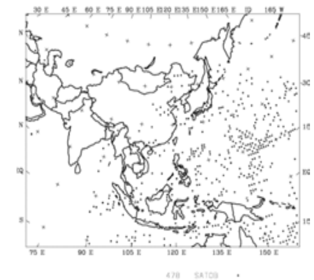


1998/05/30 Case-Study: Observation distribution

AIREP Observations



SATOB Observations

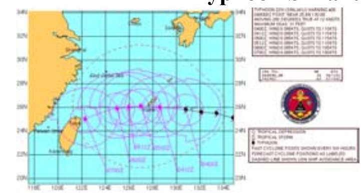


04/05/2002 06Z DMSP Data Study

SATEMs

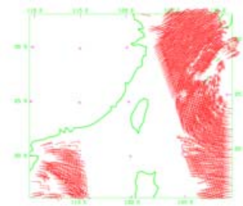
SSM/I

Typhoon Sinlaku Case Study

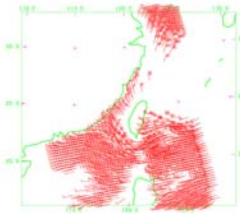


00Z September 4th 2002

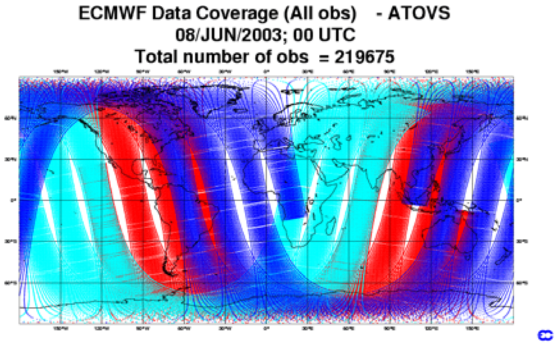
00Z September 6th 2002



Quikscat Data



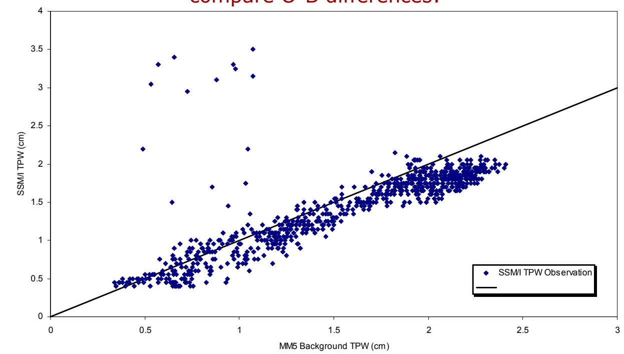
ECMWF ATOVS Radiances



Initial radiance assimilation capability planned for next release (May 2005)

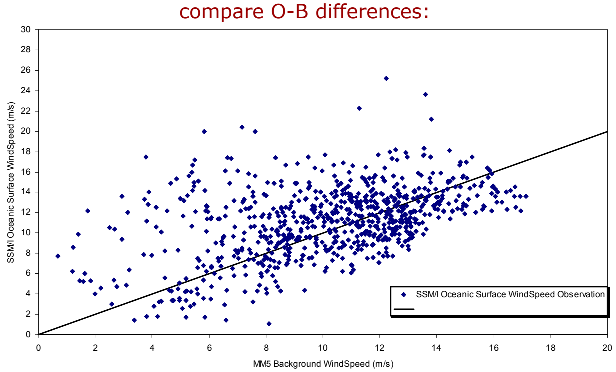
04/05/2002 SSM/I TPW Retrieval Data Study

Before attempting assimilation of new observations, compare O-B differences:



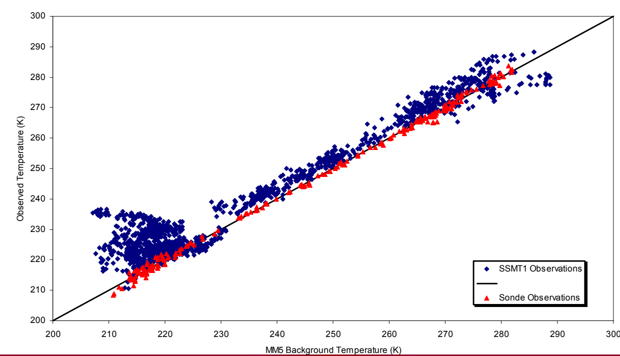
04/05/2002 SSM/I Windspeed Retrieval Data Study

Before attempting assimilation of new observations, compare O-B differences:



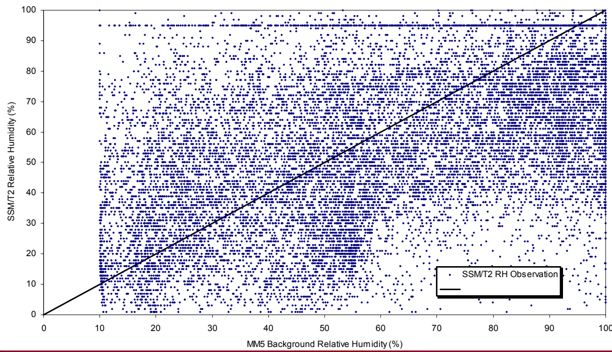
04/05/2002 SSM/T1 Temperature Retrieval Data Study

Before attempting assimilation of new observations, compare O-B differences: **bad SSM/T1 obs!**



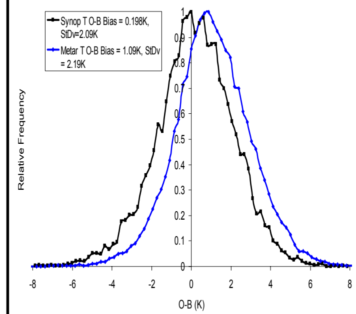
04/05/2002 SSM/T2 Relative Humidity Retrieval Data Study

Before attempting assimilation of new observations, compare O-B differences:**Terrible SSM/T2 obs!**

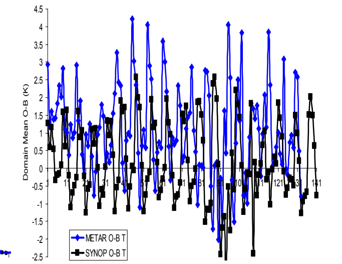


Simple Observation Increment (O-B) Diagnostics

1. Diagnosing biased observations:

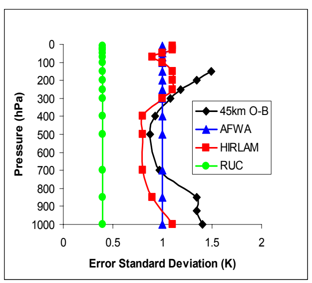


2. Diagnosing model errors in a 3hr cycling 3DVAR/Fcst. setup:

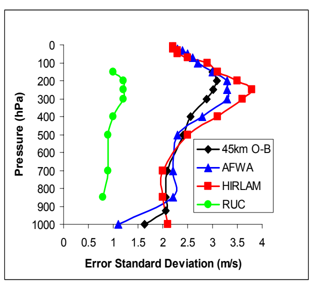


Observation error standard deviations derived from O-B data

Comparison of observation errors from different models:



Temperature



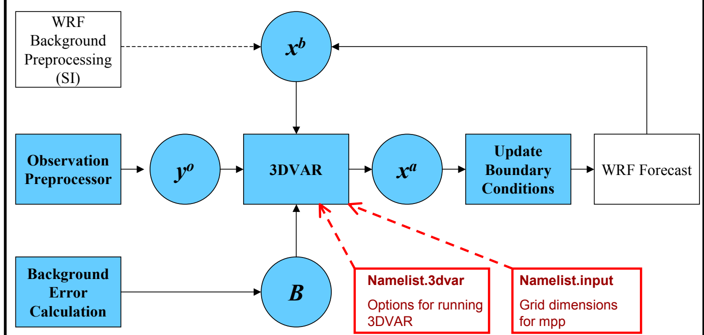
U-wind

3DVAR: Observations Used (May. 2004)

- Conventional:
  - Surface (SYNOP, METAR, SHIP, BUOY).
  - Upper air (TEMP, PIBAL, AIREP, ACARS).
- Remotely sensed retrievals:
  - Cloud-track winds (SATOBS).
  - ATOVS thicknesses (SATEMs).
  - Ground-based GPS TPW.
  - SSM/I oceanic surface wind speed and TPW.
  - SSM/T1 temperature retrievals.
  - SSM/T2 relative humidity retrievals.
  - Scatterometer (Quikscat) oceanic surface winds.
  - Radar radial velocity.
  - Wind Profiler.
- Radiances:
  - SSM/I brightness temperatures.

3. The WRF 3DVAR Algorithm

WRF 3DVAR in the WRF Modeling System



Overview I

- Assimilation system combines all sources of information:
  - Observations - $\boldsymbol{y^o}$
  - Background field - $\boldsymbol{x^b}$
  - Estimate of observation/background errors.
  - Laws of physics.
- Output of the assimilation system is the “analysis”.
- Analysis used in a number of ways:
  - Initial conditions for numerical forecasts.
  - Climatology - reanalyses.
  - Observing system justification (e.g. OSEs, OSSEs).

Overview II

- Not enough observations!!
  - Typical global model – 425 * 325 * 30 = 4.2 million gridpoints.
  - Minimum number of prognostic variables = 6 *(u, v, w, T, p, q)*.
  - Number of degrees of freedom = 25.2 million.
- Typical number of observations = $10^{5\text{-}6}$ but:
  - Inhomogeneous distribution of data.
  - Observations not always in sensitive areas.
  - Observations have errors.
- Solutions:
  - Use previous forecast to fill in gaps.
  - Use approximate balance relationships.
  - Need more/better observations.

Overview III

- Variety of algorithms used to implement 3/4DVAR.
- 3/4DVAR system developed at many centers e.g. NCEP, ECMWF, CMC, DAO, Meteo-France, UKMO, JMA, NRL, FSL, HIRLAM.
- Practical implementation requires simplifications e.g.
  - Run 3/4DVAR at lower resolution.
  - Simplified error covariances.
  - Linearized observation operators, balance equation.
  - Thinned observations.

Overview IV

- **Variational** analysis $\boldsymbol{x}^a$ is minimum $\boldsymbol{x}$ of cost-function J = -ln (P($\boldsymbol{x}$))
- Assume error probability $P(\boldsymbol{x})$ is Gaussian then

$$J(\boldsymbol{x}) = \frac{1}{2}(\boldsymbol{x}-\boldsymbol{x}^b)^T \boldsymbol{B}^{-1}(\boldsymbol{x}-\boldsymbol{x}^b) + \frac{1}{2}(\boldsymbol{y}-\boldsymbol{y}^o)^T(\boldsymbol{O}+\boldsymbol{F})^{-1}(\boldsymbol{y}-\boldsymbol{y}^o)$$

- $\boldsymbol{y} = \boldsymbol{H}(\boldsymbol{x})$. $\boldsymbol{H}$ is the nonlinear "observation operator".
- ***Error covariances:***
  B = Background (previous forecast) errors.
  O = Observation (instrumental) errors.
  F = Representivity (observation operator) errors.
- Practical implementation requires approximation….

WRF 3DVAR Algorithm

- *Define **analysis increments:*** $\boldsymbol{x}^a = \boldsymbol{x}^b + \boldsymbol{I}\,\boldsymbol{x}'$
- *Solve **incremental*** cost function:

$$J(\boldsymbol{x}') = \frac{1}{2}\boldsymbol{x}'^T \boldsymbol{B}^{-1}\boldsymbol{x}' + \frac{1}{2}(\boldsymbol{y}'-\boldsymbol{y}'^o)^T(\boldsymbol{O}+\boldsymbol{F})^{-1}(\boldsymbol{y}'-\boldsymbol{y}'^o)$$

  where $\boldsymbol{y}' = \mathbf{H}\boldsymbol{x}'$, $\boldsymbol{y}^{o\prime} = \boldsymbol{y}^o - \boldsymbol{y}$.

- ***Preconditioned control variable*** $\boldsymbol{v}$ analysis space:

$$\boldsymbol{x}' = U\boldsymbol{v} = U_p U_v U_h \boldsymbol{v}$$

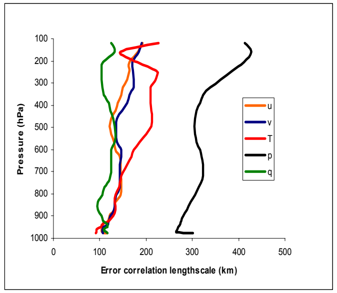
  where U transform defined by $\boldsymbol{B} = UU^T$.

  Here we'll talk more details on control variables and background error statistics in NCAR/UKMO's approach (*cv_options=2*).

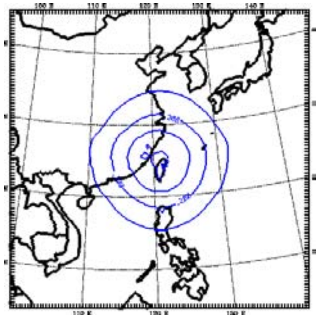
WRF 3DVAR Control Variables I

U_h: Isotropic/homogeneous recursive filter algorithm.

e.g. 45km CAA Domain 2



Single T ob (O-B=1K, p~500hPa)



WRF 3DVAR: Control Variables II

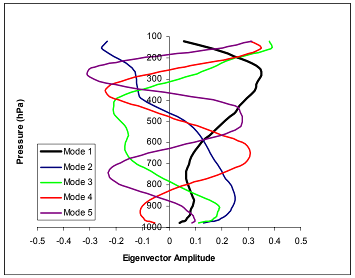
$$\mathbf{x}'(i,j,k) = U\mathbf{v} = U_p U_v U_h \mathbf{v}(i,j,m)$$

- U_v: Transform to model levels k from m vertical eigenvectors.
- Eigenvectors $\boldsymbol{E}$ and eigenvalues Λ given by decomposition of vertical background error covariance matrix $\boldsymbol{B} = \boldsymbol{E}\,\Lambda\,\boldsymbol{E}^T$.
- Spreads analysis increments in the vertical.
- Can be used to precondition, filter noise and reduce size of problem.

WRF 3DVAR Control Variables II

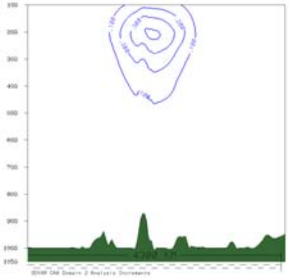
U_v: Projection from EOFs of climatological vertical background error.

45km MM5 - CAA Domain 2

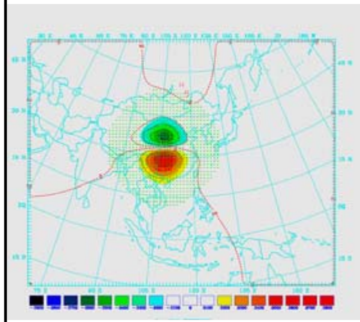


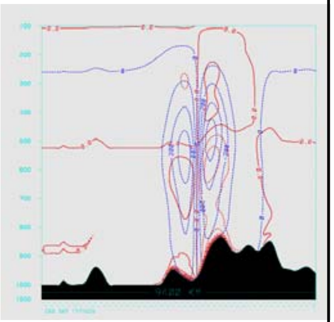
First 5 eigenvectors of psi background error

Single u ob (O-B=1m/s, p-200hPa

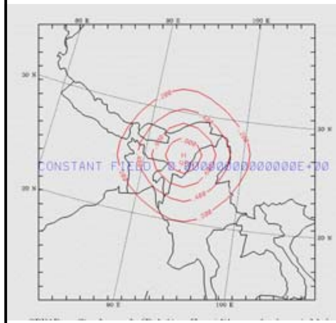


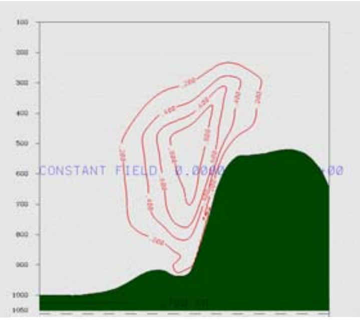
Single u Observation Test



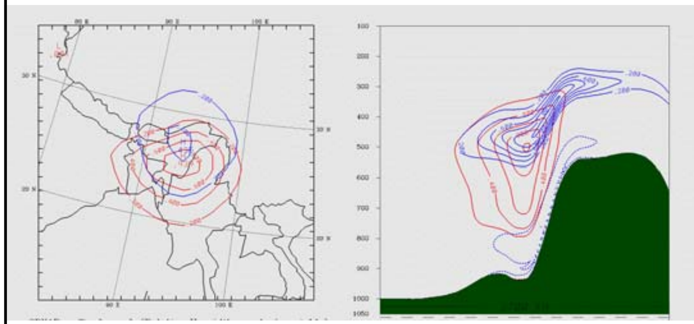


Single q Observation Test – q control variable





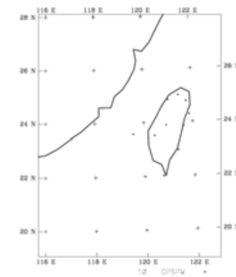
Single q Observation Test – RH control variable

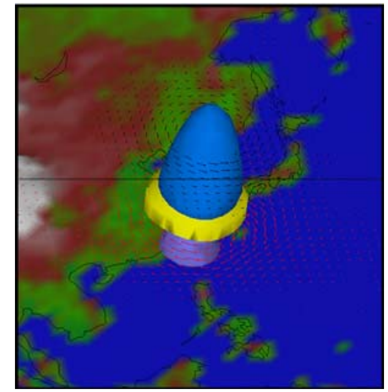


WRF 3DVAR System: Use of New Observation Sources

Assimilation of TPW retrieval from ground-based GPS data

TPW O-B = 1mm at Taipei





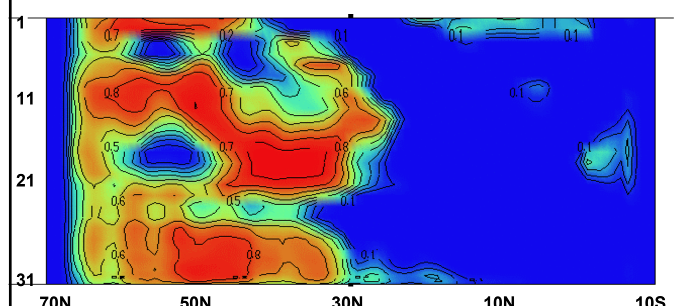
WRF 3DVAR Control Variables III

$$\boldsymbol{x}'(i,j,k) = U\boldsymbol{v} = U_p U_v U_h \boldsymbol{v}(i,j,m)$$

- U_p: Transform to model variables (u', v', T', p' and q') from physical control variable increments (ψ', χ', p'_u and q').
- Unbalanced pressure control variable p'_u defined by
  $$p'_u = p - Cp'_b$$
- Where
  $$\nabla^2 p'_b = -\nabla \cdot \overline{\rho}[\overline{\boldsymbol{v}} \cdot \nabla \boldsymbol{v}' + \boldsymbol{v}' \cdot \nabla \overline{\boldsymbol{v}} + f\boldsymbol{k} \times \boldsymbol{v}']$$
- Balance equation represents linearized geostrophic and cyclostrophic balance.
- Test balance equation by applying to forecast difference statistics.

Accuracy Test For Balanced Pressure

$$\nabla^2 p'_b = -\nabla \cdot \overline{\rho}[\overline{\mathbf{v}} \cdot \nabla \mathbf{v}' + \mathbf{v}' \cdot \nabla \overline{\mathbf{v}} + f\mathbf{k} \times \mathbf{v}']$$



Correlation between pressure and balanced pressure increment

Control variables and background error statistics in NCEP approach (cv_options=3).

- **Control variables**: ψ, χ_u, t_u, rh_p and $psfc_u$
- **Background Error Statistics**: $\mathbf{B} = (\mathbf{VB_zB_xB_y})\,(\mathbf{VB_zB_xB_y})^T$

Reference

http://www.mmm.ucar.edu/wrf/WG4/wrf3dvar_cvoptions3.htm

Wu, Wan-Shu and R. James Purser, 2002: Three-dimensional variational analysis with spatially inhomogeneous covariances. *Mon. Wea. Rev.*, **130**, 2905-2916.

4. Background Errors

Current WRF 3DVAR Approximations

- **Climatological background errors:** Estimated via "tuned" NMC-method statistics:

$$B = \overline{(x^b - x^t)(x^b - x^t)^T} \approx A\,\overline{(x^{t2} - x^{t1})(x^{t2} - x^{t1})^T}$$

- **Simplified horizontal background error covariances:** represented by simple "recursive filters".
- **Uncorrelated observation errors**.
- **Neglect error correlations between analysis variables (**streamfunction, potential, "unbalanced" pressure and a humidity variable (q or RH)**.**
- **Approximate balance relationships used:** geostrophic, cyclostrophic, hydrostatic **increments.**

$$J = \frac{1}{2}\sum_i v_i^2 + \frac{1}{2}\sum_n \frac{(y' - y'^O)_n^2}{\sigma_{on}^2}$$

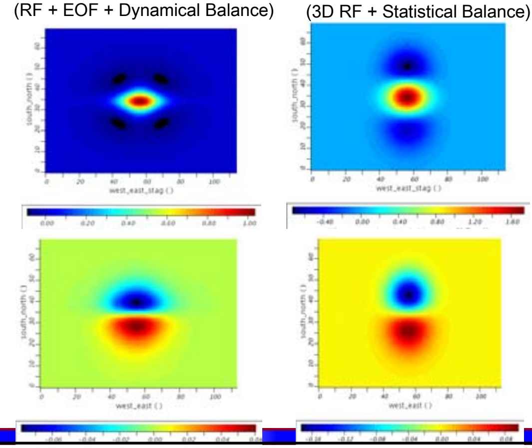
NCAR/UKMO BE model (RF + EOF + Dynamical Balance)

NCEP BE model (3D RF + Statistical Balance)

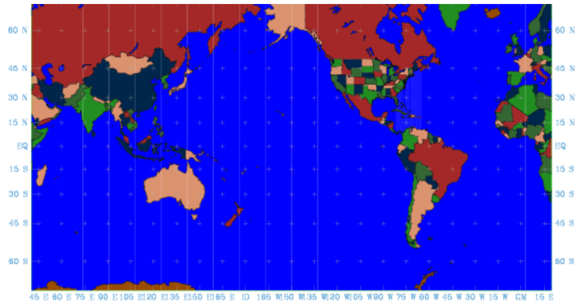
U Increment

Single u ob: O-B=2m/s.

T Increment



"Global" Domain For Calculation Of Background Errors (cv_options=2 described here)

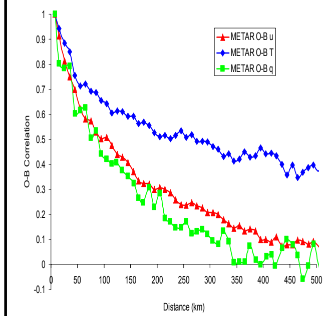


Note: These statistics are provided as a starting point for the user. In order to get the optimal use of your data, you need to create background errors for your own domain.

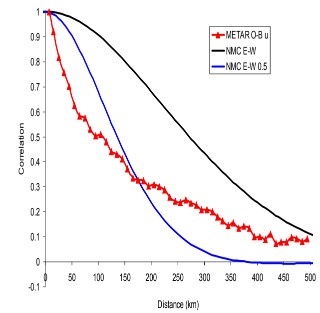
Background error lengthscales derived from innovations

Can tune NMC-statistics with O-B data:

Dependence on variable:



Comparison with NMC-method:



5. Computational Efficiency

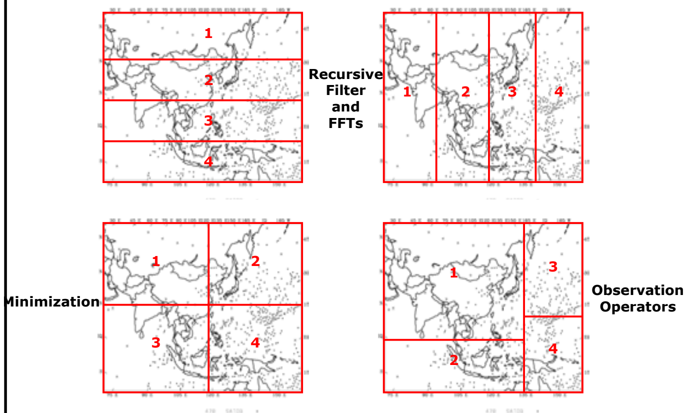
Data Compression Via Truncation Of Vertical EOFS

Example Cost For 100x100x31 CAA 45km 3DVAR with conventional obs:

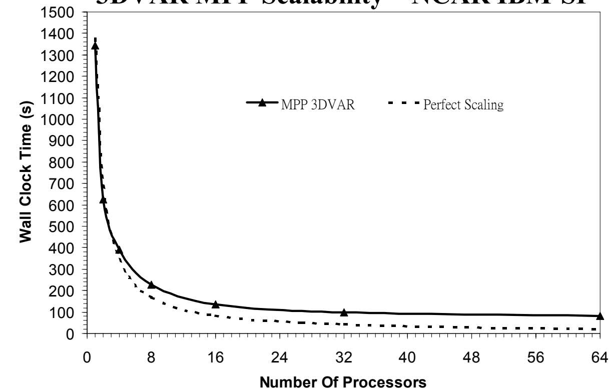
Variance	# psi	# chi modes	# pu modes	# q modes	CV Size	Its	Final J (x10^4)	CPU (s)	Mem (Mb)
99.9%	17	17	10	22	438438	25	1.33	251	220
100%	31	31	31	31	823723	24	1.32	420	316

Conclusion: Halve 3DVAR cost with data compression. Negligible scientific impact.

3DVAR MPP Domain Decompositions



3DVAR MPP Scalability – NCAR IBM-SP

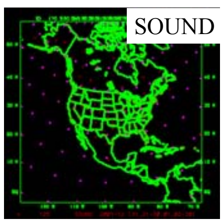


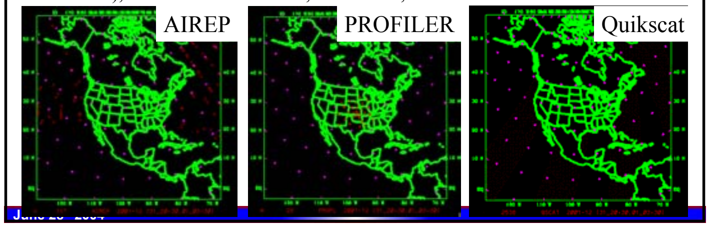
- **Test Case: 140x150x41 AFWA 45km "T4 theater" – 25th Jan 2002.**
- **Background error tuning – Old Its = 98, New = 49 (64PE = 58s).**

6. Preliminary WRF 3D-Var/WRF Verification

3D-Var/WRF Cycling (CONUS)

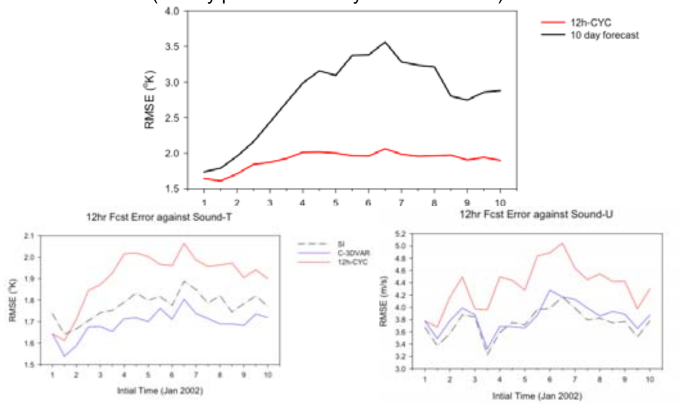
- Domain: CONUS, 100km and 40km resolution.
- WRF 3D-Var/WRF Version 2.0.
- NCEP background error model used.
- 12-hourly full cycling, obs. from NCAR MSS.
- Limitations: Reduced obs (e.g. 6/18Z, AMDAR, radiances), BE not tuned for WRF, Not FGAT, etc.





CONUS 40km Forecast Verification (vs sondes)

(10 day period - January 1st - 10th 2002)



6. WRF 3D-Var Releases

WRF 3D-Var Version 2.0 (Released May 2004)

- i=x, k=1 at bottom (cut MM5 legacy!).
- Vertical velocity analysis.
- New ob. types: radar radial velocity, SSM/I radiances, buoy, and wind-profiler.
- Choice of minimization options (Conjugate Gradient, Quasi-Newton).
- Outer-loop (“adaptive” QC, and nonlinear effects).
- Multiple background error covariance models.
- WRF 3D-Var/WRF coupling.

WRF 3/4D-Var Version 3.0 Release (May 2005?)

- First Guess at Appropriate Time (FGAT).
- Radar reflectivity, GPS refractivity, improved radiance assimilation.
- Global WRF 3D-Var.
- Ensemble-based background errors.
- Digital filter/Incremental Analysis Update (IAU).
- Platforms: IBM-SP, DEC, Linux (Alpha, PC), SGI, Fujitsu VPP5000, Cray X1.
- Initial WRF 4D-Var capability: WRF 3D-Var + WRF EM (adiabatic) core.