A Three-Dimensional Variational (3DVAR) Data Assimilation System For The MM5 Community

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and many others……..

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Click: Online 3DVAR tutorial

Outline Of Talk

1. Motivation.
2. Observations
3. The MM5/WRF VAR Algorithm.
4. Tuning Of Background Error Statistics.
5. Computational Efficiency.
6. Impact Of Hydrometeor Spin-Up.
7. The Grid in MM5 3DVAR?

1. Motivation

Goals For 3DVAR Project

a) **Operational** in Taiwan (CAA) and US (AFWA) in 2002. Semi-operational in South Korea (KMA).

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

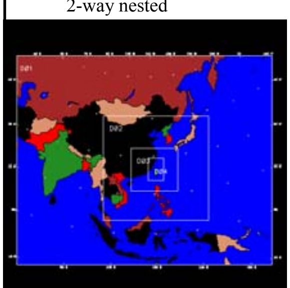
c) **Flexible** to expansion e.g. new observations, flow-dependent background errors, 4DVAR, etc.

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

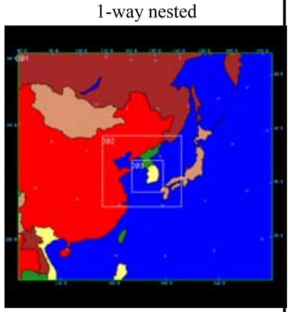
e) Applicable to both **MM5** and **WRF** models.

3DVAR/MM5 East-Asia Real-Time Applications

135/45/15/5km Taiwanese MM5
2-way nested

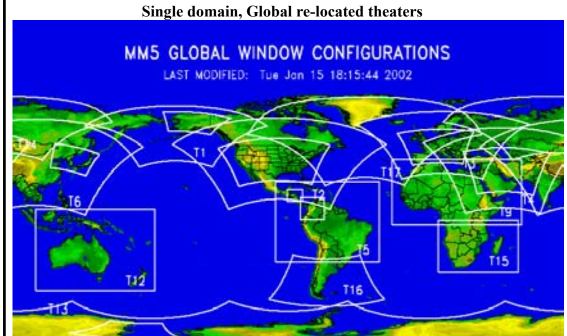


30/10/5 km Korean MM5
1-way nested

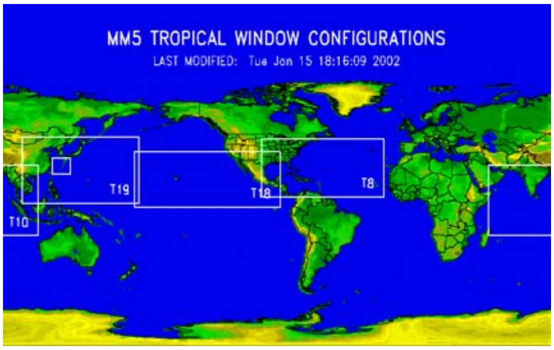


3DVAR/MM5 US Air Force Weather Agency (AFWA) Theaters

Single domain, Global re-located theaters



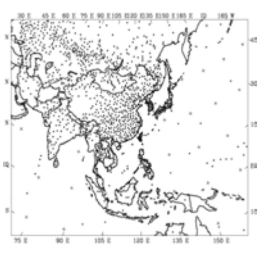
3DVAR/MM5 AFWA Tropical Theaters



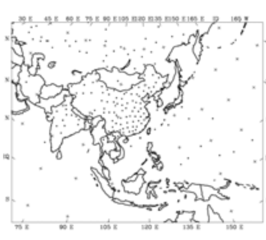
2. Observations

1998/05/30 Case-Study: Observation distribution

Surface Observations

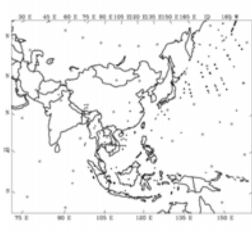


Radiosonde Observations

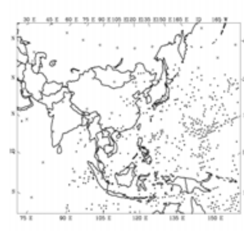


1998/05/30 Case-Study: Observation distribution

AIREP Observations



SATOB Observations

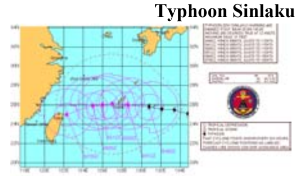


04/05/2002 06Z DMSP Data Study

SATEMs

SSM/I

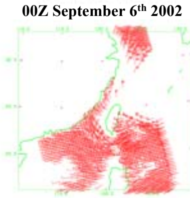
Typhoon Sinlaku Case Study



00Z September 4th 2002

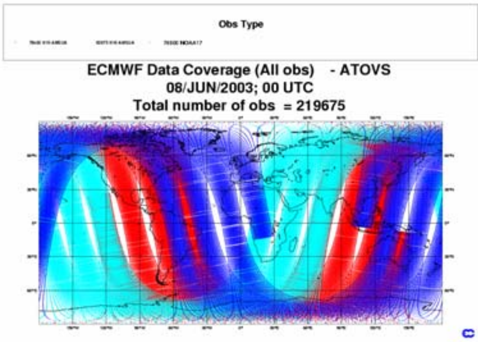
00Z September 6th 2002

Quikscat Data



NCAR Mesoscale and Microscale Meteorology

ECMWF ATOVS Radiances



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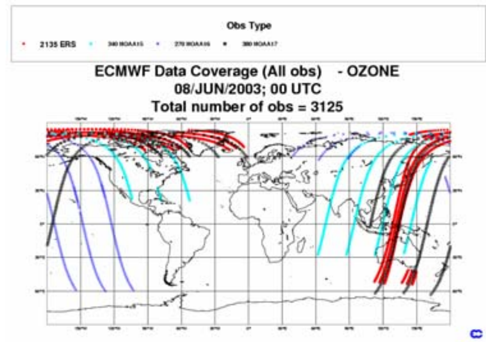
ECMWF Ozone



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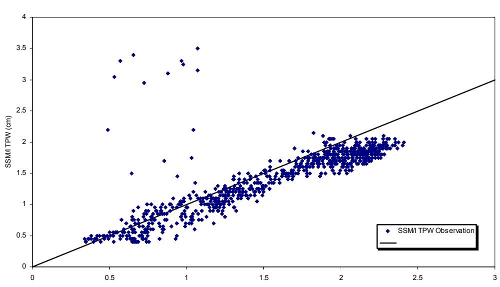
04/05/2002 SSM/I TPW Retrieval Data Study



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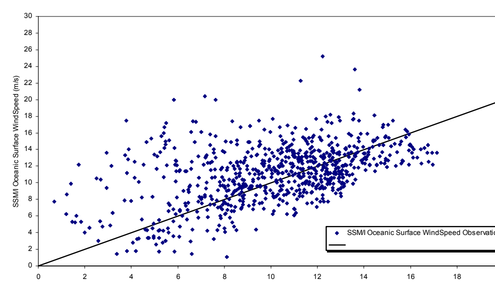
04/05/2002 SSM/I Windspeed Retrieval Data Study



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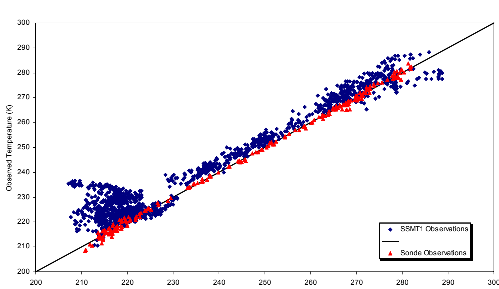
04/05/2002 SSM/T1 Temperature Retrieval Data Study



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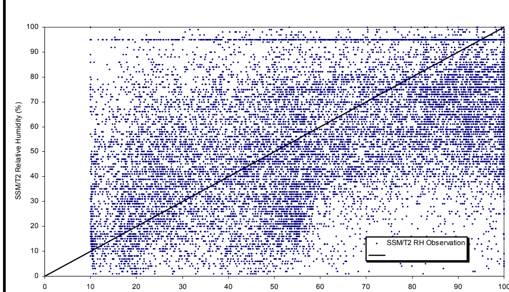
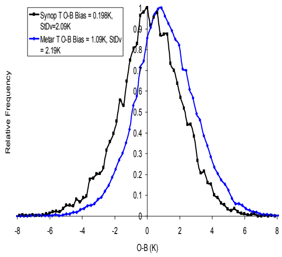
04/05/2002 SSM/T2 Relative Humidity Retrieval Data Study

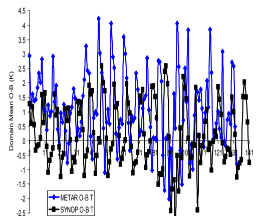


Simple Observation Increment (O-B) Diagnostics

1. Diagnosing biased observations:

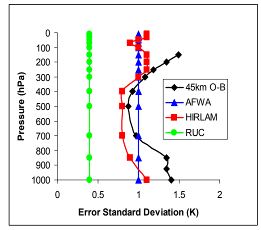


2. Diagnosing model errors in a 3hr cycling 3DVAR/MM5 setup:

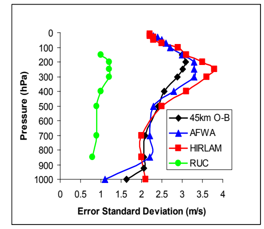


Observation error standard deviations derived from O-B data

Comparison of observation errors from different models:



Temperature



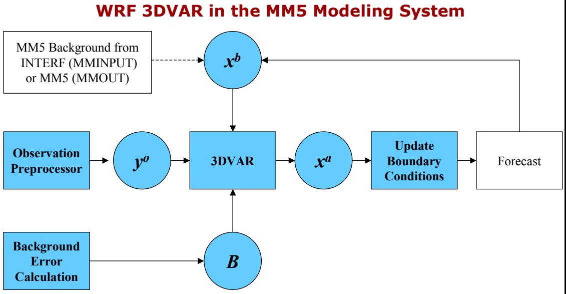
U-wind

3DVAR: Observations Used (Nov. 2002)

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

3. The MM5/WRF 3DVAR Algorithm

WRF 3DVAR in the MM5 Modeling System



Overview I

- Assimilation system combines all sources of information:
  - Observations - y^o
  - Background field - 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($\boldsymbol{x}$)) Or a maximum the likelihood estimate.
- Assume error probability P($\boldsymbol{x}$) is Gaussian then

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

- $y = H(x)$. 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….

MM5/WRF 3DVAR Algorithm

Incremental approach

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

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

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

Preconditioned control variable v analysis space:

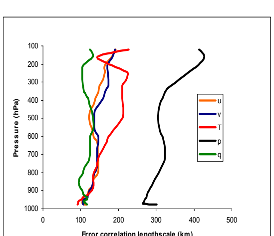
$$\mathbf{x}' = U\mathbf{v} = U_p U_v U_h \mathbf{v}$$

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

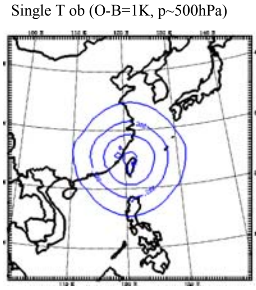
WRF 3DVAR Control Variables I

U_h: Isotropic/homogeneous recursive filter algorithm.

e.g. 45km MM5 - CAA Domain 2



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



MM5 3DVAR: Control Variables II

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

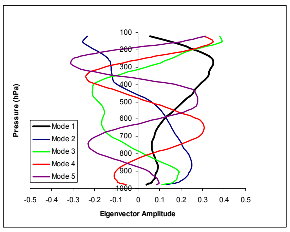
- U_v: Transform to model levels k from m vertical eigenvectors.
- Eigenvectors ***E*** and eigenvalues Λ given by decomposition of vertical background error covariance matrix $\boldsymbol{B} = \boldsymbol{E}\,\Lambda\,\boldsymbol{E}^T$.
- Spreads analysis increments in the vertical.
- Can be used to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

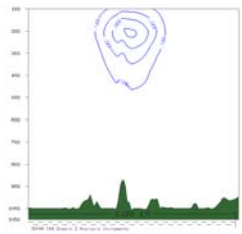
WRF 3DVAR Control Variables II

U_v: Projection from EOFs of climatological vertical background error.

e.g. 45km MM5 - CAA Domain 2

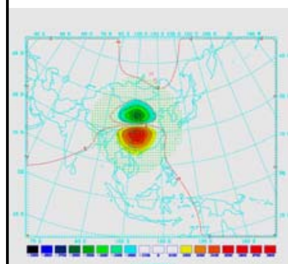
Single u ob (O-B=1m/s, p~200hPa)

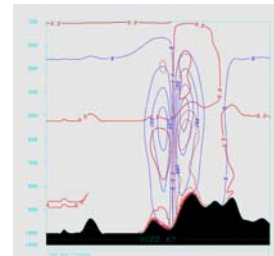




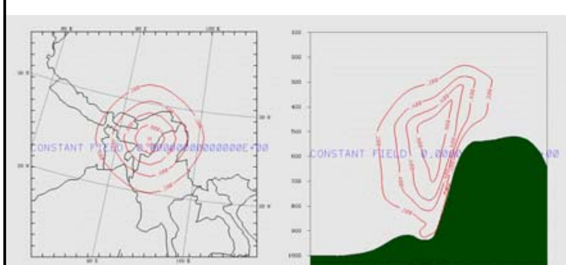
First 5 eigenvectors of psi background error

Single u Observation Test

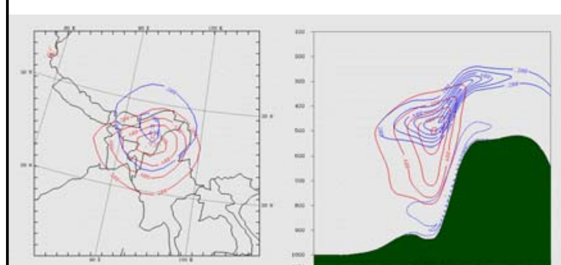




Single q Observation Test – q control variable



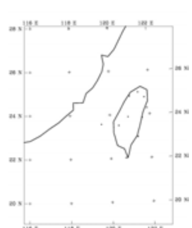
Single q Observation Test – RH control variable

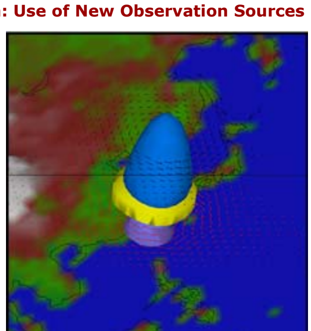


MM5 3DVAR System: Use of New Observation Sources

Assimilation of TPW retrieval from ground-based GPS data

TPW O-B = 1mm at Taipei





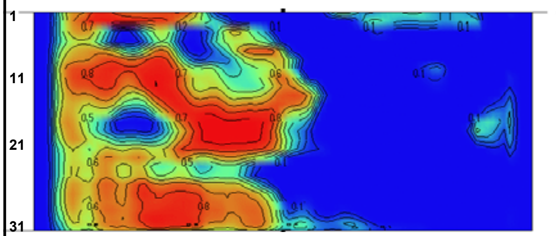
WRF 3DVAR Control Variables III

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

- 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
  $$\nabla^2 p'_b = -\nabla \cdot \bar{\rho}[\bar{\mathbf{v}} \cdot \nabla \mathbf{v}' + \mathbf{v}' \cdot \nabla \bar{\mathbf{v}} + f\mathbf{k} \times \mathbf{v}']$$
- Balance equation represents linearized geostrophic and cyclostrophic balance.
- Test balance equation by applying to forecast difference statistics.

Accuracy Test For Balanced Pressure

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



Correlation between pressure and balanced pressure increment

NCAR Mesoscale and Microscale Meteorology

Summary of the control variables

- U_p transformation: u', v', t', p', q' (rh) to $\psi', \chi', p_u', q'(rh')$
- U_v trnasformation: $\psi', \chi', p_u', q'(rh')$ in physical space to the *cv1, cv2, cv3, cv4* in the eigenvector space.

  cv → Coefficients of the eigen Vectors or Control Variable.
- U_h trandformation is applied to the *cv1, cv2, cv3, cv4* in modeling the horizontal covariance.
- Minimization algorithm is applied to the control variables *cv1, cv2, cv3, and cv4.*

NCAR Mesoscale and Microscale Meteorology

4. Background Errors

NCAR Mesoscale and Microscale Meteorology

Current MM5/WRF 3DVAR Approximations

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

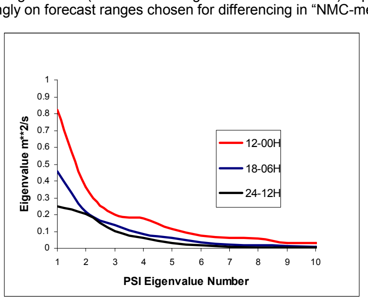
  $$B = \overline{(\mathbf{x}^b - \mathbf{x}^t)(\mathbf{x}^b - \mathbf{x}^t)^T} \approx A\overline{(\mathbf{x}^{t2} - \mathbf{x}^{t1})(\mathbf{x}^{t2} - \mathbf{x}^{t1})^T}$$
- **Simplified horizontal background error covariances:** represented by simple "recursive filters".
- **Uncorrelated observation 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 Mesoscale and Microscale Meteorology

Dependence of eigenvalues on forecast difference range

Size of eigenvalues (and hence background error variances) depends strongly on forecast ranges chosen for differencing in "NMC-method".



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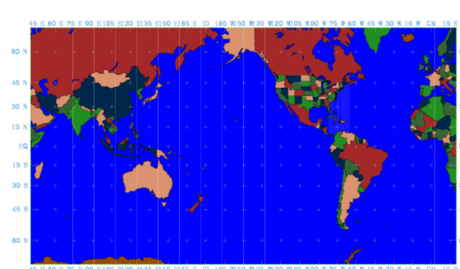
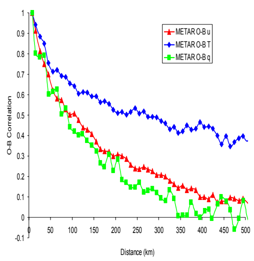
"Global" Domain For Calculation Of AVN Background Errors

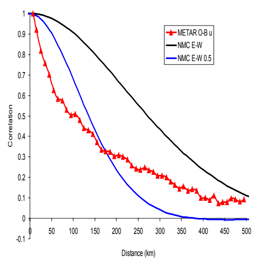


Background error lengthscales derived from O-B data

Dependence on variable:



Comparison with NMC-method:



5. Computational Efficiency

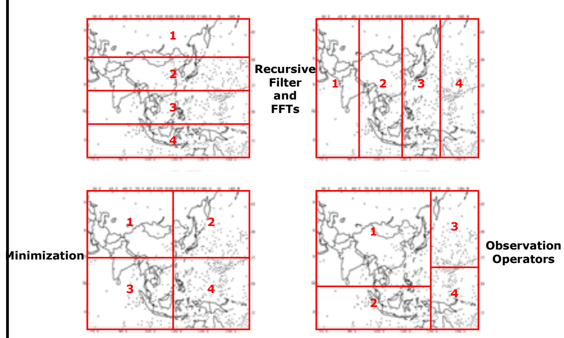
Data Compression Via Truncation Of Vertical EOFS

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

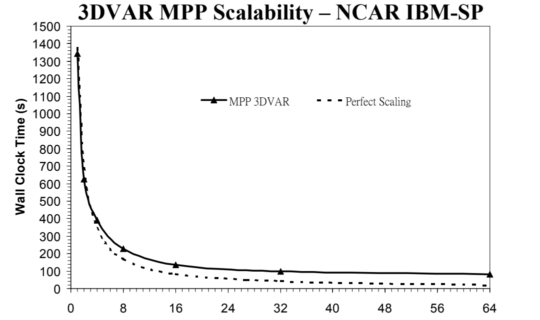
Variance	# psi	# chi modes	# pu modes	# q modes	CV Size	Its	Final J ($x10^4$)	CPU (s)	Mem (Mb)
99.9%	17	17	10	22	438438	25	1.33	251	220
100%	31	31	31	31	823723	24	1.32	420	316

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

3DVAR MPP Domain Decompositions



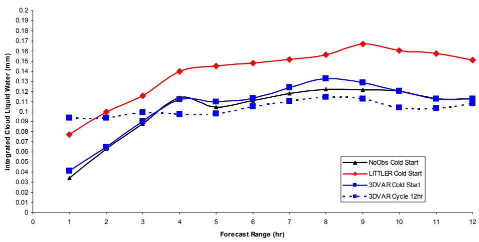
3DVAR MPP Scalability – NCAR IBM-SP



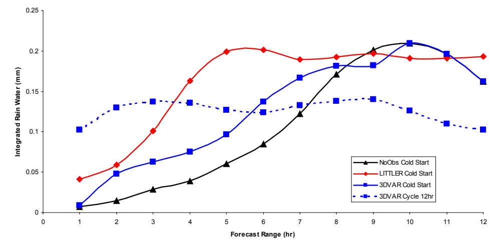
- **Test Case: 140x150x41 AFWA 45km "T4 theater" – 25th Jan 2002.**
- **Background error tuning – Old Its = 98, New = 49 (64PE = 58s).**

6. Impact of Hydro-Meteor Spin-Up

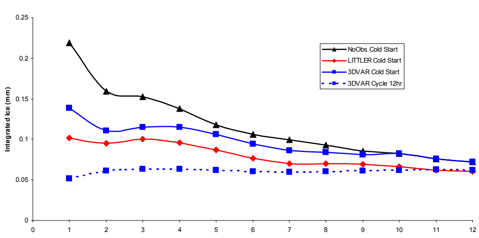
Spin-up of integrated CLW for 45km CAA domain



Spin-up of integrated rain-water for 45km CAA domain



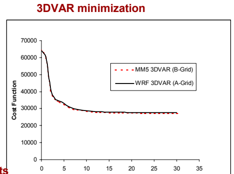
Spin-up of integrated cloud ice for 45km CAA domain



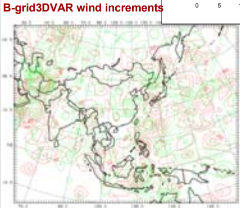
7. The Grid in MM5 3DVAR?

Impact of grid-stagger change in 3DVAR

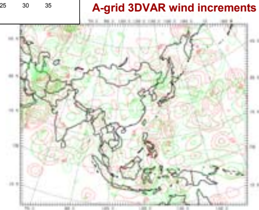
3DVAR minimization



B-grid3DVAR wind increments



A-grid 3DVAR wind increments



Thank you!