How EnKF can benefit from or contribute to 4D-Var (an EnKF perspective)

Takemasa Miyoshi

Takashi Kadowaki, Yoshiaki Sato

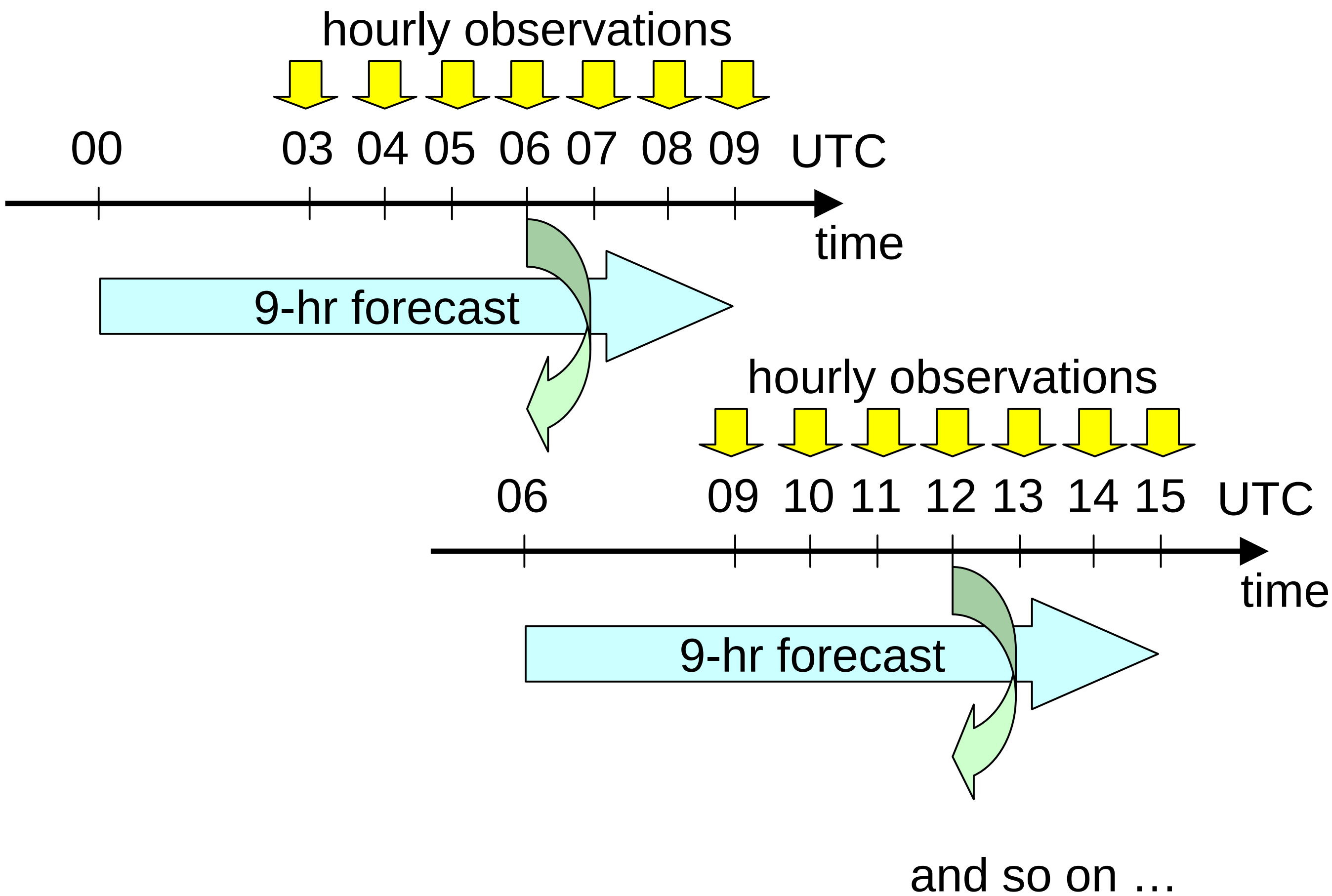
Numerical Prediction Division, Japanese Met. Agency

Outline

- JMA's experience on…
  - 4D-Var with flow-dependent background error variance
    - Miyoshi and Kadowaki (2008, SOLA)
  - EnKF development
    - Miyoshi, Sato, and Kadowaki

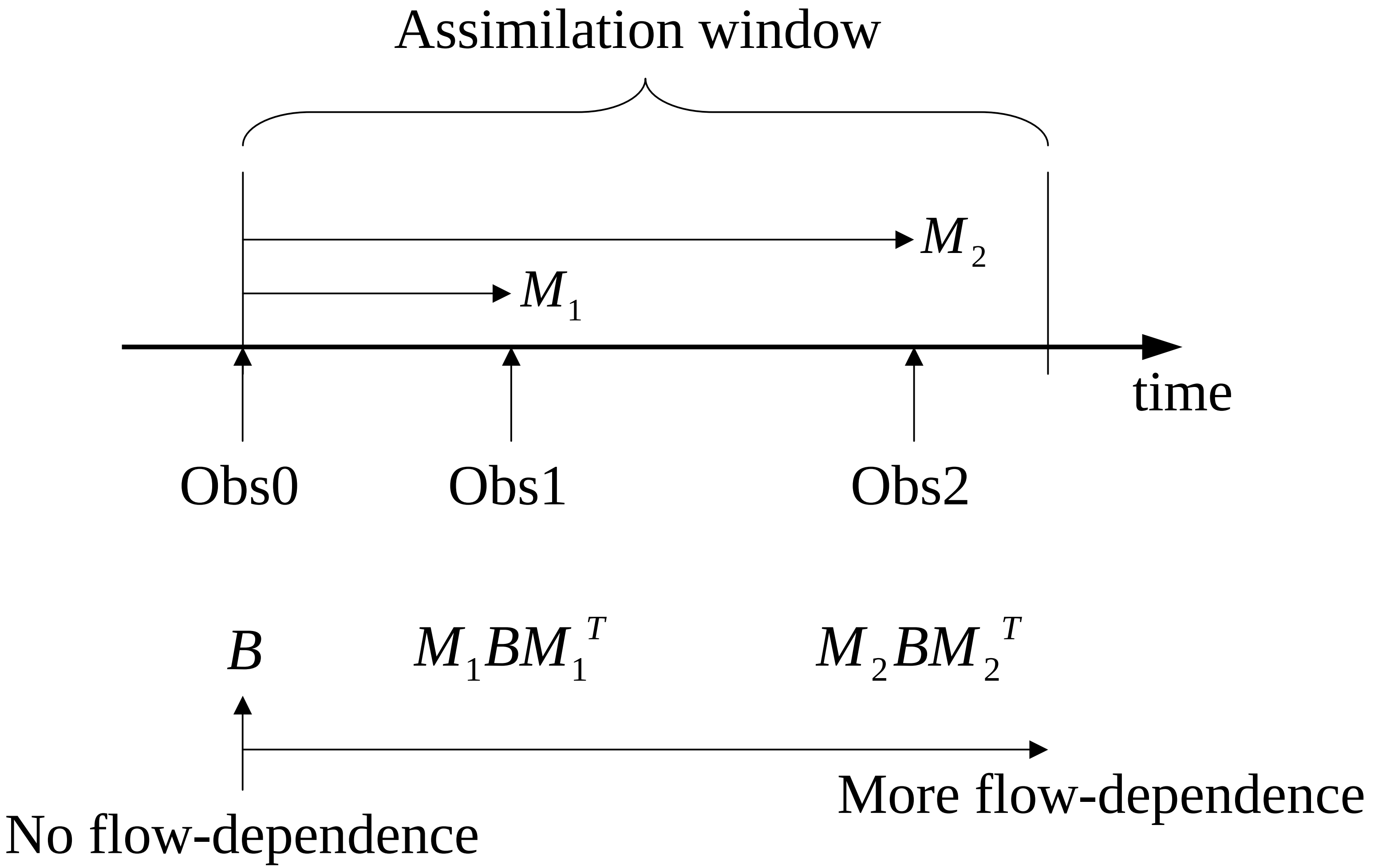
- Synergies in an EnKF perspective:
  - The comparison helps the EnKF development
    - To identify errors
    - To come up with ideas to simulate VarBC

JMA's forecast-analysis cycle



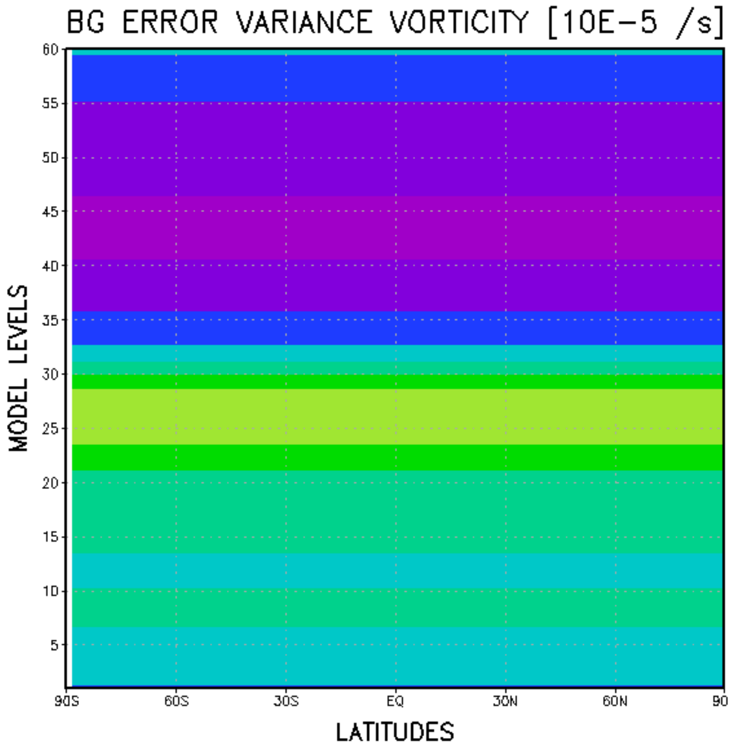
Flow-dependence in 4D-Var

- In theory

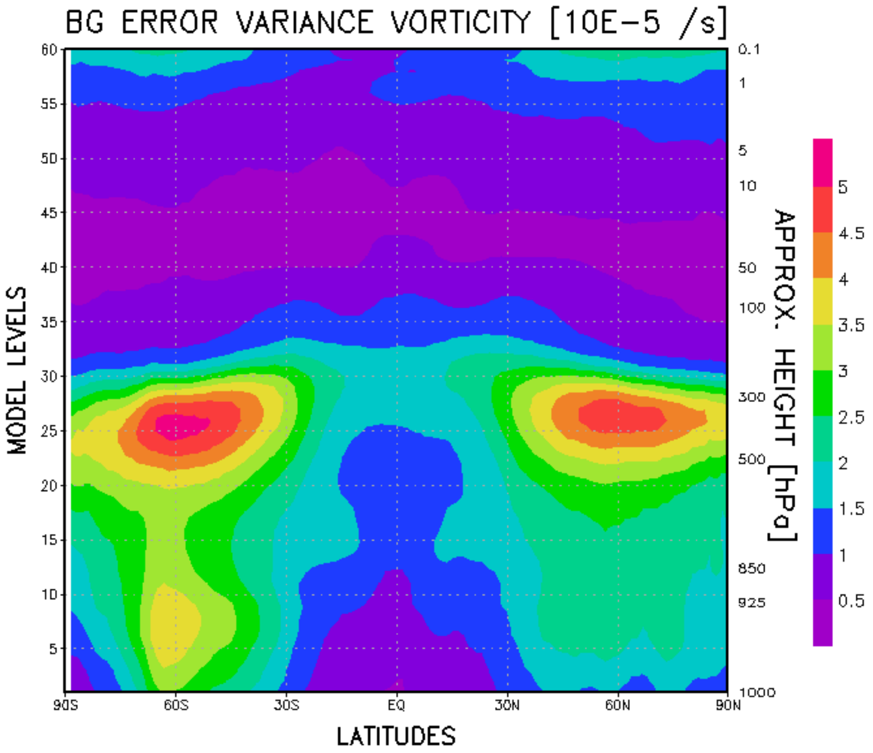


B in JMA 4D-Var

Currently operational



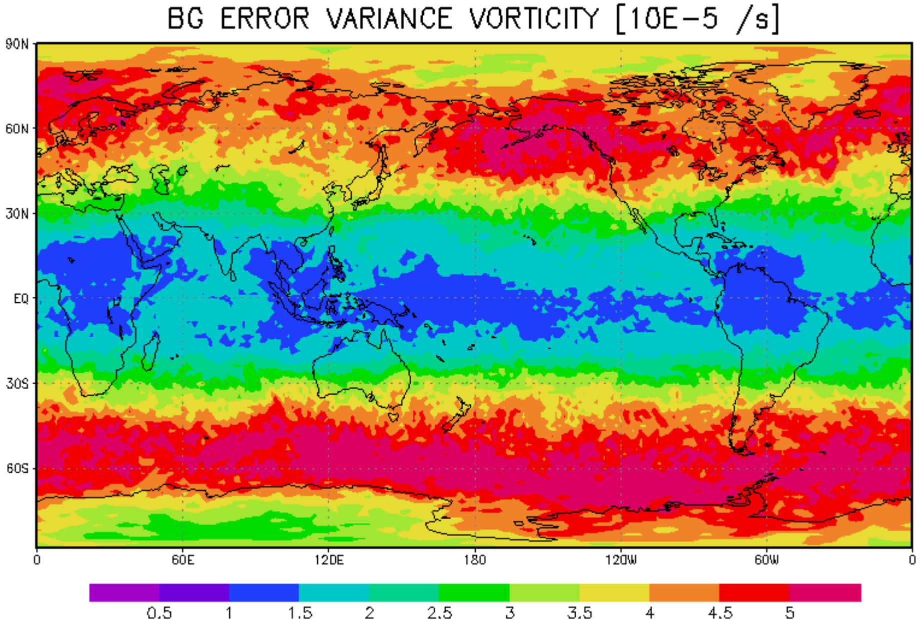
Raw statistics



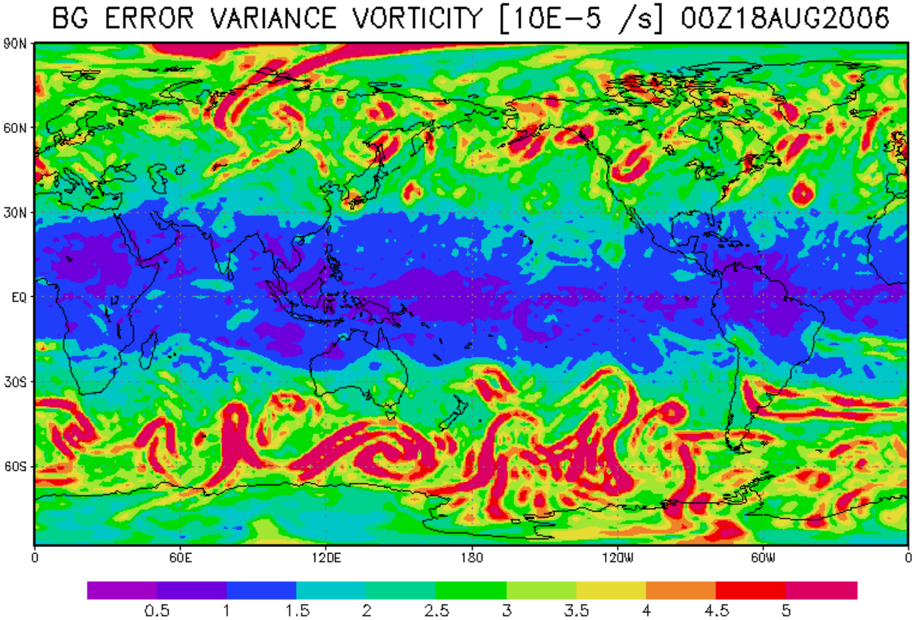
The operational system assumes horizontal homogeneity.

Flow-dependent B estimate

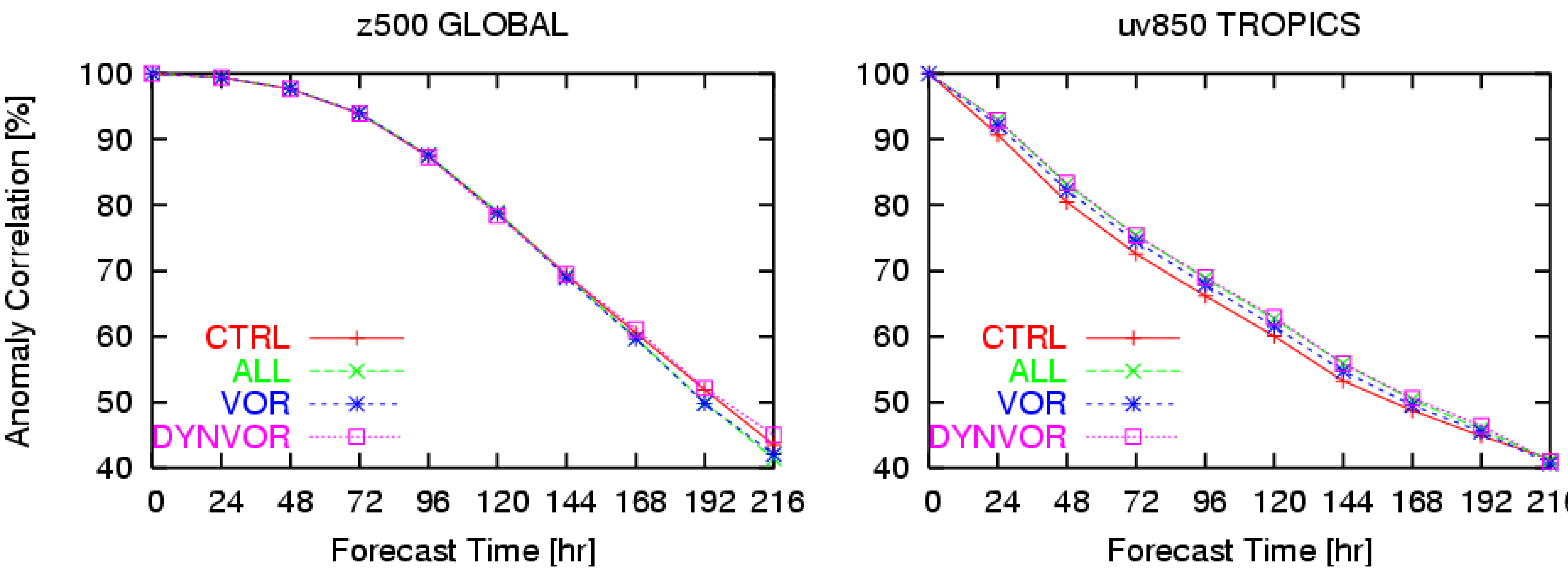
1-year average



Snapshot



Impact of B in 4D-Var



CTRL	Operational 4D-Var
ALL	Spatially inhomogeneous B for all variables
VOR	Spatially inhomogeneous B for vorticity
DYNVOR	Spatially and temporally inhomogeneous B for vorticity

Flow-dependent B in 4D-Var

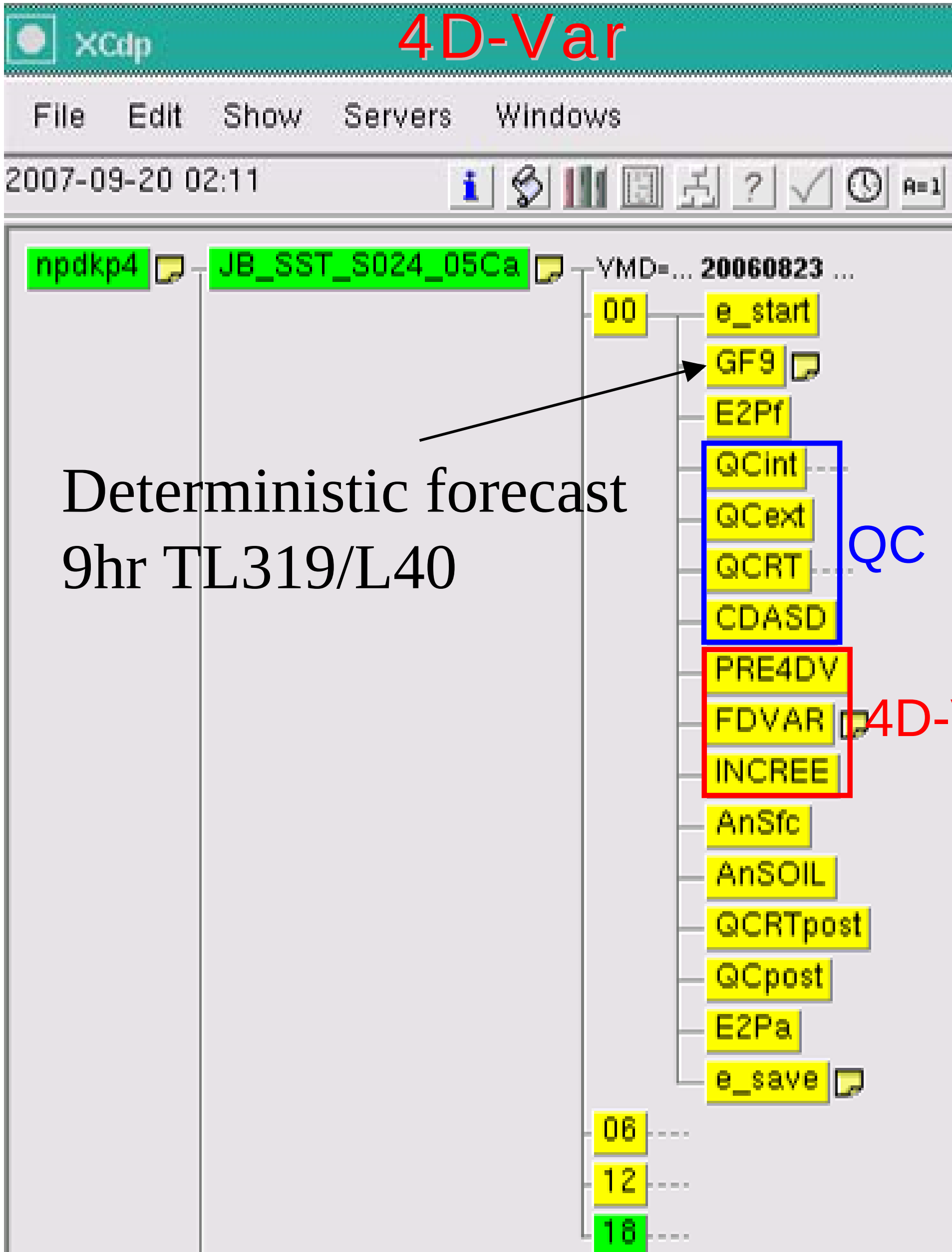
- 4D-Var shows weak sensitivity to the choice of B (variance)
- EnKF could provide flow-dependent B to improve 4D-Var

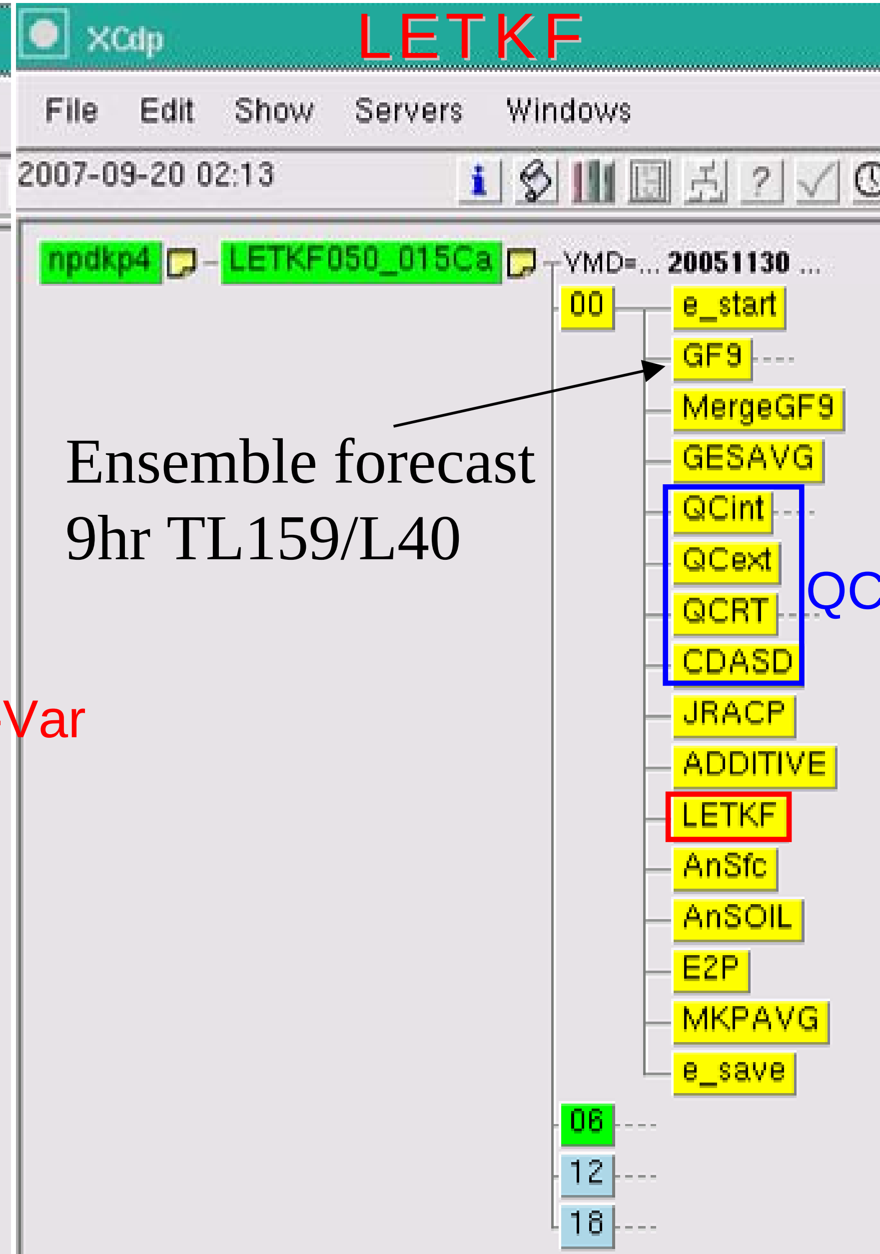
Development of EnKF – JMA's experience

- Local ensemble transform Kalman filter (LETKF, Hunt et al. 2007; Ott et al. 2004) has been applied to JMA global spectral model (GSM)

- Embedded into the quasi-operational experimental system (NAPEX by K. Onogi)

Quasi-operational Experimental System





Computational time

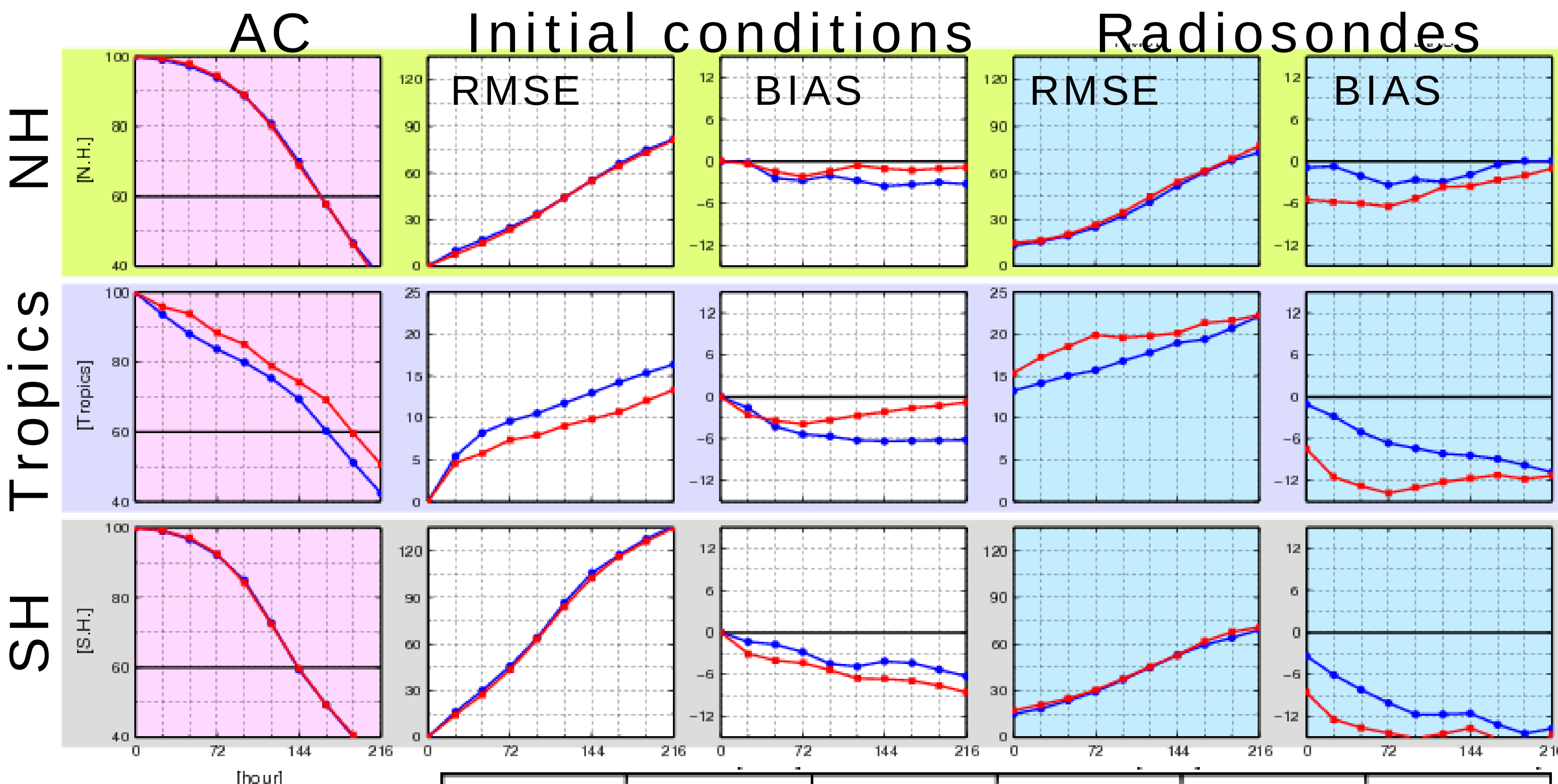
LETKF	4D-Var
11 min x 60 nodes 5 min for LETKF 6 min for 9-hr ensemble forecasts	13 min x 60 nodes (Operations)
TL319/L60/M50 (estimated)	Inner: T159/L60 Outer: TL959/L60

6 min (measured) x 8 nodes for LETKF with TL159/L40/M50

At first LETKF was slower than 4D-Var, but now it's faster after improvement.

4D-Var was a benchmark to improve EnKF!

Overall comparison with 3D-Var



Red: LETKF

Blue: 3D-Var

Z500

	PseaSurf	T850	Z500	Wspd850	Wspd250
Global	3.62	3.07	4.67	9.55	7.60
N. Hem.	0.32	4.32	5.28	7.93	5.09
Tropics	15.23	15.15	22.76	21.33	18.00
S. Hem.	3.84	0.23	4.00	6.08	5.41

Period: August 2004

Overall comparison with 4D-Var

	PseaSurf	T850	Z500	Wspd850	Wspd250
Global	–9.00	–10.45	–10.64	2.38	0.13
N. Hem.	–4.47	–2.95	–1.72	3.74	0.66
Tropics	0.48	–11.66	–17.60	11.69	9.88
S. Hem.	–10.90	–14.51	–13.00	–1.52	–3.81

Apply adaptive bias correction

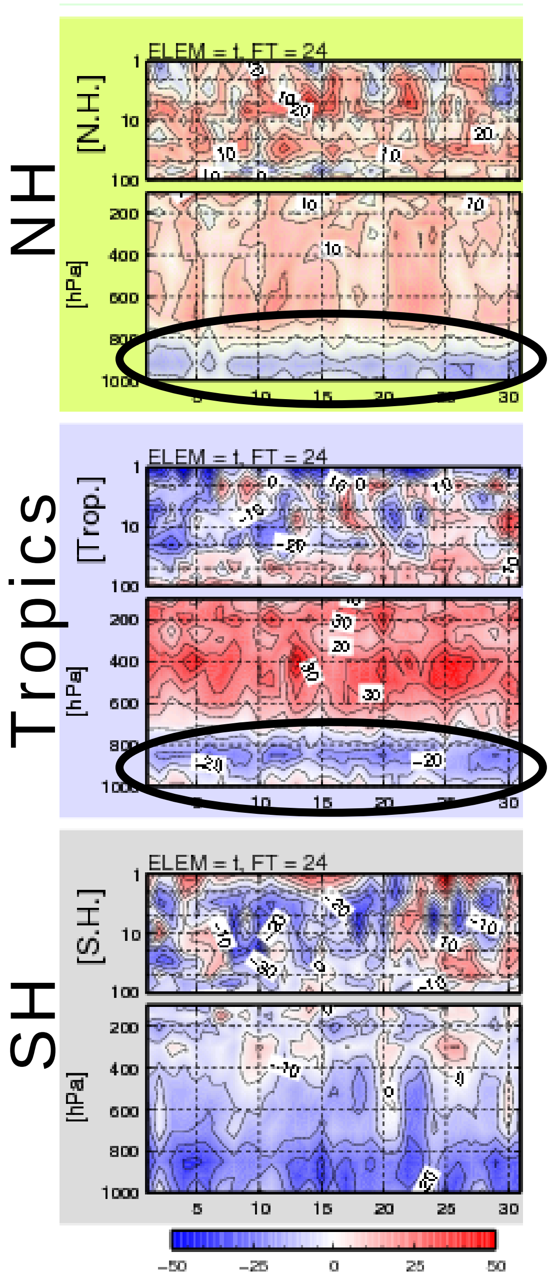
	PseaSurf	T850	Z500	Wspd850	Wspd250
Global	–6.19	–4.36	–5.71	3.66	1.32
N. Hem.	–4.18	1.12	0.91	3.98	0.57
Tropics	6.86	3.39	3.09	14.07	10.21
S. Hem.	–7.60	–8.91	–7.91	–0.08	–1.62

Some bugs fixed in surface emissivity calculation

	PseaSurf	T850	Z500	Wspd850	Wspd250
Global	–5.21	–2.33	–4.21	3.94	1.73
N. Hem.	–3.89	2.06	1.32	4.30	1.30
Tropics	7.05	6.49	7.44	13.58	9.57
S. Hem.	–6.35	–6.47	–6.20	0.39	–1.14

Period: August 2004

Cold bias was identified

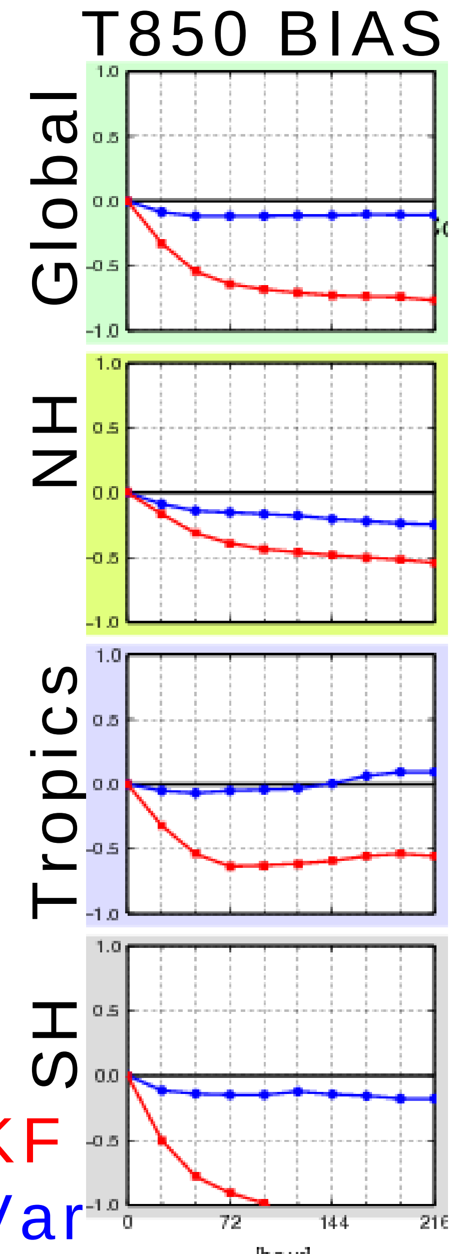


RED: LETKF is better

BLUE: 4D-Var is better

Period: August 2004

Significant low temperature bias in the lower troposphere



Red: LETKF

Blue: 4D-Var

Satellite radiance bias correction

Observation y has a bias b

$$b = b^{scan} + b^{air}$$

Air mass bias (dependent on atmospheric state)

Scan bias (constant)

Statistically estimated offline

Coefficients β of predictors p are estimated statistically

$$b^{air} = p^T \beta$$

- Zenith angle
- Surface temperature
- Constant
- etc.

Adaptive bias correction

Coefficients would change partly due to the deterioration of sensors

Allow temporal variation of the coefficients using data assimilation

Variational bias correction (e.g., Dee 2003; Sato 2007)

$$J(x) = \tfrac{1}{2}(x - x^f)B^{-1}(x - x^f)^T + \tfrac{1}{2}(y - Hx^f)R^{-1}(y - Hx^f)^T$$

$$J(x,\beta) = \tfrac{1}{2}(x - x^f)B^{-1}(x - x^f)^T + \underline{\tfrac{1}{2}(\beta - \beta^f)B_\beta^{-1}(\beta - \beta^f)^T}$$

$$+ \tfrac{1}{2}(y \underline{- p^T \beta} - Hx^f)R^{-1}(y \underline{- p^T \beta} - Hx^f)^T$$

Find the minimizer β of the cost function J through the variational procedure

Adaptive bias correction with LETKF

Analytical solution of the variational problem: minimizer (x, β)

$$\begin{cases} \delta x = (B_x^{-1} + H^T R^{-1} H)^{-1} H^T R^{-1} (d - p^T \delta\beta) \\ \delta\beta = (B_\beta^{-1} + p R^{-1} p^T)^{-1} p R^{-1} (d - H\delta x) \end{cases}$$

Adaptive bias correction with LETKF

1. Solve the LETKF data assimilation problem first

$$\delta x = B_x H^T (H B_x H^T + R)^{-1} d = (B_x^{-1} + H^T R^{-1} H)^{-1} H^T R^{-1} d$$

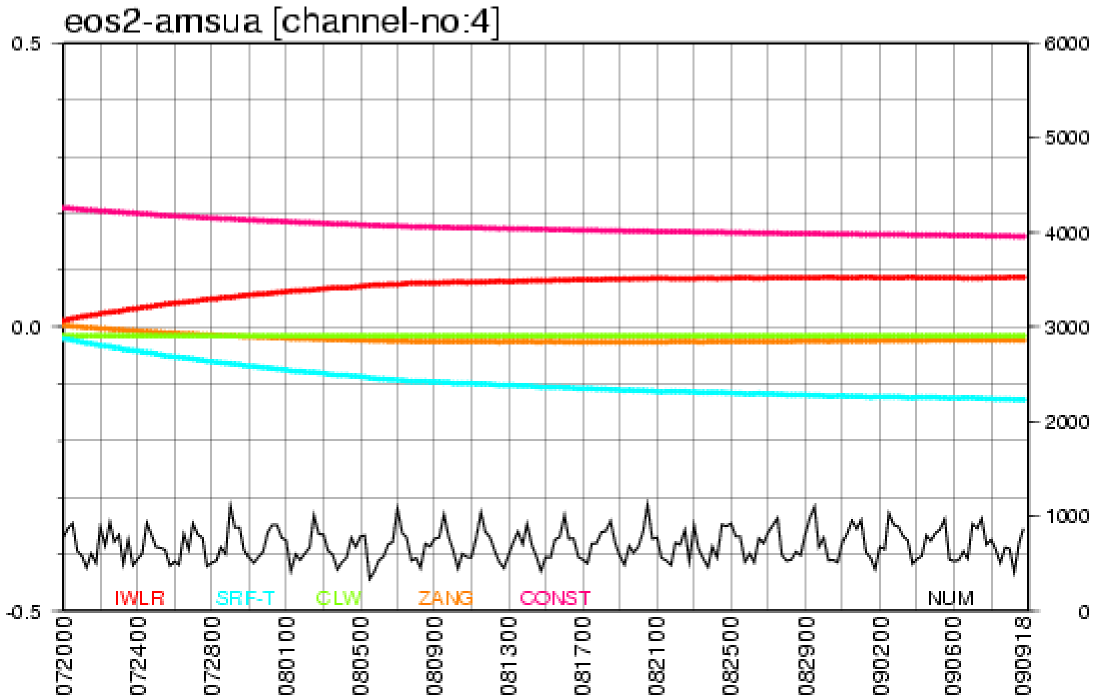
$- p^T \delta\beta$ difference

2. Solve the equation for β explicitly

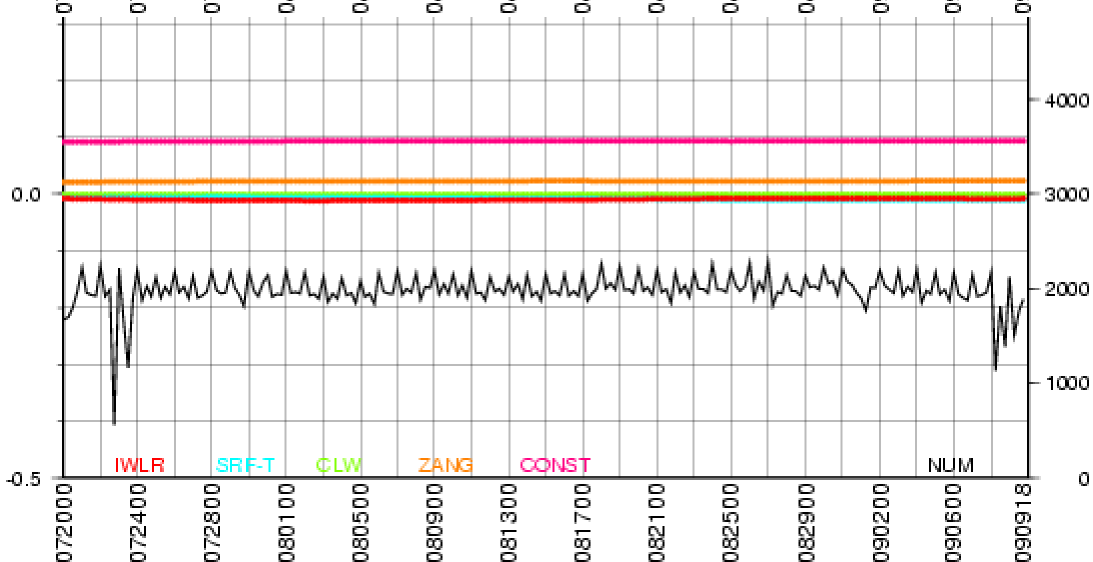
$$\delta\beta = (B_\beta^{-1} + p R^{-1} p^T)^{-1} p R^{-1} (d - H\delta x)$$

This coincides with the variational BC

Time series of bias coefficients

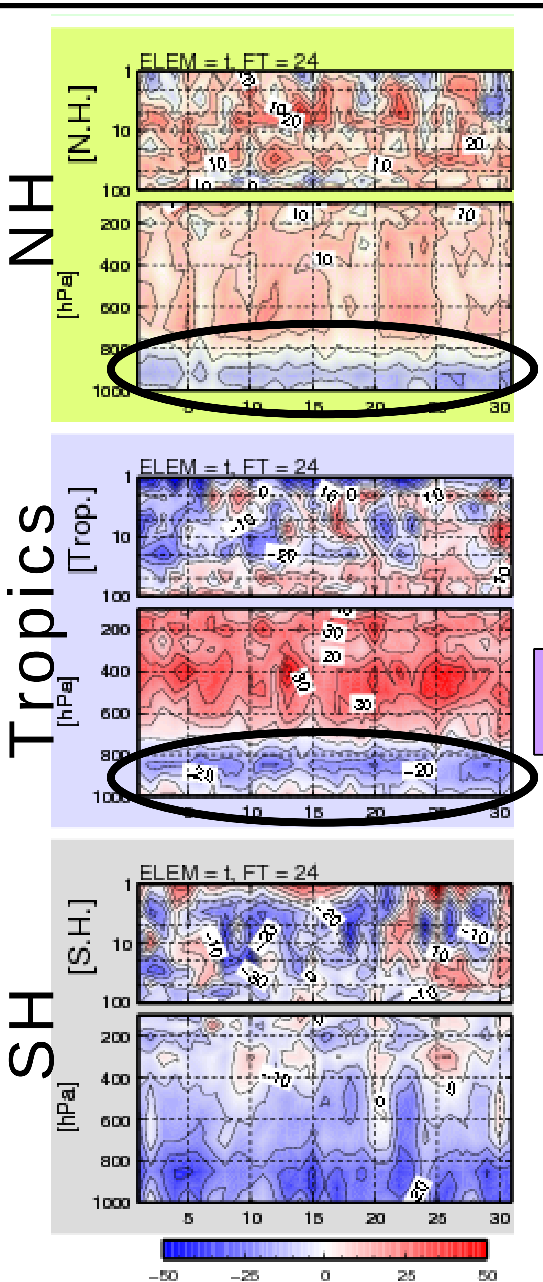


AMSU-A 4ch (sensitive to middle-lower troposphere) indicates significant drift from those estimated by 4D-Var



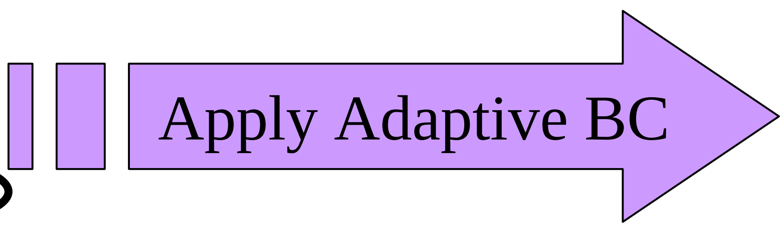
AMSU-A 6ch (sensitive to upper troposhere) and other sensors/channels indicate no significant drift

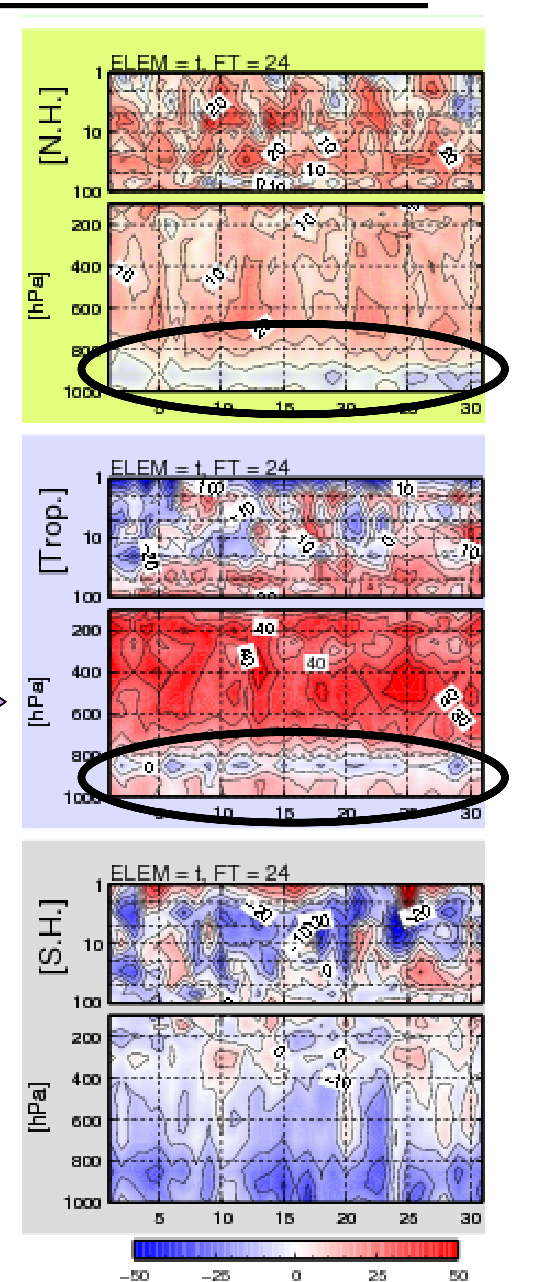
Impact by adaptive bias correction



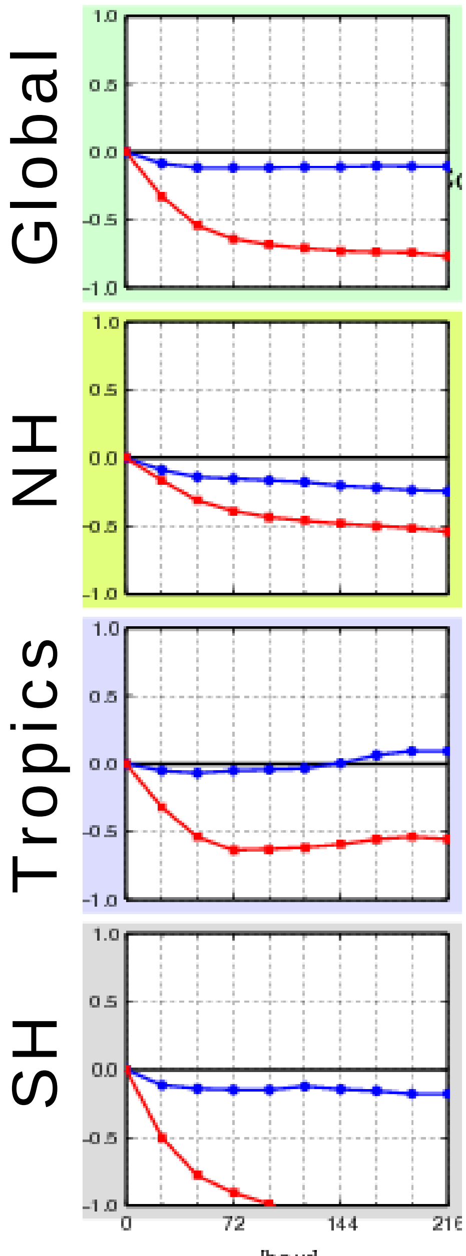
24hr temperature forecast error improvements relative to 4D-Var

RED: LETKF is better
BLUE: 4D-Var is better



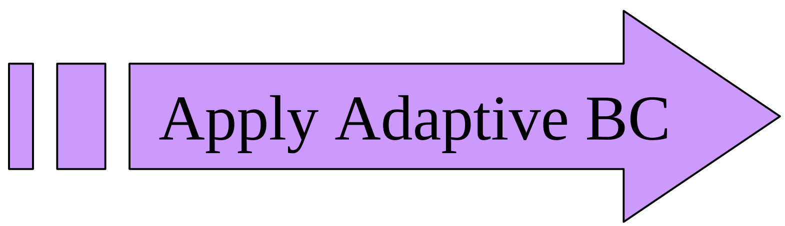


Bias reduction

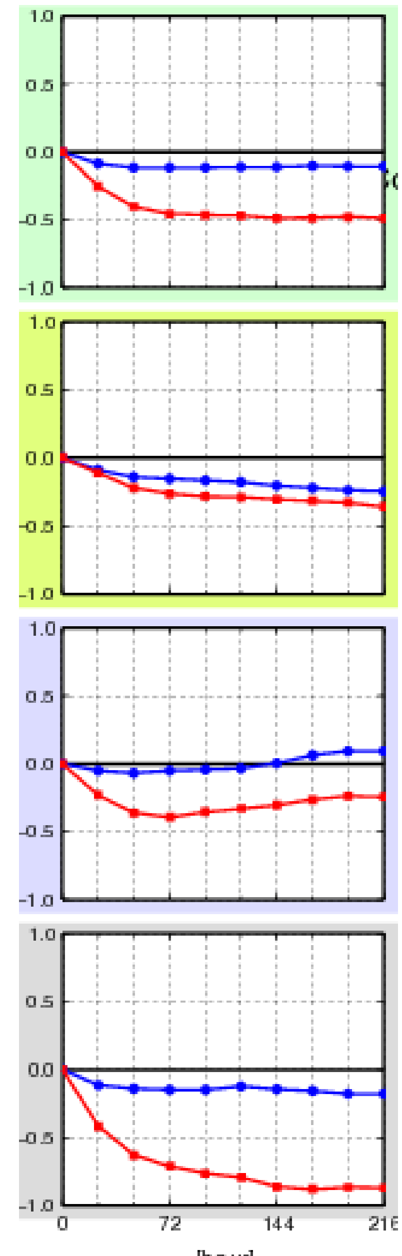


T850 forecast bias against initial condition

Red: LETKF
Blue: 4D-Var



The improvements would be due to the bias reduction



Reason for bias drifts in AMSU-A 4ch

FACTS:

✓ 4D-Var uses RTTOV-7

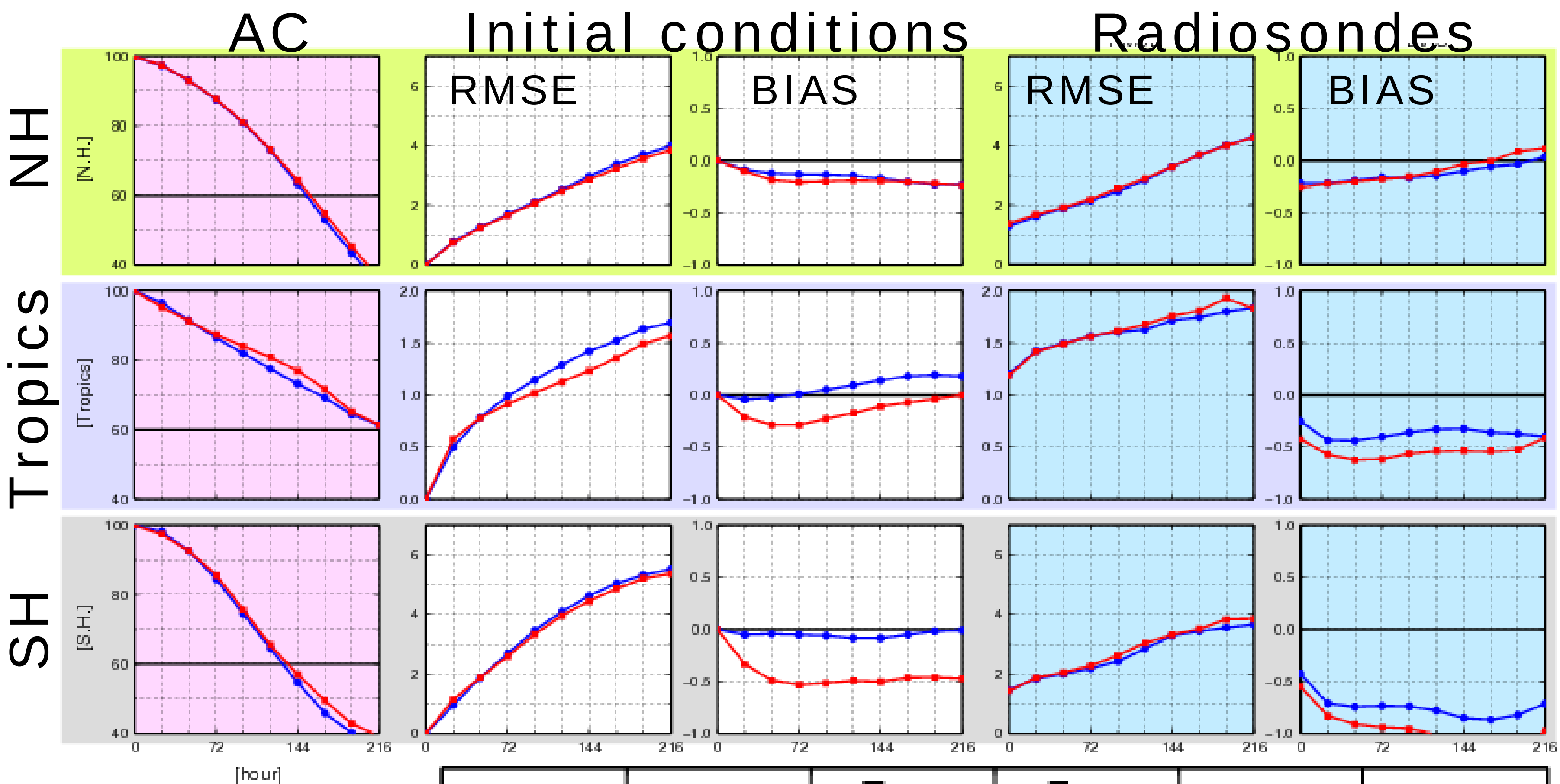
✓ LETKF uses RTTOV-8

✓ AMSU-A ch.4 is sensitive to surface emissivity and lower tropospheric temperature

✓ A known bug in the surface emissivity model "FASTEM-2" in RTTOV-7, where the surface emissivity is spuriously overestimated

- 4D-Var VarBC corrects the "spurious" bias caused by the bug
- Therefore, observed radiances (bias corrected) are too large for LETKF
- Thus, the lower troposphere is heated by assimilating the too large radiance observations, which explains the cold forecast bias relative to analysis (because analysis is too warm)
- The adaptive BC within LETKF corrects the wrong bias

Experiments without satellite radiances



Red: LETKF
Blue: 4D-Var

T850

9–days	PseaSurf	T850	Z500	Wspd850	Wspd250
Global	2.68	1.69	2.10	6.60	4.30
N. Hem.	–0.72	2.98	3.09	5.88	3.22
Tropics	8.45	6.19	1.13	14.43	11.60
S. Hem.	3.19	0.52	2.10	4.66	2.34

Future work

- Improve the use of satellite radiances
  - QC system with RTTOV-8
    - 4D-Var began to use RTTOV-8 since Oct 15, 2008
  - Applying a better localization method

- Test with a different model
  - It is known that JMA model has a significant bias

Conclusion

Synergistic development

- We learned from the comparison with 4D-Var to identify problems in EnKF
  - We could easily find the cold forecast bias in EnKF
- Overcome inferior points
  - Computational time: tuned to be faster than 4D-Var
  - Adaptive bias correction to simulate VarBC
  - Covariance localization for temporally/spatially integrated observations

Finding superior/inferior points through inter-comparison is important and beneficial for both 4D-Var and EnKF.


Thank you
for your attention!

Recent improvements

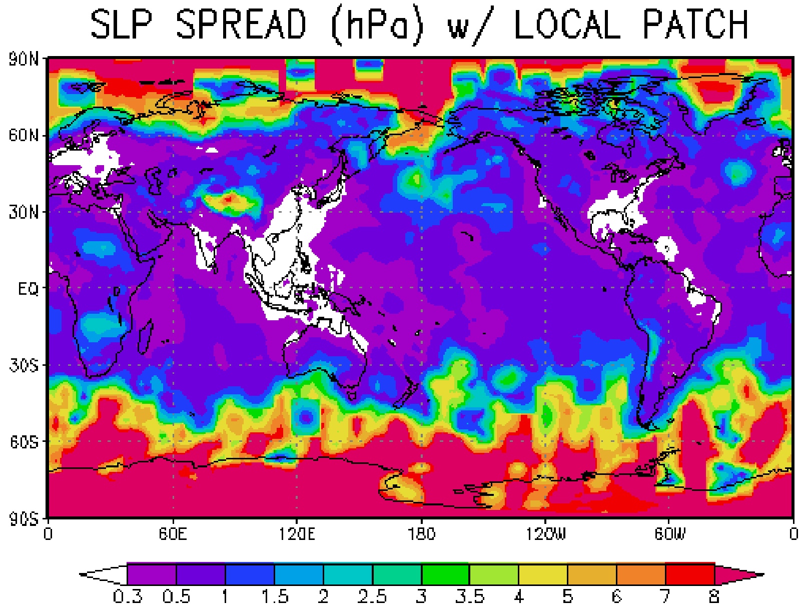
- Assimilation of satellite radiances
  - greatly improves the analysis accuracy

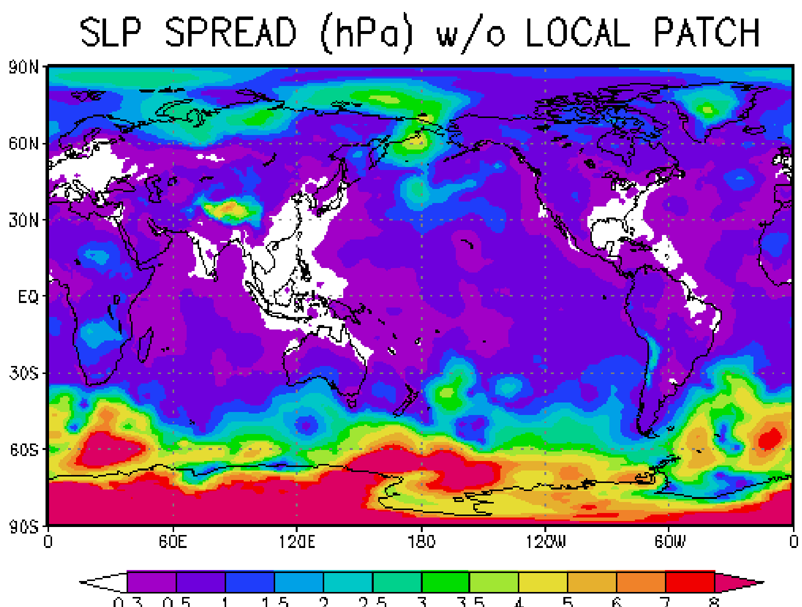
    Miyoshi and Sato, 2007: *SOLA*, 37-40.
- Removing local patches
  - solves the discontinuity problem near the Poles

    Miyoshi et al., 2007: *SOLA*, 89-92.
- Efficient MPI parallel implementation
  - solves the load imbalance problem
  - accelerates by a factor of 3

    about 30% faster than operational 4D-Var with similar settings
- Adaptive satellite bias correction
  - a new idea analogous to the variational bias correction
  - showing great positive impact

LETKF without local patches



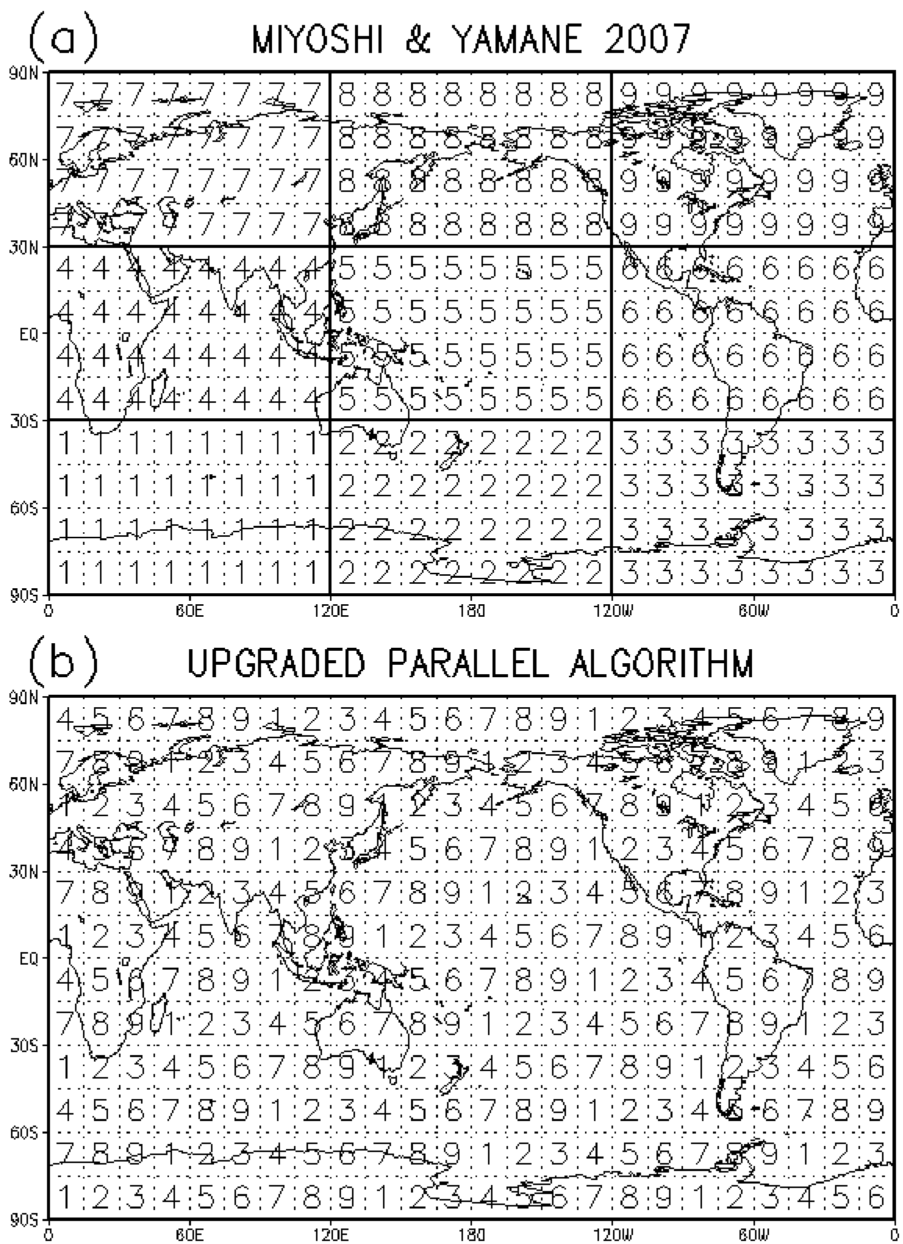


SLP analysis ensemble spread after the first analysis step

The discontinuities caused by the local patches disappear.

Miyoshi et al. 2007

Efficient parallel implementation

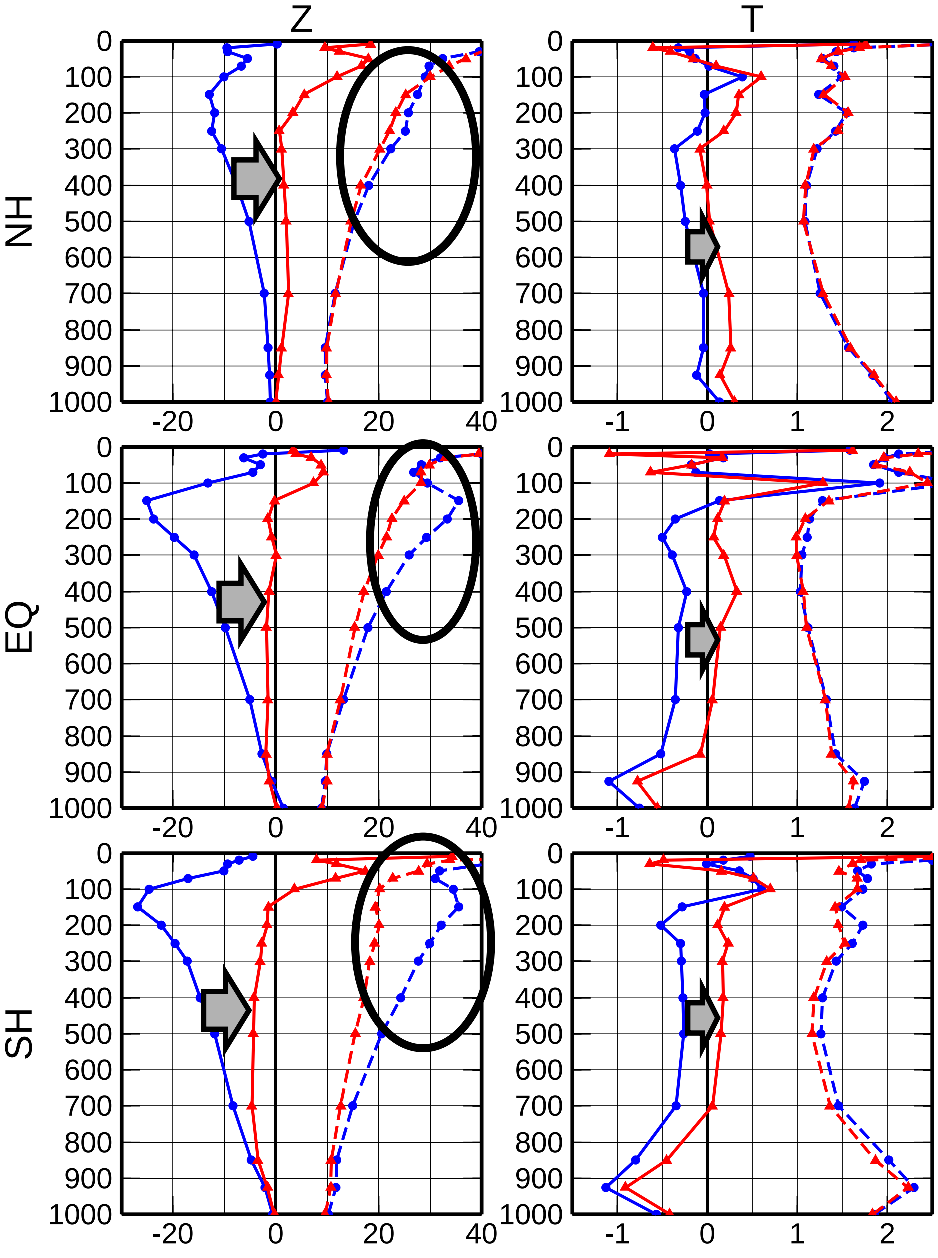


In the case of 9 comp. nodes

Irregular observing network causes significant load imbalances

Revising the node separation, we solved the load-imbalance problem almost completely;
~3 times faster computation

Impact by satellite radiances



RMSE and bias against radiosondes

Blue: w/o satellite radiances

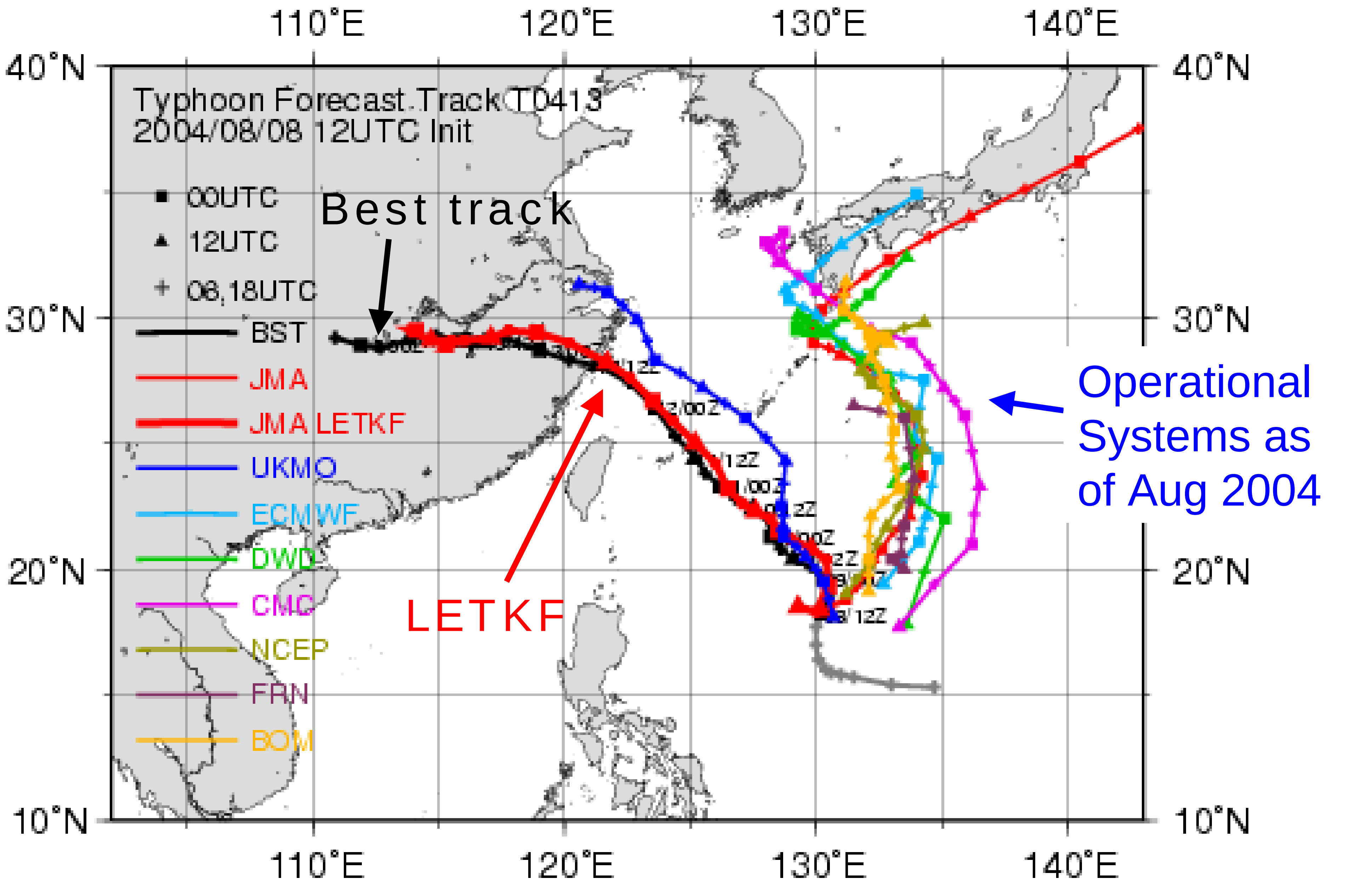
Red: w/ satellite radiances

Reduced negative bias of Z and T

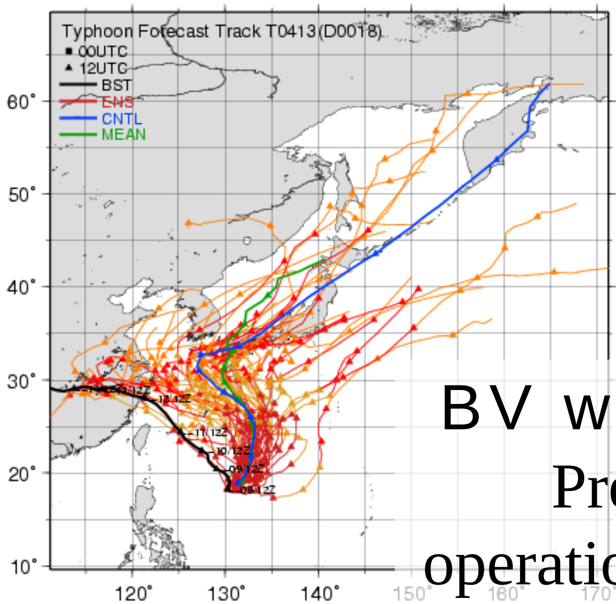
Reduced RMSE of Z in mid-upper troposphere (500-100hPa), especially in the SH and Tropics

20 members

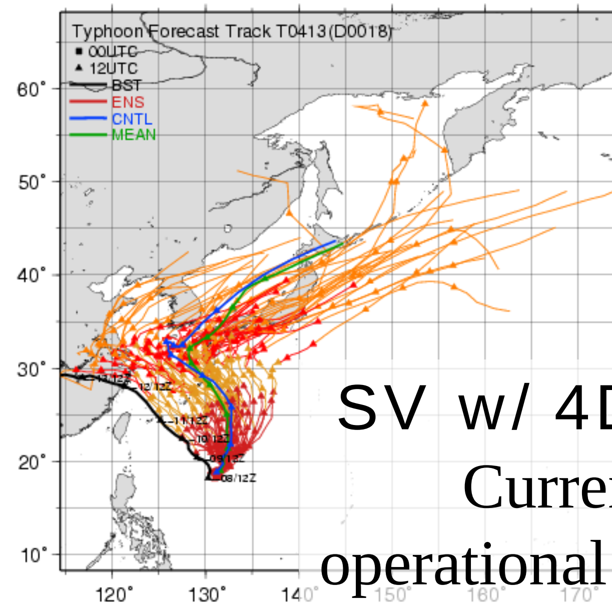
Typhoon Rananim, August 2004



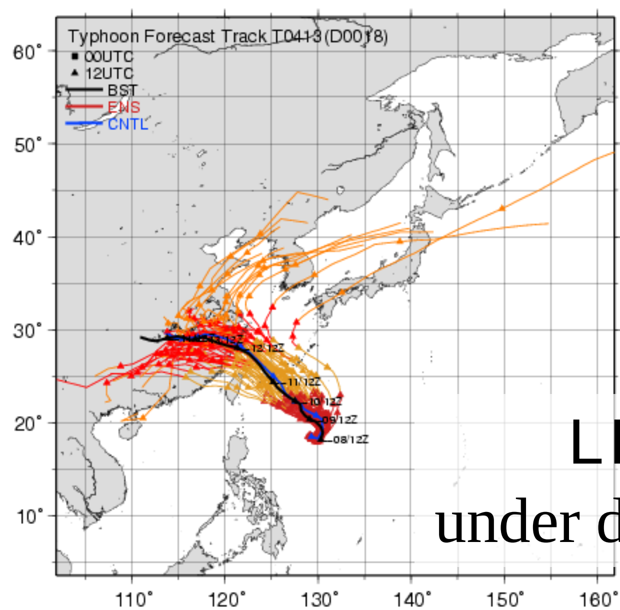
TC track ensemble prediction



BV w/ 4D-Var
Previous operational system



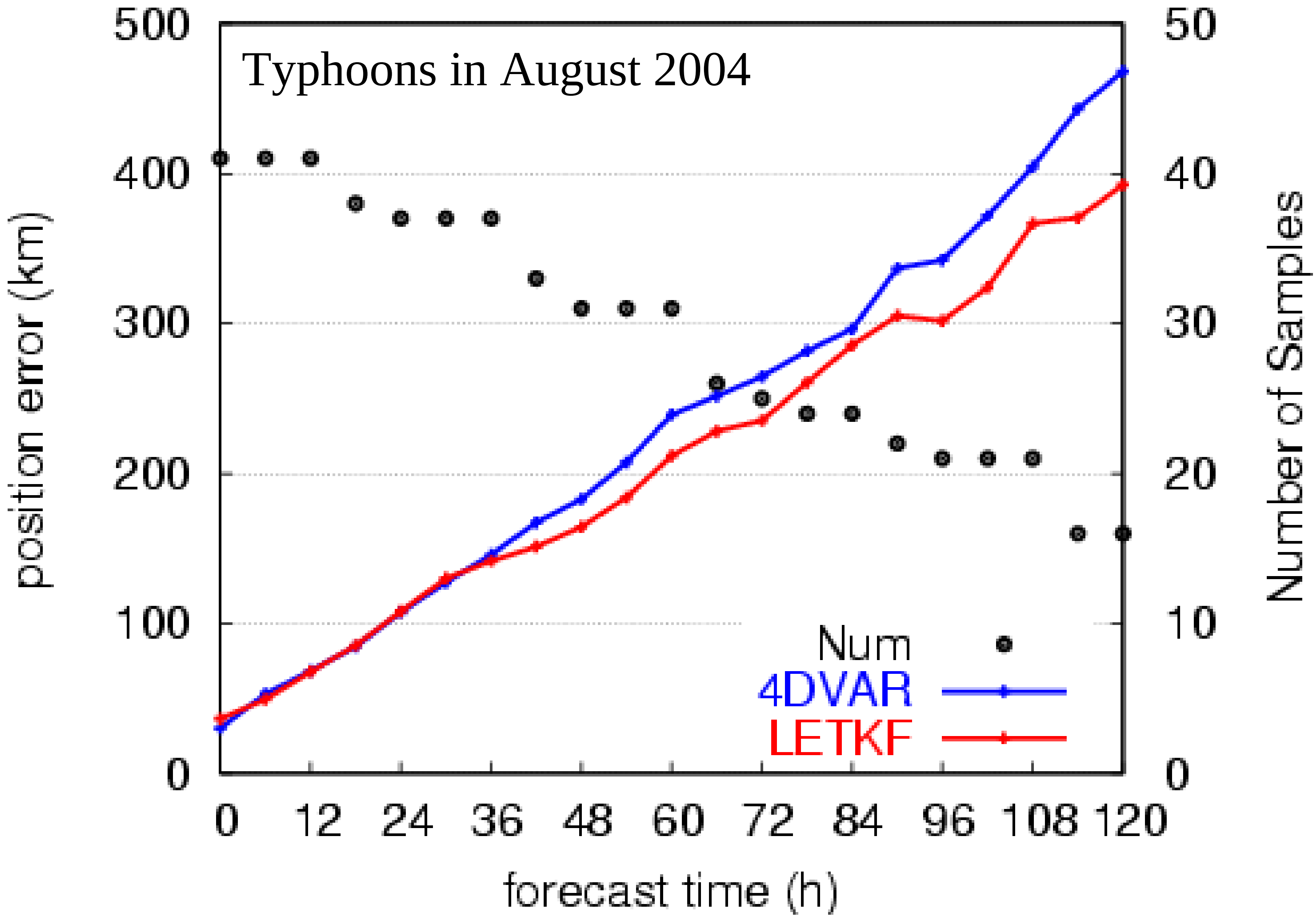
SV w/ 4D-Var
Current operational system



LETKF
under development

LETKF performs excellent in this typhoon case.

Statistical typhoon track errors



Improvement (%) relative to 4D-Var

August 2004

	PseaSurf	T850	Z500	Wspd850	Wspd250
Global	–2.53	–2.04	–1.57	5.51	3.56
N. Hem.	–2.77	2.16	2.09	4.91	1.63
Tropics	7.05	4.90	4.95	14.92	11.81
S. Hem.	–3.06	–5.49	–2.68	2.62	1.91

December 2005

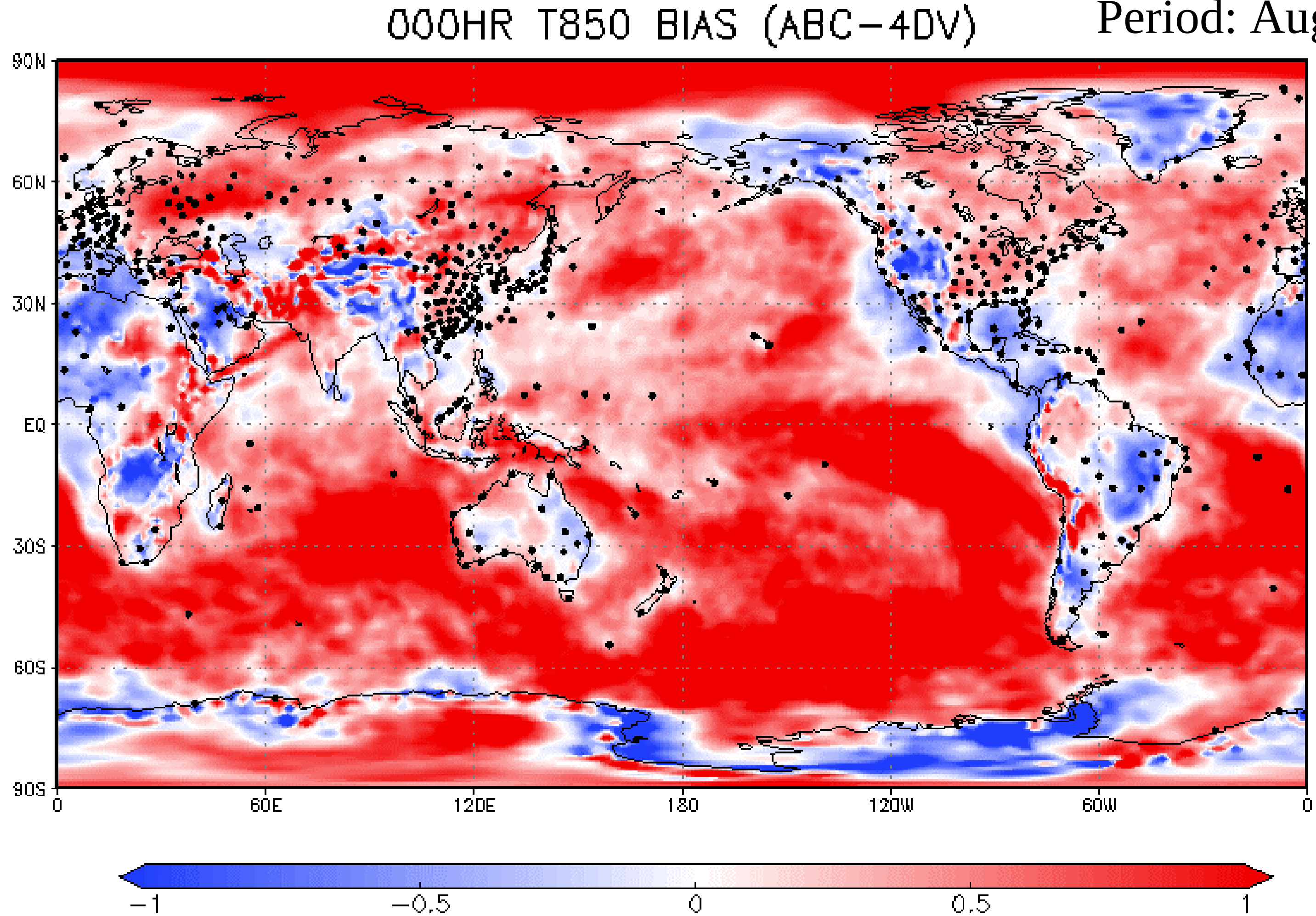
	PseaSurf	T850	Z500	Wspd850	Wspd250
Global	–3.39	–1.27	–2.60	4.91	2.69
N. Hem.	–5.60	–0.29	–4.46	1.16	0.83
Tropics	8.74	4.94	13.43	16.52	12.10
S. Hem.	–1.06	–4.98	–0.82	3.79	0.15

LETKF is advantageous in the summer hemisphere

850 hPa temperature bias

850 hPa Temperature bias of (LETKF – 4D-Var)

Period: August 2004



Even without radiance assimilation, generally this pattern remains.
Namely, satellite radiances do not perfectly explain the positive bias.

話の流れのアイデア

- 4D-Varの背景誤差をいじると、良くなるらしい
  - Flow dependentなBをEnKFから作ってあげると4D-Varはうれしいかも。という話
- JMAでのEnKF開発のこれまでを紹介
  - 4D-Varと比較しながらEnKFを改良してきた
  - 改善点の把握に4D-VarがBaselineとして役立つ
- EnKFのこれまでの開発で、4D-Varから学んできたこと
  - VarBCを参考にしたAdaptive BCの開発
  - バイアスの容易な発見
- 現在のEnKFには、まだ弱点がある
  - 時空間積分量の観測に対するLocalizationなど
- EnKFが4D-Varよりも劣っている点を今後も改良していくという状況はしばらく続くだろう