Development of an Ensemble Data Assimilation System for Mesoscale Ensemble Prediction

Japan Meteorological Agency
Numerical Prediction Division
Tadashi Fujita

Meso ensemble prediction system

Objective: provide information on uncertainty in operational numerical prediction from the meso scale model (MSM)

JMA is testing various methodologies for possible operational use.

This presentation reports on our development of a system using LETKF(Local Ensemble Transform Kalman Filter (Hunt 2005))

Application of EnKF on JMANHM (non hydrostatic model used in operation):
LETKF（Local Ensemble Transform Kalman Filter）:
T. Miyoshi, and K. Aranami, 2006: SOLA, 2, 128-131.
positive impact in a perfect model experiment.

↓

Development for possible operational use of the LETKF.

Current plan of JMA Meso ensemble prediction (may subject to change)
resolution ~10km
ensemble size ~ 5 members

Design of the LETKF analysis cycle

Analysis cycle at a lower resolution, but with a larger ensemble size

a large ensemble size is desirable for a stable analysis cycle
ensemble forecast from selected members at a higher resolution

Analysis cycle on a larger domain than the forecast domain

generate boundary and initial perturbations for ensemble forecast

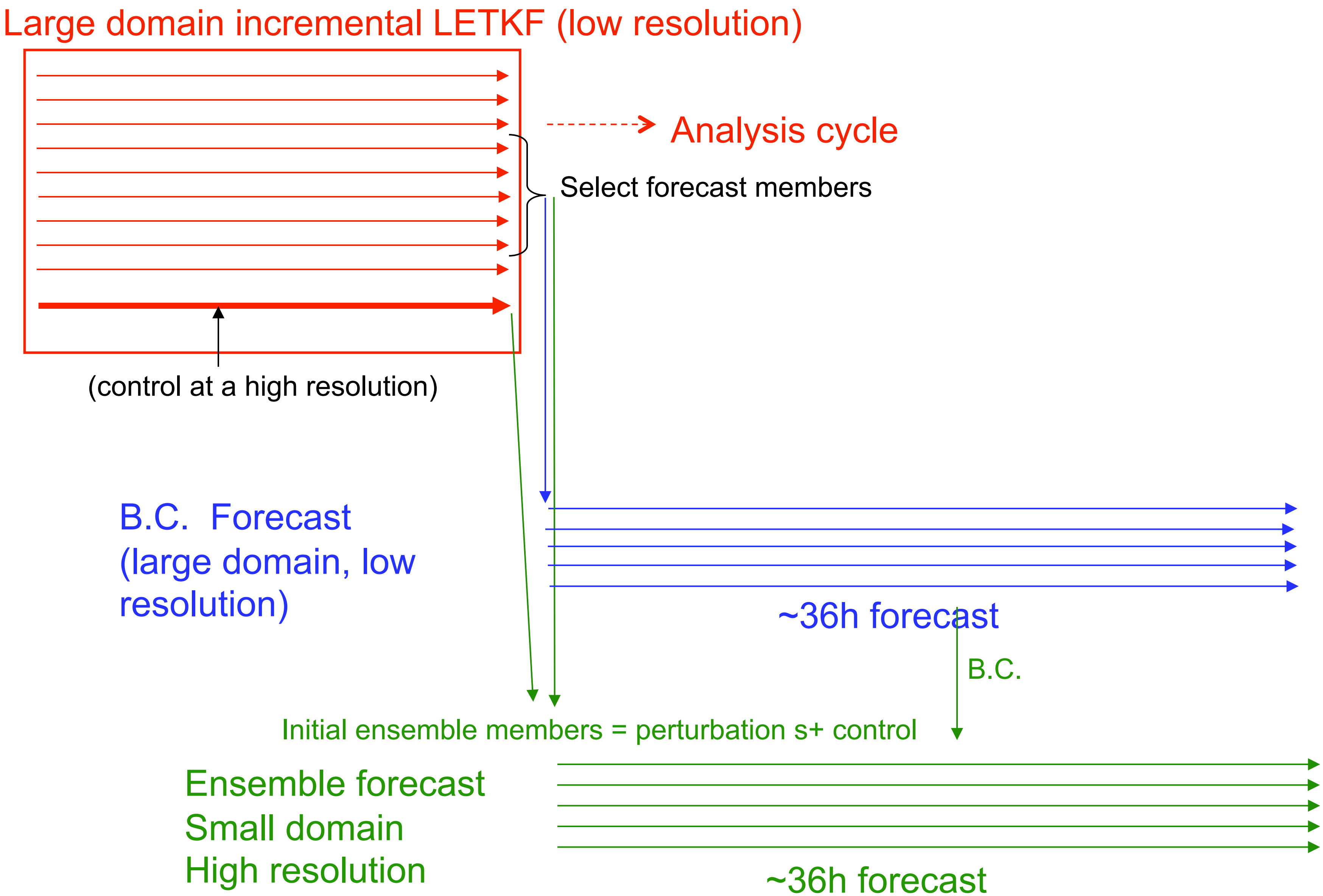
Consistent initial and boundary perturbations from a single LETKF system

Try to handle perturbations corresponding to severe events
coming into the inner forecast domain through the boundary

(Boundary of the larger analysis domain currently is not perturbed.)

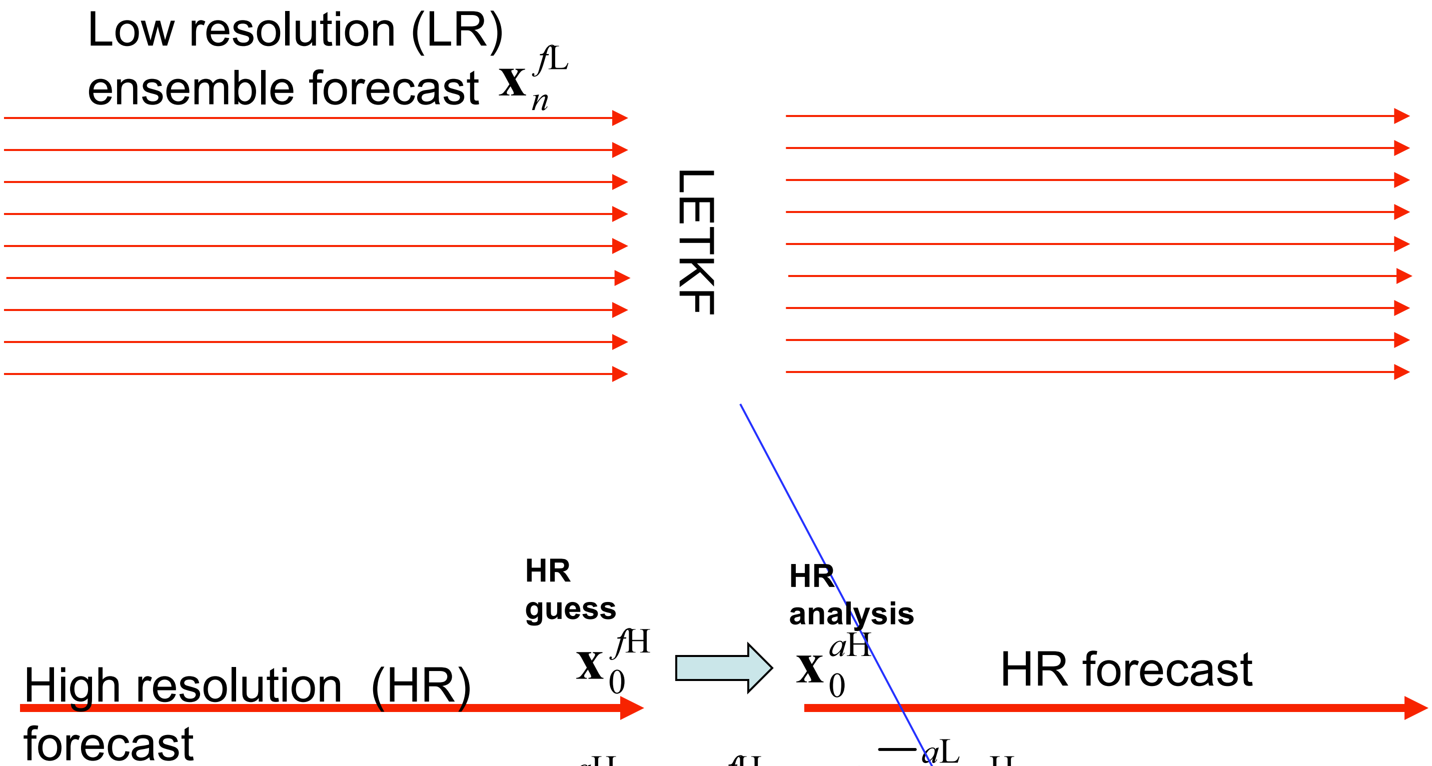
Incremental LETKF: low resolution ensemble + high resolution control

Dual Resolution EnKF (Gao and Xue, 2008: *Mon. Wea. Rev.*, 136, 945-963.)



Incremental LETKF: Low resolution ensemble + High resolution control

Dual Resolution EnKF (Gao and Xue, 2008: *Mon. Wea. Rev.*, **136**, 945-963.)



$$\mathbf{x}_0^{a\mathrm{H}} = \mathbf{x}_0^{f\mathrm{H}} + [\Delta\overline{\mathbf{x}'}^{a\mathrm{L}}]^{\mathrm{H}}$$

K : from LR ensemble

Interpolate increment into HR

HR innovation

$$\Delta\overline{\mathbf{x}'}^{a\mathrm{L}} = \mathbf{K}^{\mathrm{L}}(\mathbf{y} - H^{\mathrm{H}}(\mathbf{x}_0^{f\mathrm{H}}))$$

$[\cdot]^{\mathrm{H}}$: interpolation from LR to HR

LETKF analysis cycle experiment

24 Aug. 2008.08.24 12UTC – 28 Aug. 2008 00UTC

LR：40km 50 members
HR:20km

Larger domain: 20km , 281x305 grid points

50 vertical levels

Observational data: conventional data + Doppler velocity
Observation operator from operational meso analysis (4DVar)

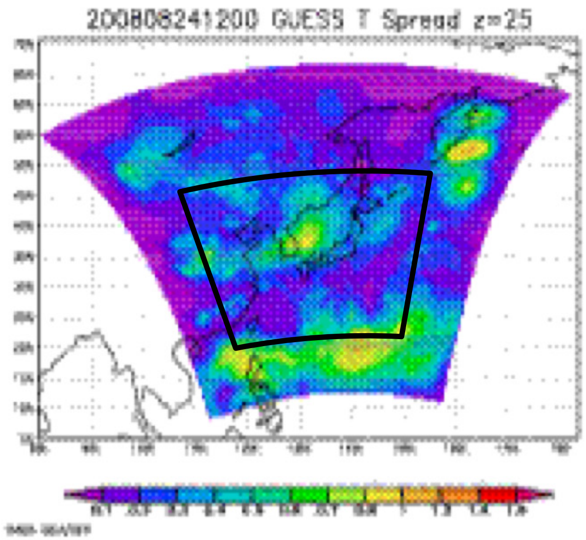
Localization scale: horrizontal 5 grid points (200km), vertical 3 levels

Assimilation window 3h

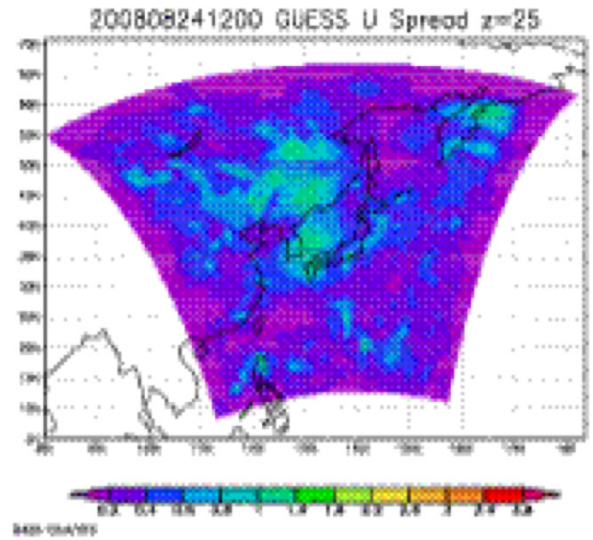
Forecast 28 Aug. 00UTC – 29 Aug. 12UTC
20km 181x145x50 grid points

Spread (25th vertical level ~ 500hPa)

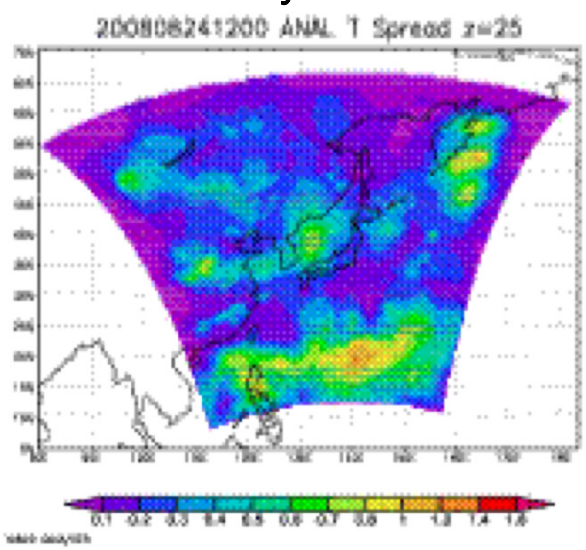
T Guess



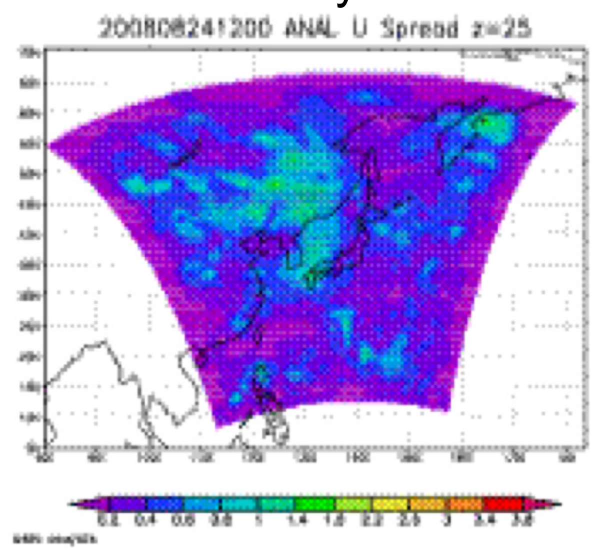
U Guess



T Analysis

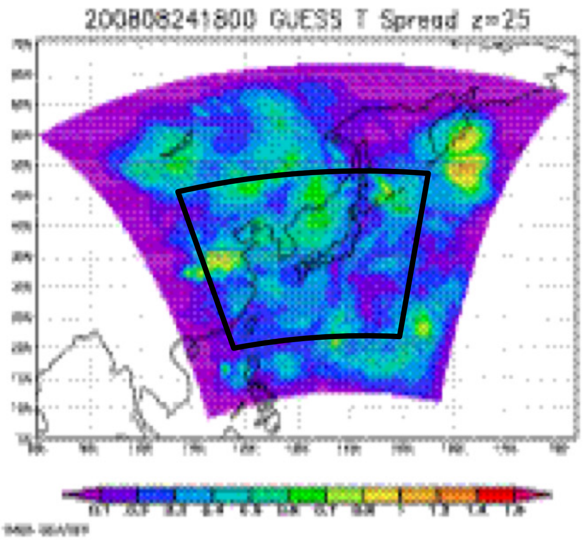


U Analysis

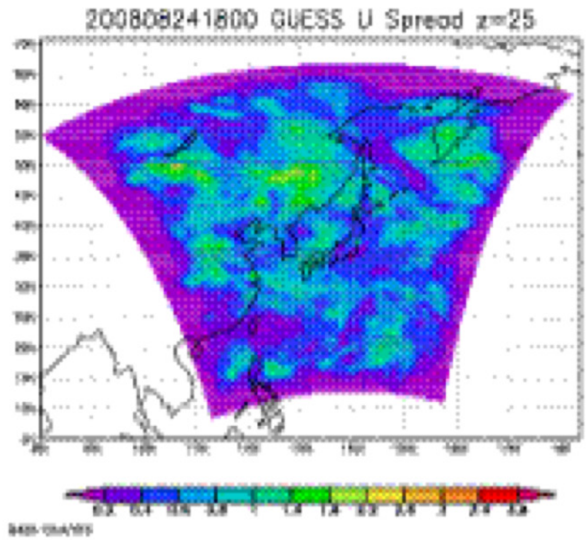


Spread (25th vertical level ~ 500hPa)

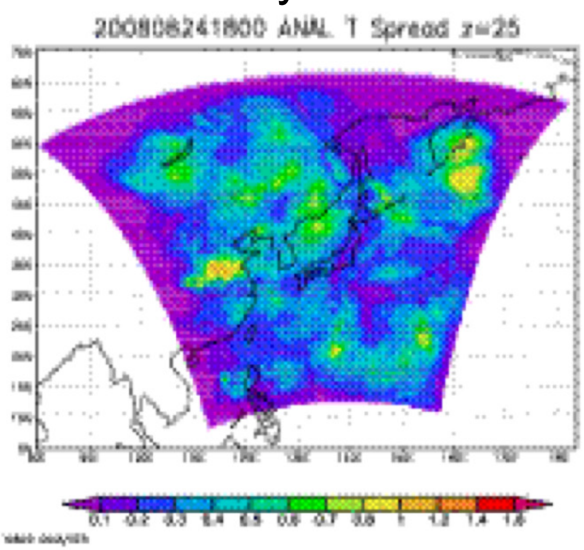
T Guess



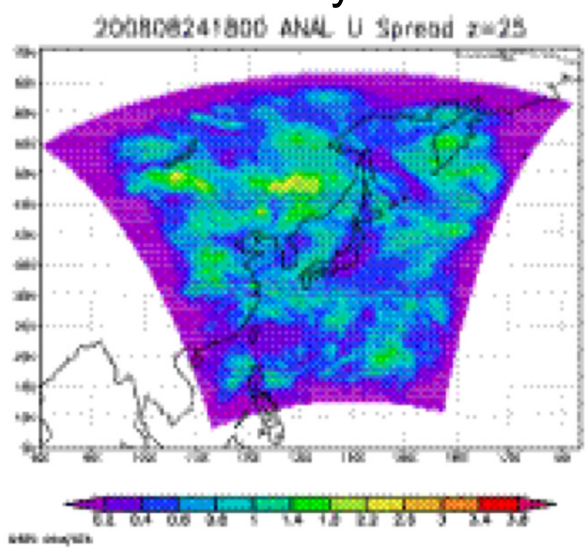
U Guess



T Analysis

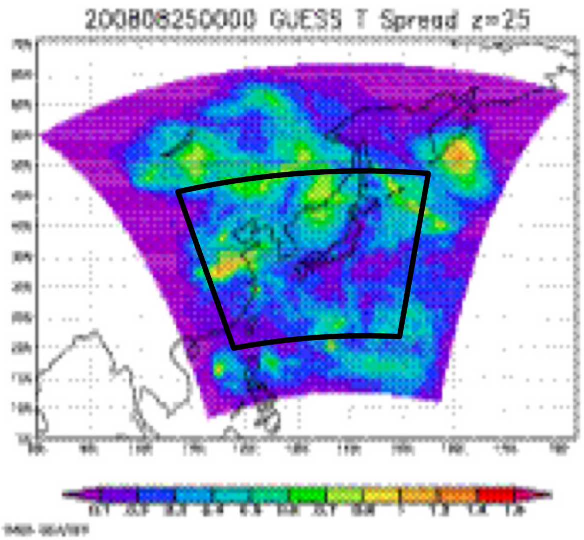


U Analysis

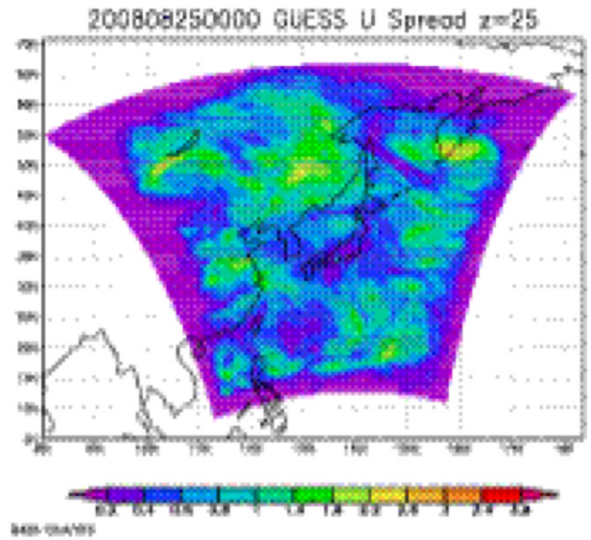


Spread (25th vertical level ~ 500hPa)

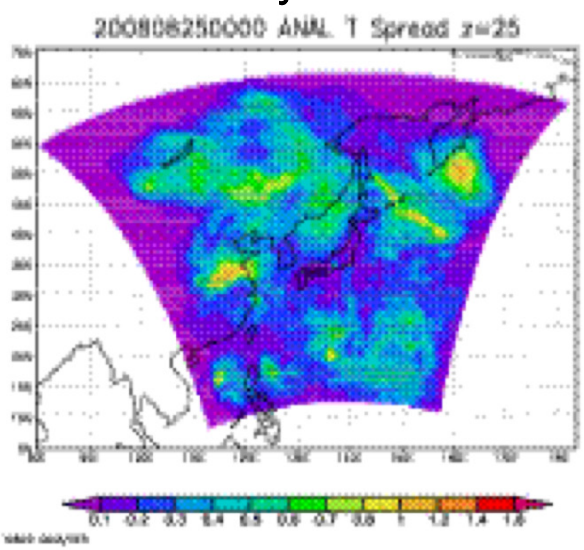
T Guess



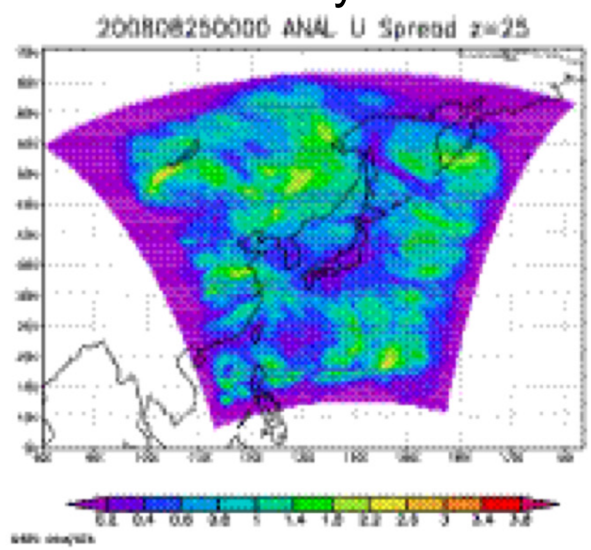
U Guess



T Analysis

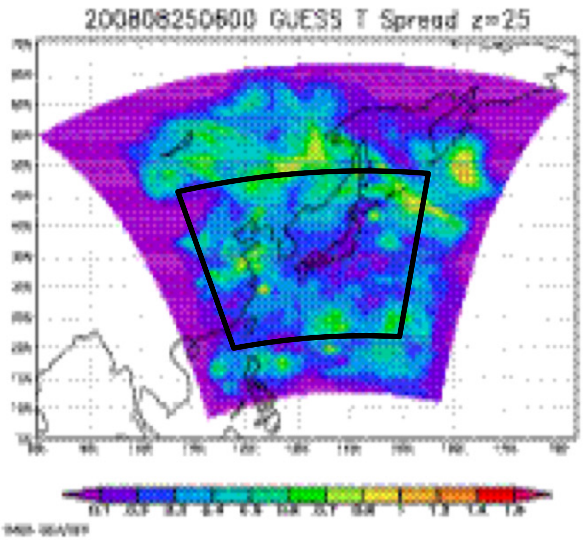


U Analysis

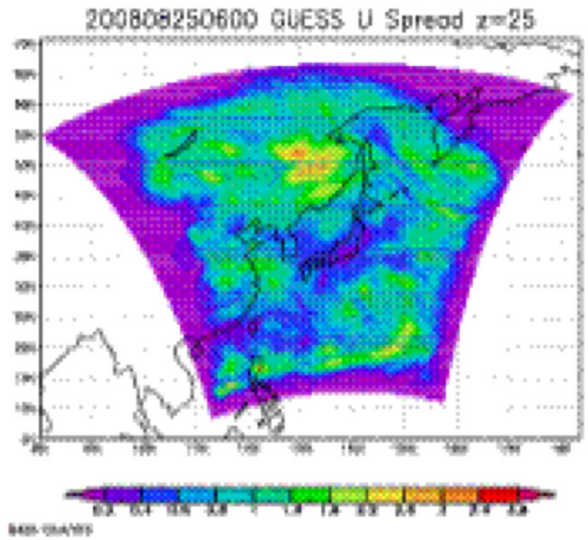


Spread (25th vertical level ~ 500hPa)

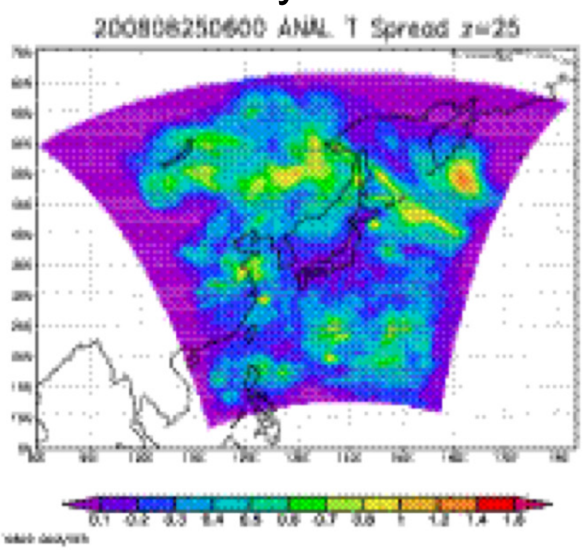
T Guess



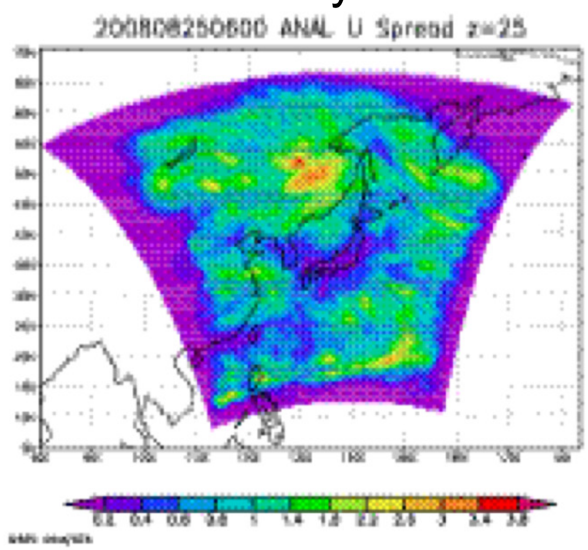
U Guess



T Analysis



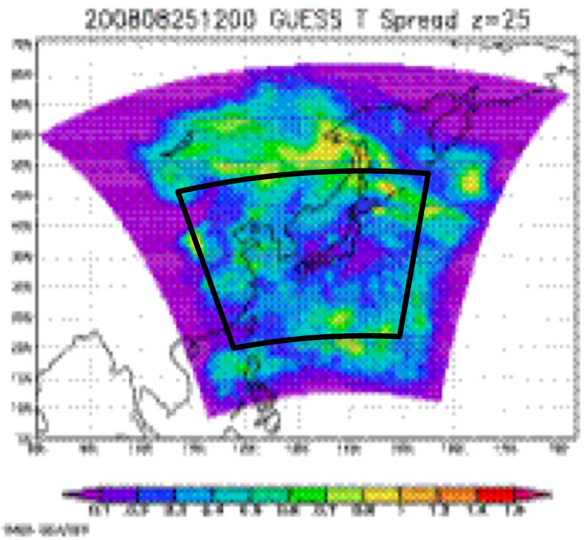
U Analysis

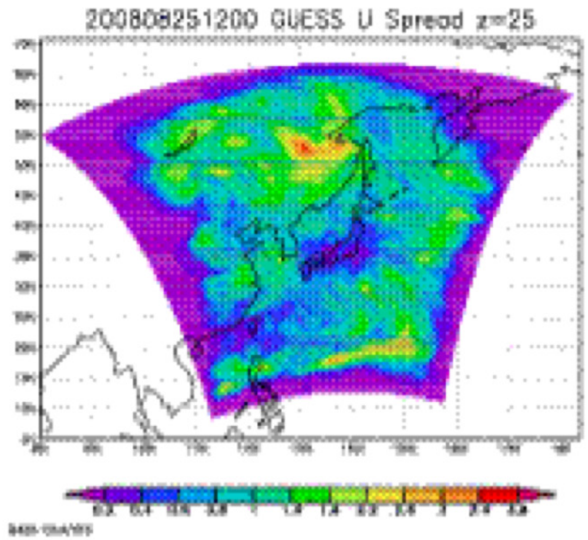


Spread (25th vertical level ~ 500hPa)

T Guess

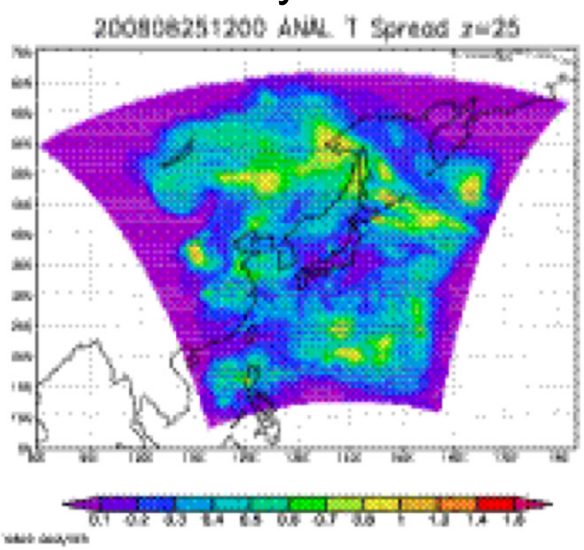
U Guess

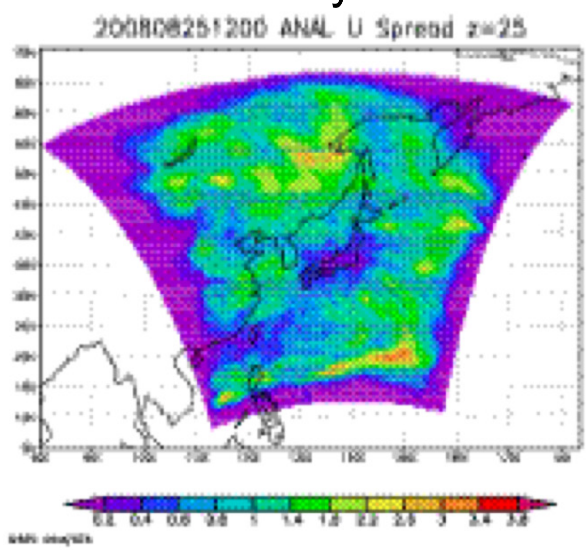




T Analysis

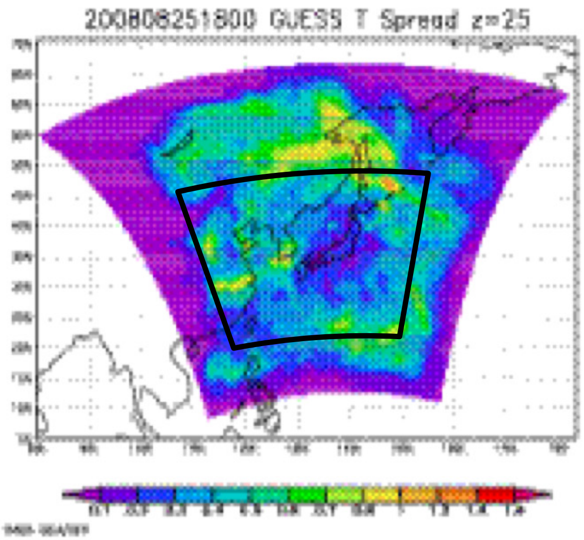
U Analysis



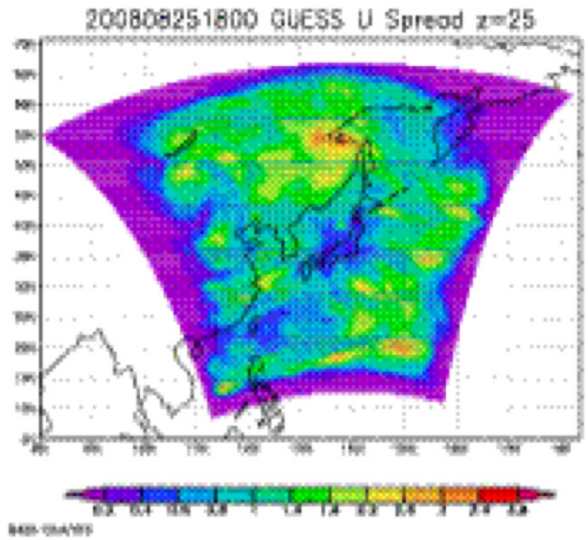


Spread (25th vertical level ~ 500hPa)

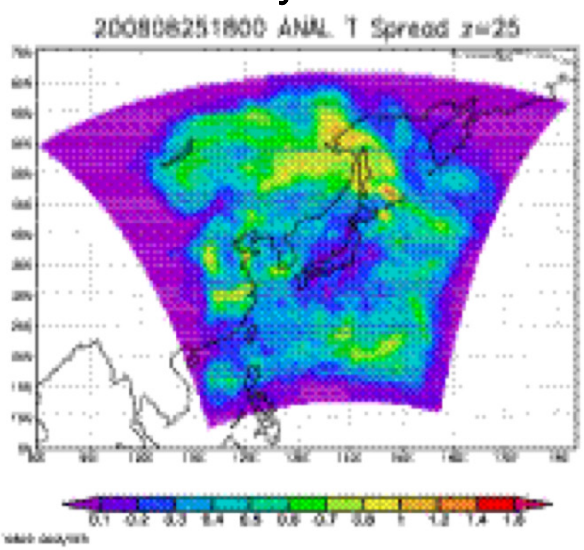
T Guess



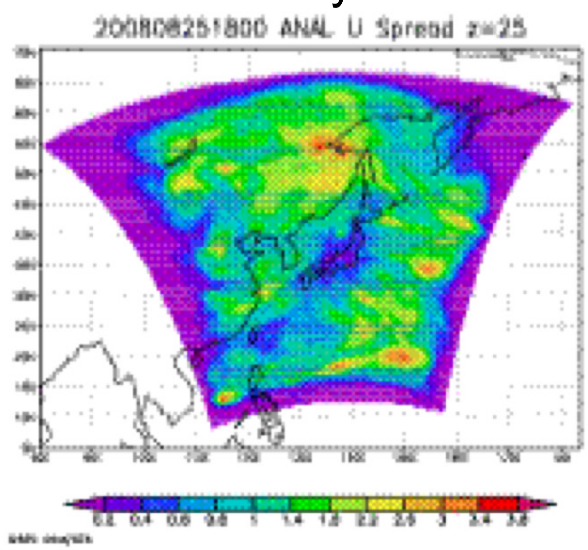
U Guess



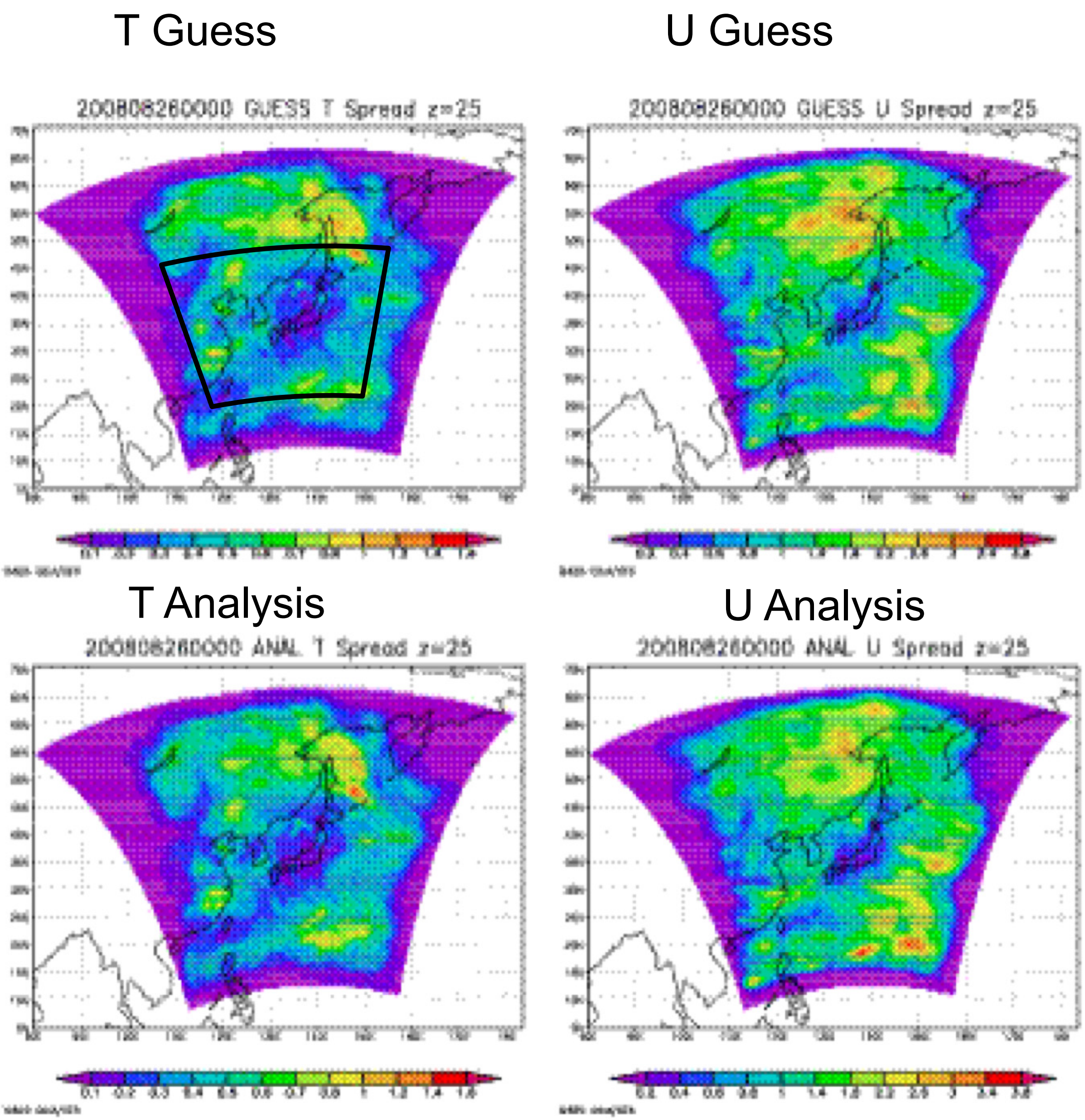
T Analysis



U Analysis

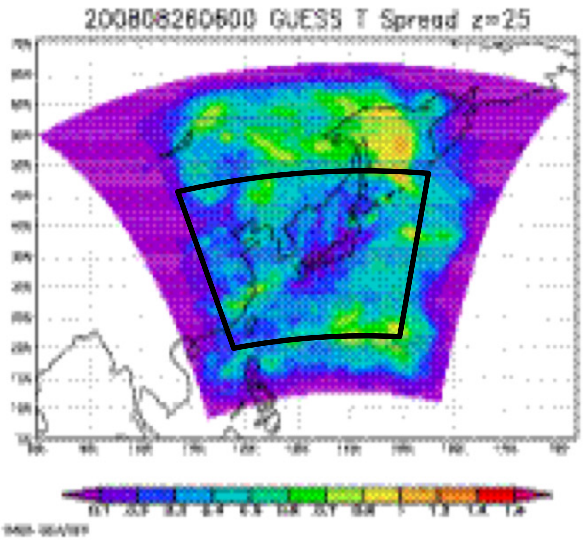


Spread (25^{th} vertical level ~ 500hPa)

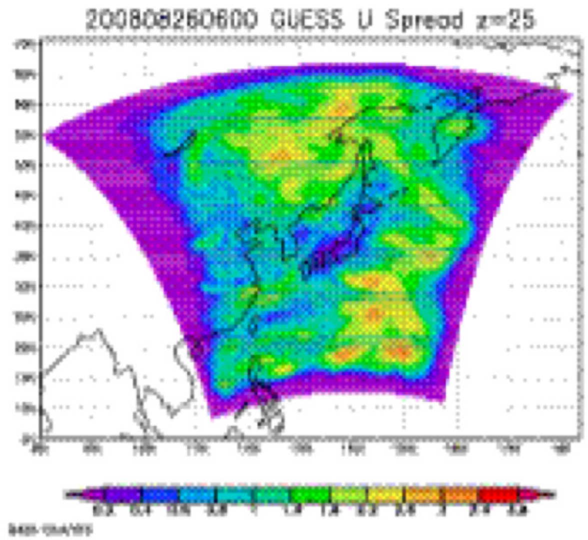


Spread (25^{th} vertical level ~ 500hPa)

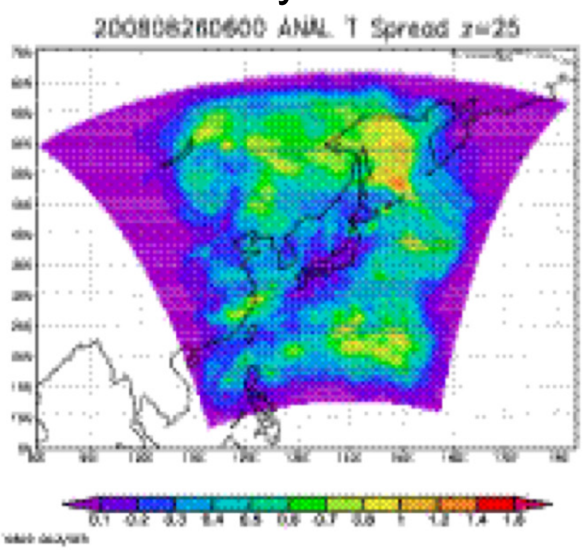
T Guess



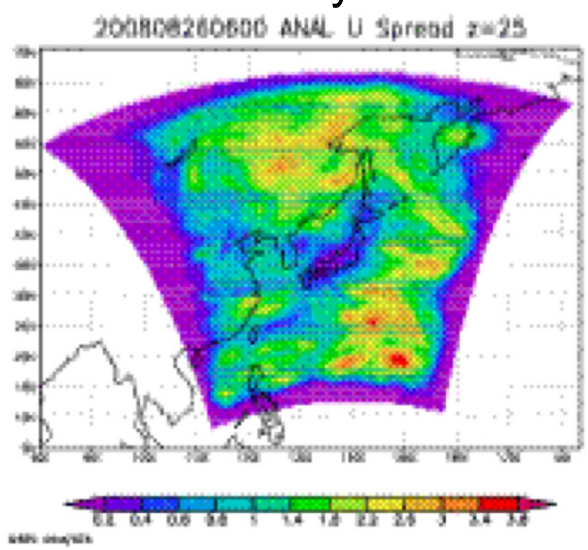
U Guess



T Analysis

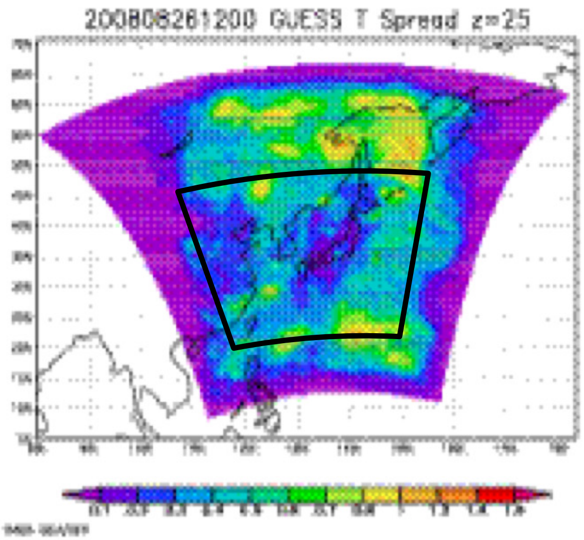


U Analysis

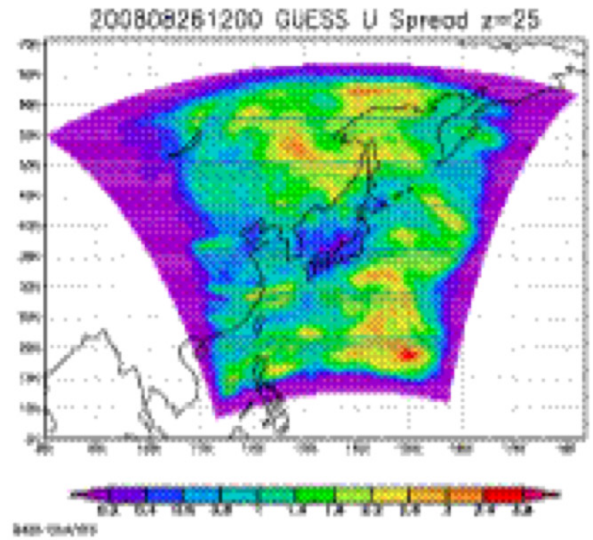


Spread (25th vertical level ~ 500hPa)

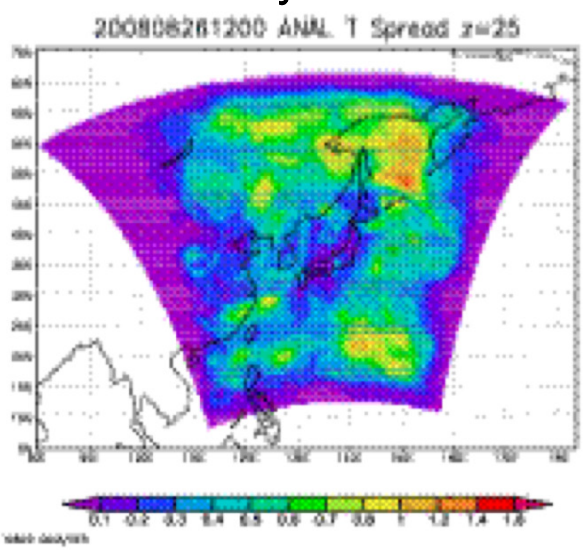
T Guess



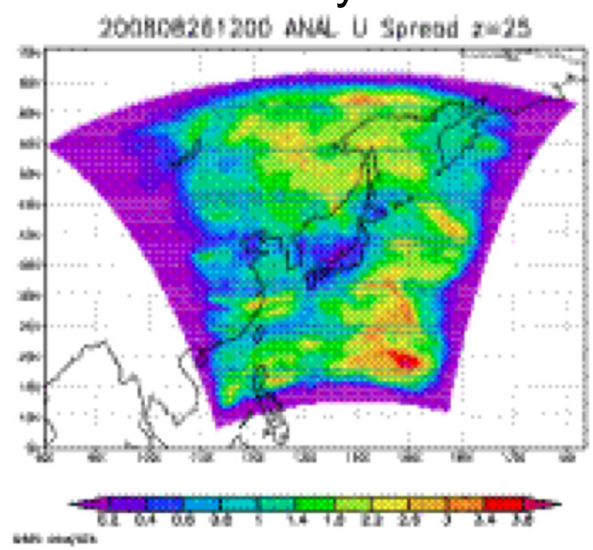
U Guess



T Analysis

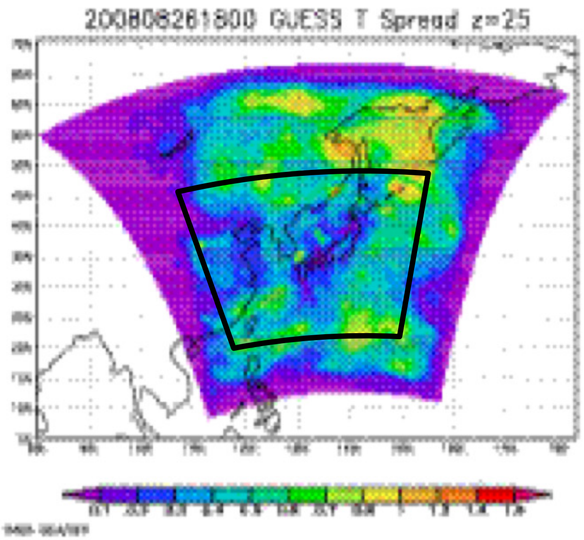


U Analysis

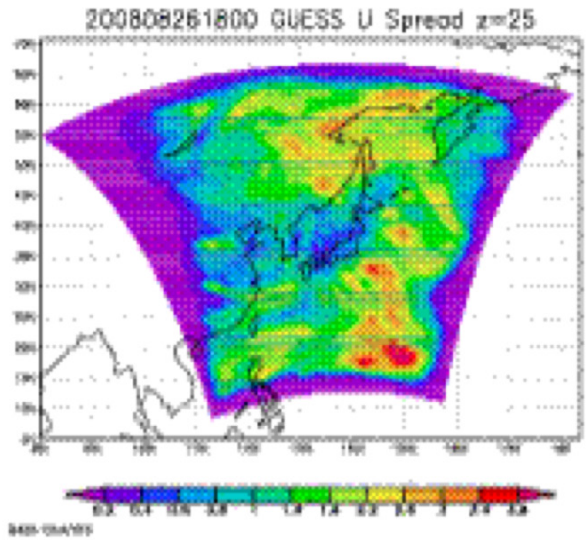


Spread (25th vertical level ~ 500hPa)

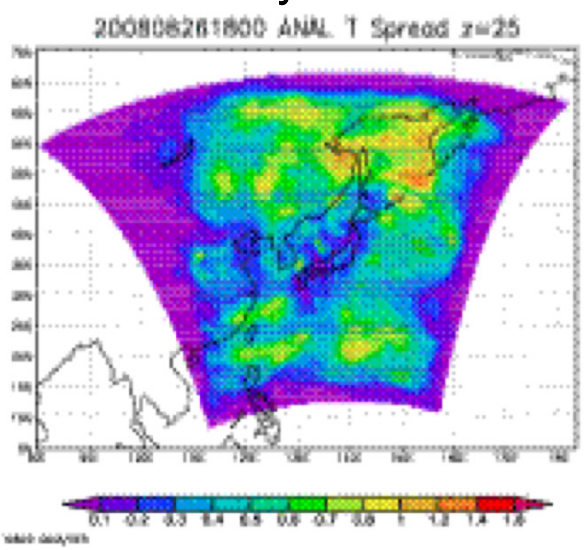
T Guess



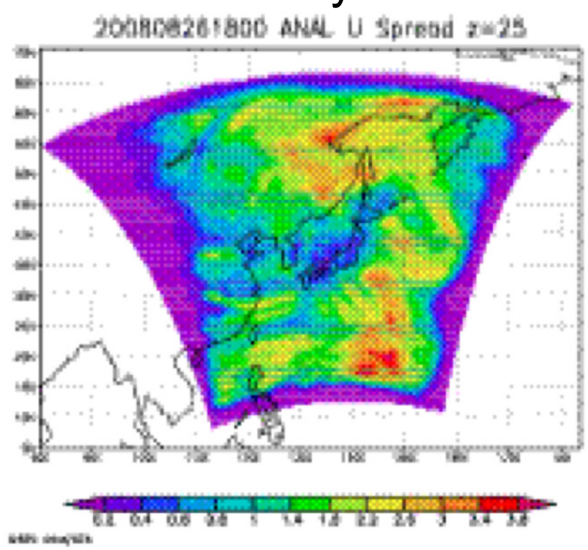
U Guess



T Analysis

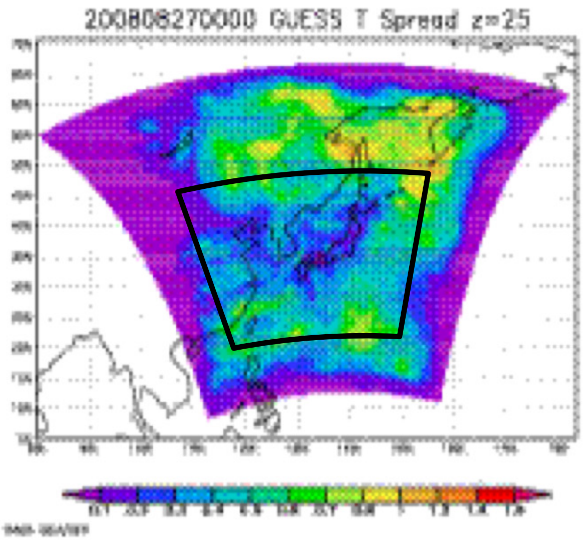


U Analysis

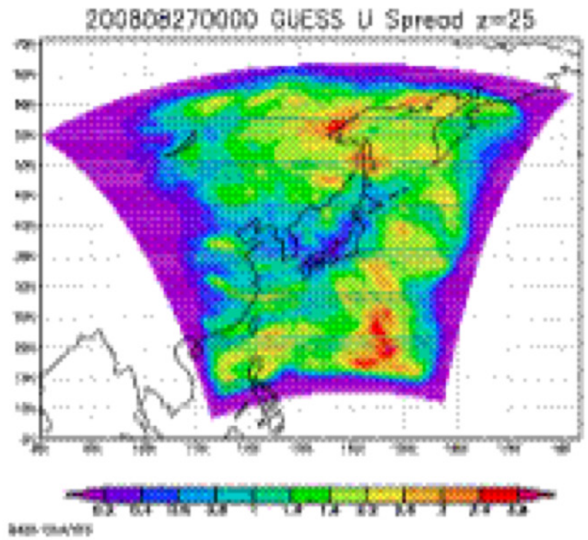


Spread (25th vertical level ~ 500hPa)

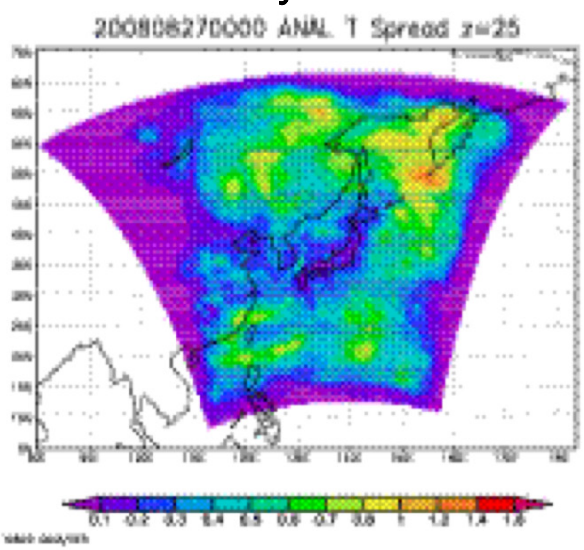
T Guess



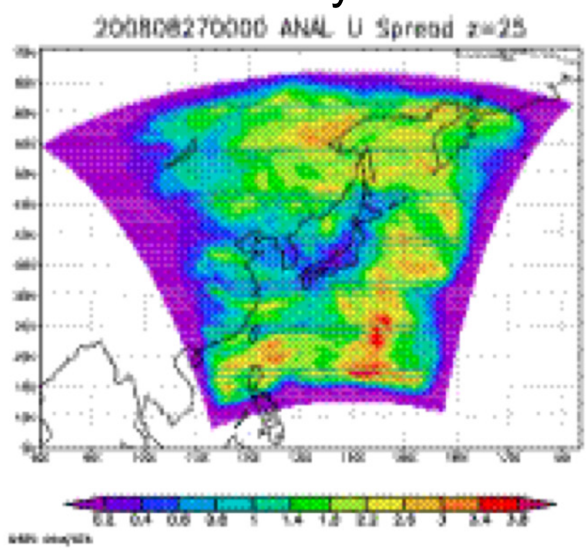
U Guess



T Analysis

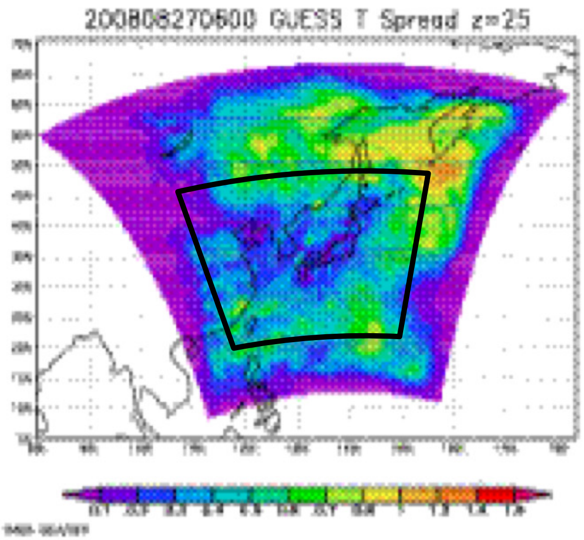


U Analysis

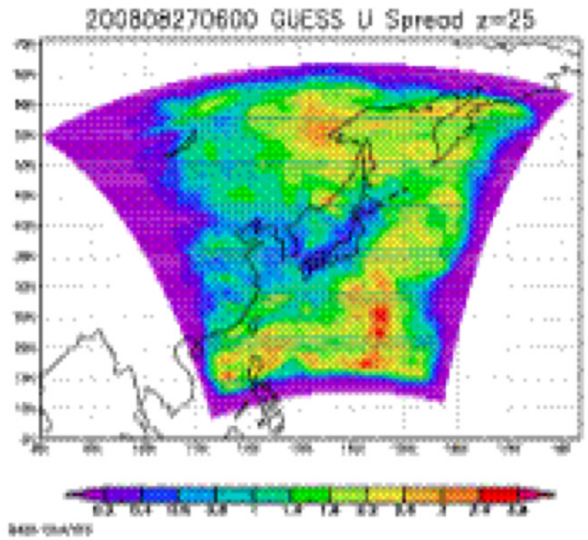


Spread (25th vertical level ~ 500hPa)

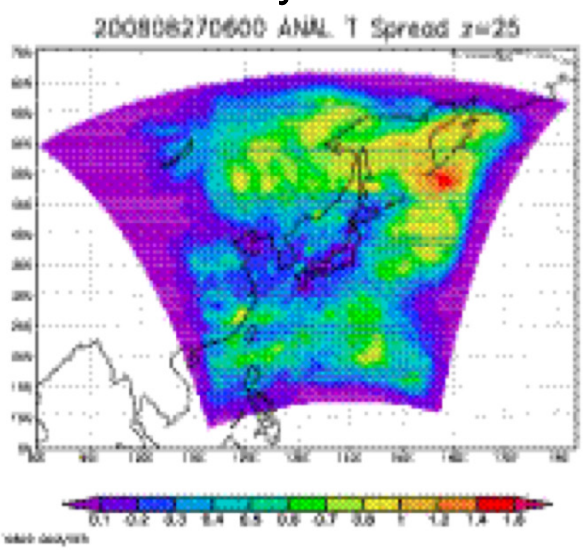
T Guess



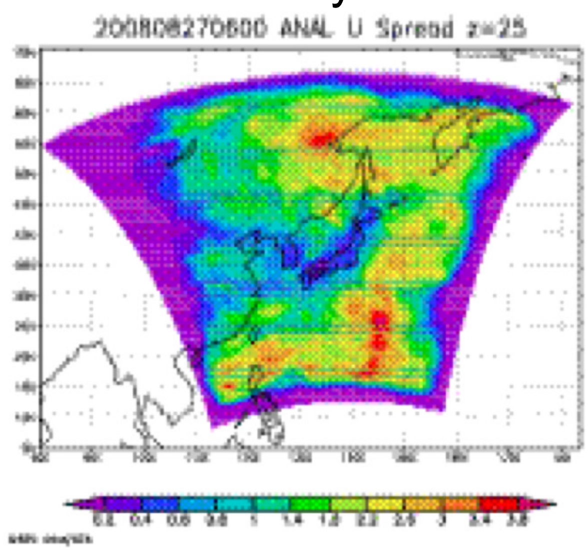
U Guess



T Analysis

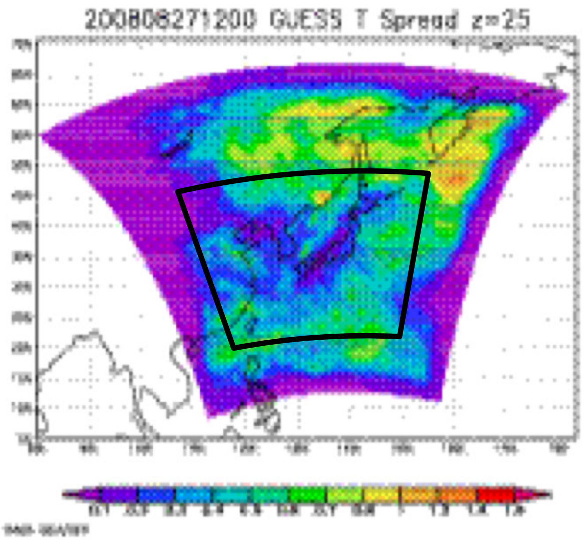


U Analysis

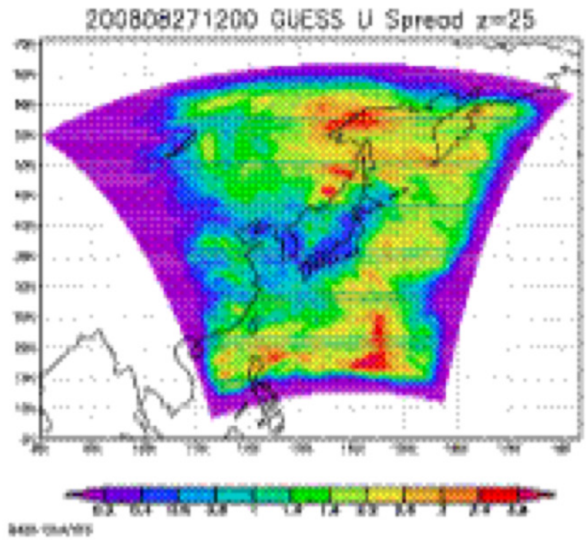


Spread (25th vertical level ~ 500hPa)

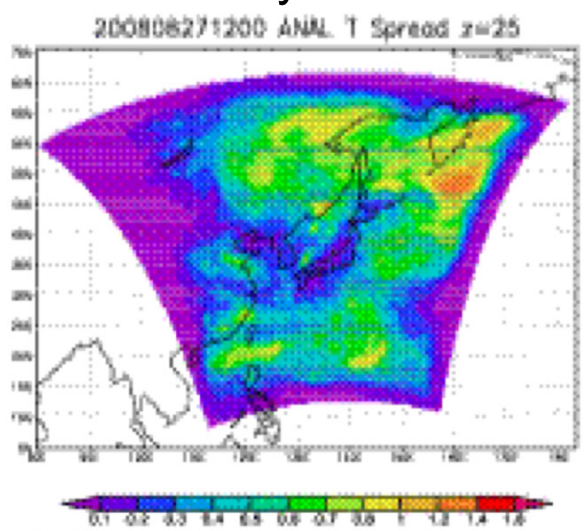
T Guess



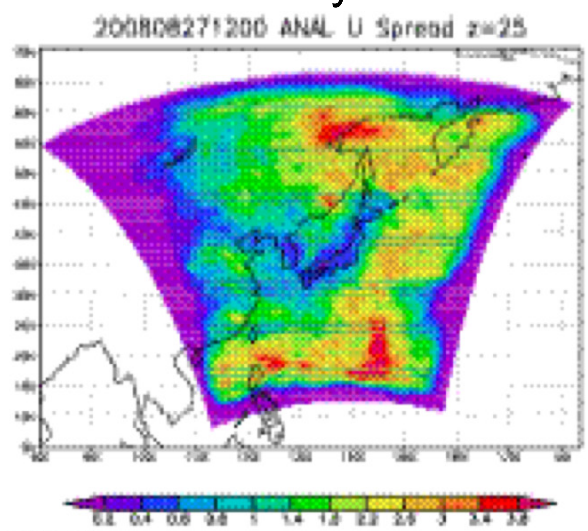
U Guess



T Analysis

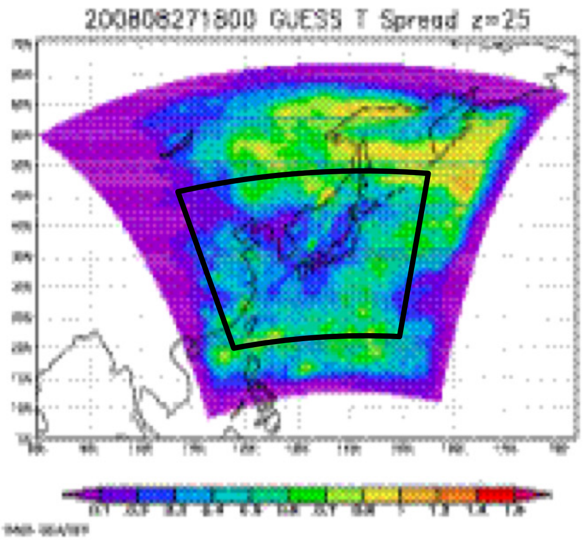


U Analysis

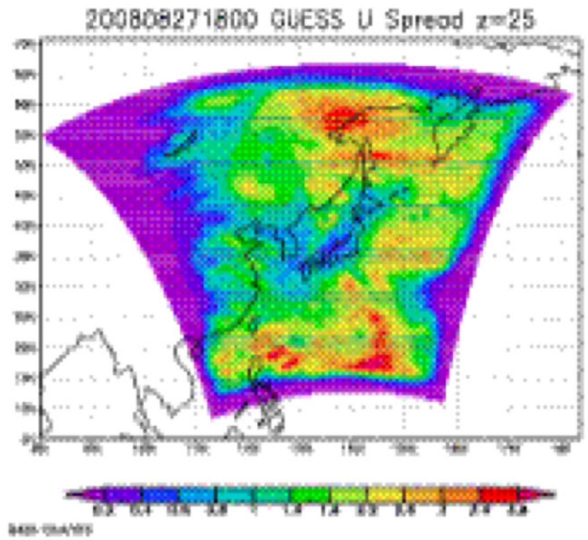


Spread (25th vertical level ~ 500hPa)

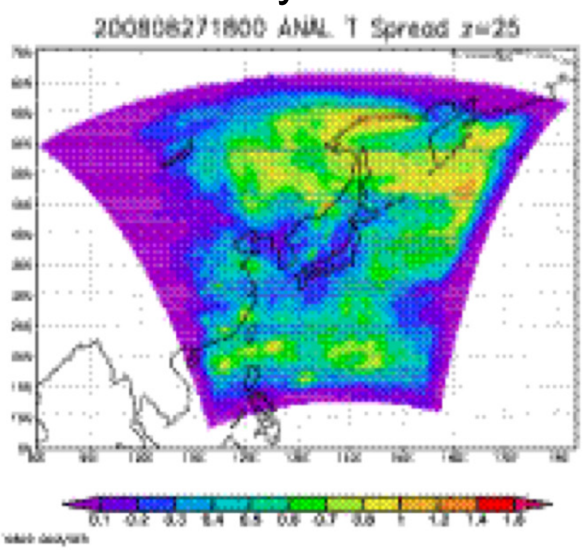
T Guess



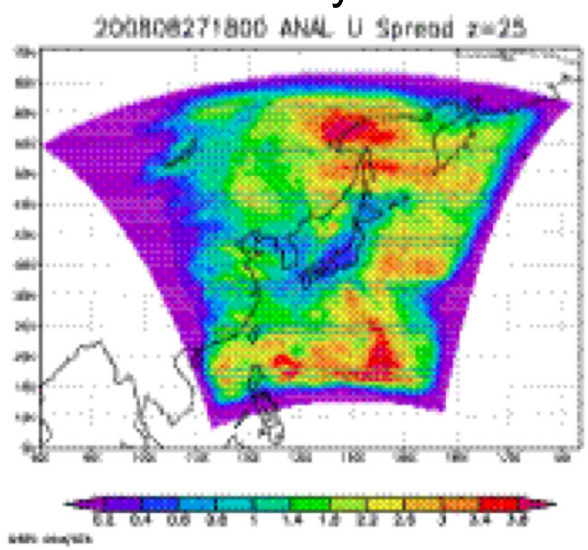
U Guess



T Analysis

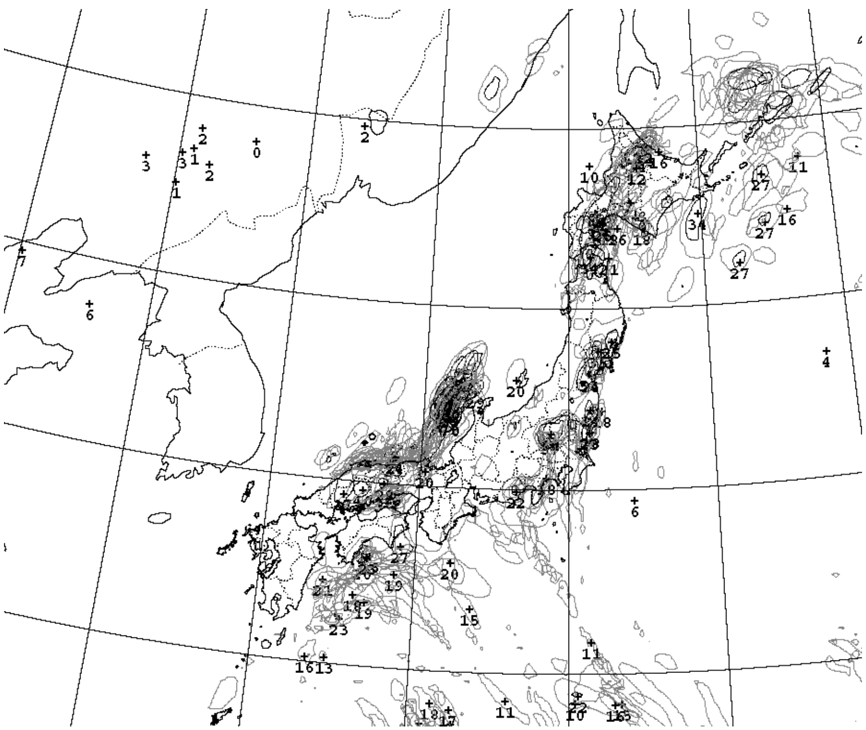


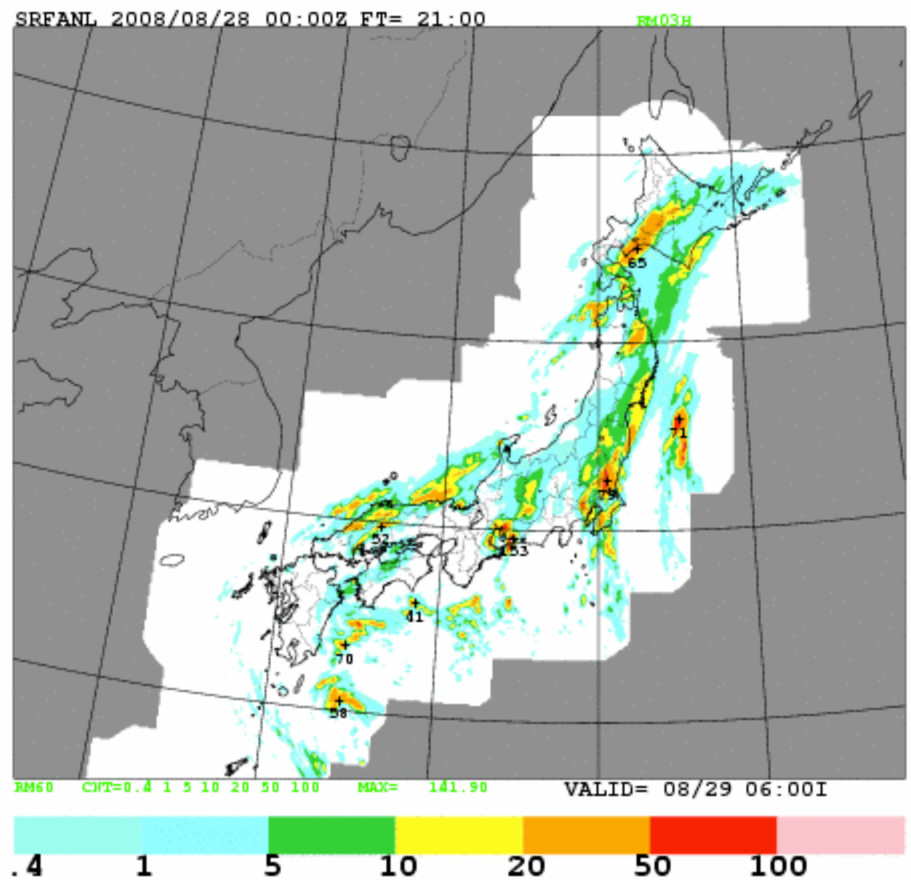
U Analysis



28 Aug. 21UTC
3h Accumulated precipitation

Ensemble forecast from the LETKF analysis FT=21 (30 members)
gray:10mm/3h, black: 20mm/3h

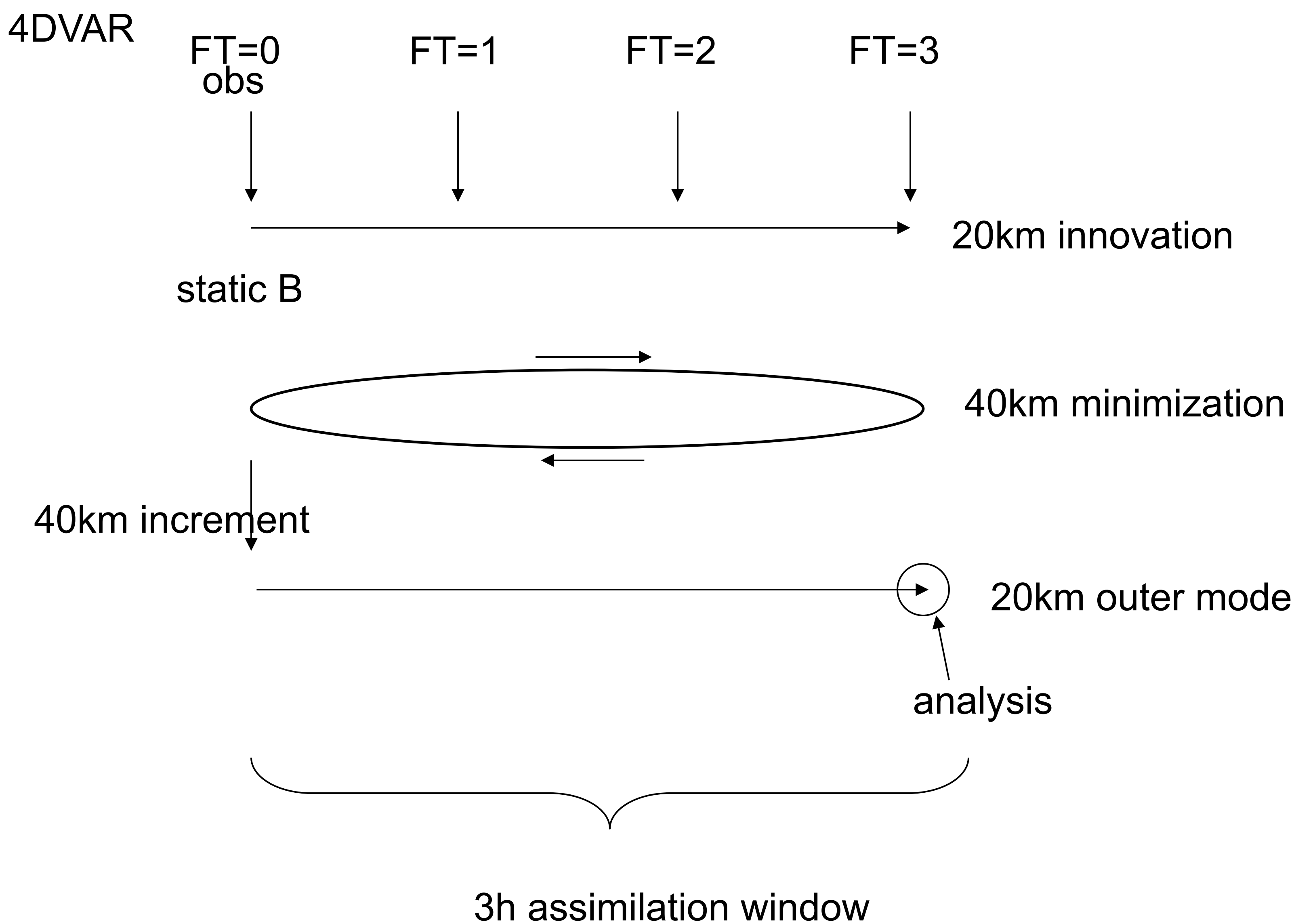


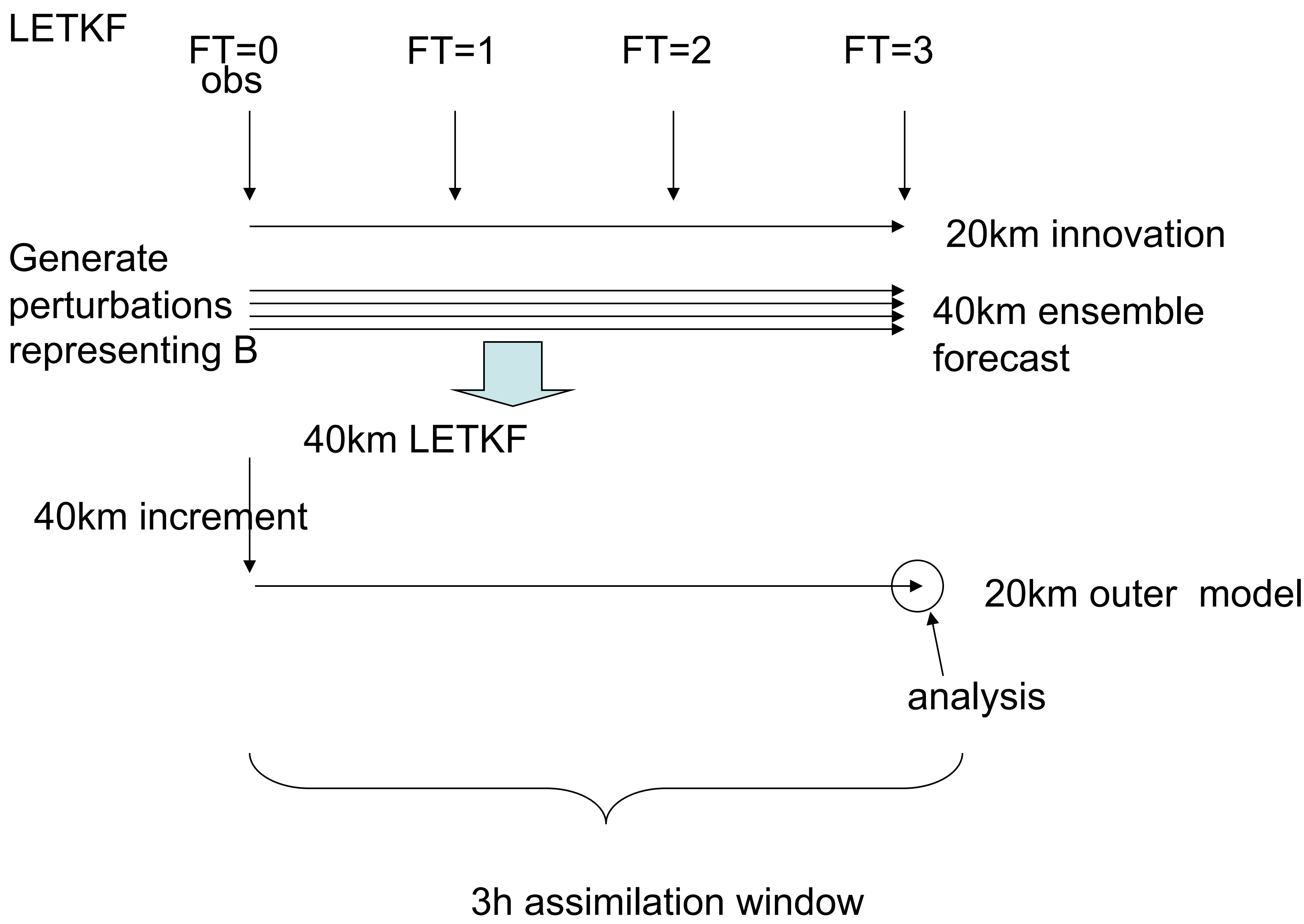


LETKF with static B

LETKF using perturbations based on Background error covariance in variational method.

Compare LETKF and 4DVAR under the same condition (assimilation window, resolution, innovation)


4DVAR
FT=0
obs
FT=1
FT=2
FT=3
20km innovation
static B
40km minimization
40km increment
20km outer model
analysis
3h assimilation window


LETKF
FT=0
obs
FT=1
FT=2
FT=3
20km innovation
Generate perturbations representing B
40km ensemble forecast
40km LETKF
40km increment
20km outer model
analysis
3h assimilation window

Ensemble covariance

$$\mathbf{P} = \mathbf{E}\mathbf{E}^T$$

$$\mathbf{E} = \frac{1}{\sqrt{m-1}}[\delta\mathbf{x}^{(1)} \mid \cdots \mid \delta\mathbf{x}^{(m)}]$$

Static covariance

$$\mathbf{B} = \mathbf{F}\mathbf{F}^T \qquad \mathbf{F} = [\mathbf{v}^{(1)} \mid \cdots \mid \mathbf{v}^{(m)}]$$

$$\mathbf{v}^{(l)} = \mathbf{B}^{1/2}\mathbf{w}^{(l)}$$

$$\mathbf{w}^{(1)} = \begin{pmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{pmatrix}, \quad \mathbf{w}^{(2)} = \begin{pmatrix} 0 \\ 1 \\ 0 \\ \vdots \end{pmatrix}, \quad \cdots \qquad \mathbf{w}^{(1)}\mathbf{w}^{(1)T} + \mathbf{w}^{(2)}\mathbf{w}^{(2)T} + \cdots = 1$$

Need huge ensemble size

(equal to number of degrees of freedom of the system)

=> reduce ensemble size

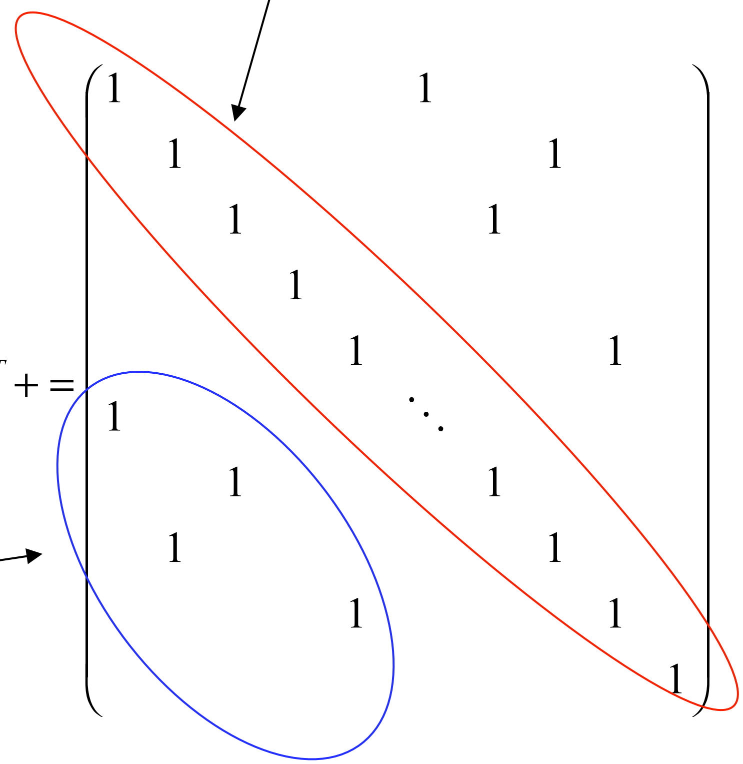
static B perturbation
reduction of ensemble size (1)

$$\mathbf{w}^{(1)} = \begin{pmatrix} 1 \\ 0 \\ \vdots \\ 0 \\ 1 \\ 0 \\ \vdots \\ 0 \\ 1 \\ 0 \end{pmatrix}, \quad \mathbf{w}^{(2)} = \begin{pmatrix} 0 \\ 1 \\ 0 \\ \vdots \\ 0 \\ 1 \\ 0 \\ \vdots \\ 0 \\ 1 \end{pmatrix}, \cdots$$

Enough spacing: larger than error correlation range

No duplication

$$\mathbf{w}^{(1)}\mathbf{w}^{(1)T} + \mathbf{w}^{(2)}\mathbf{w}^{(2)T} + =$$



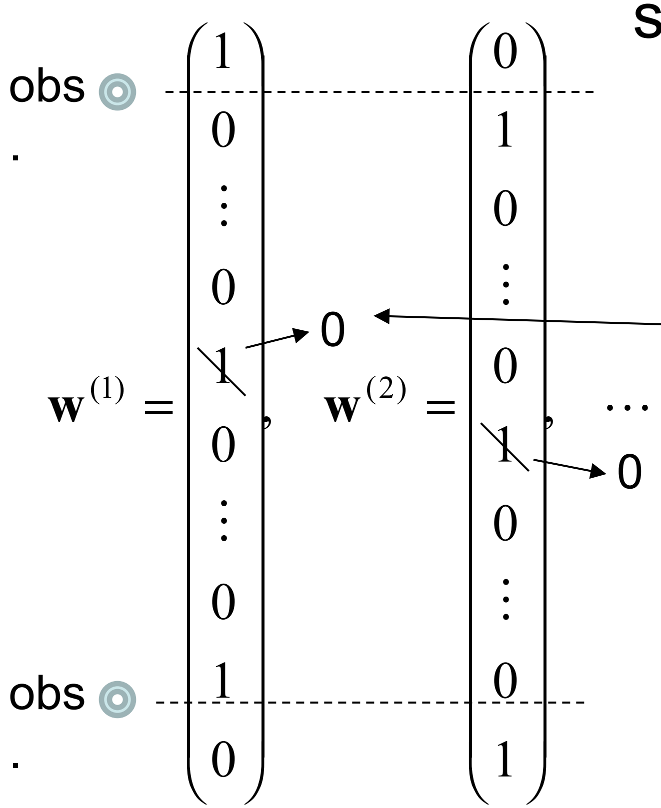
With localization, only elements near diagonal are referred in the analysis.

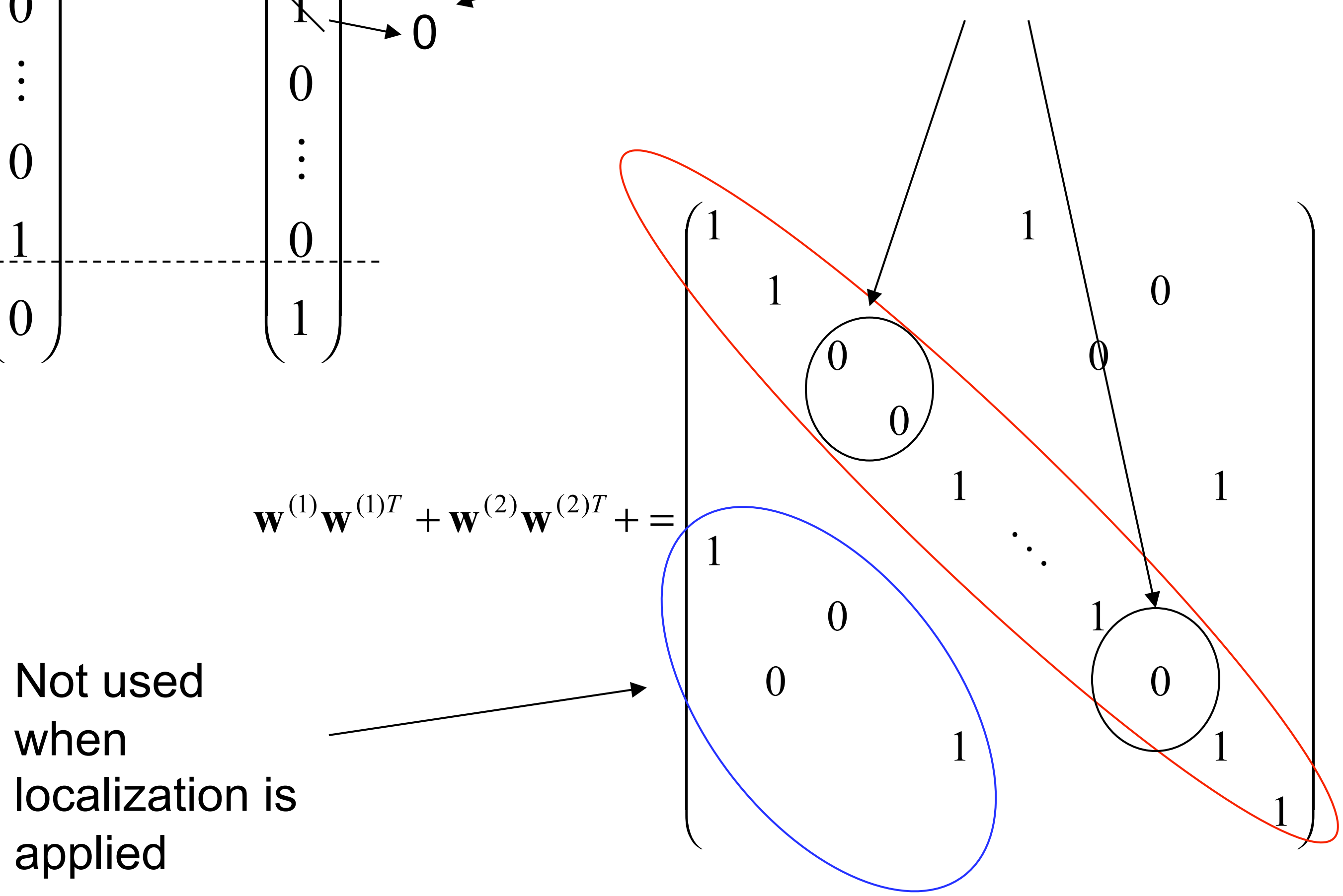
Not referred when localization is applied

static B perturbation
reduction of ensemble size (2)

Only need background error covariance near observations

No perturbation is added if far from obs.





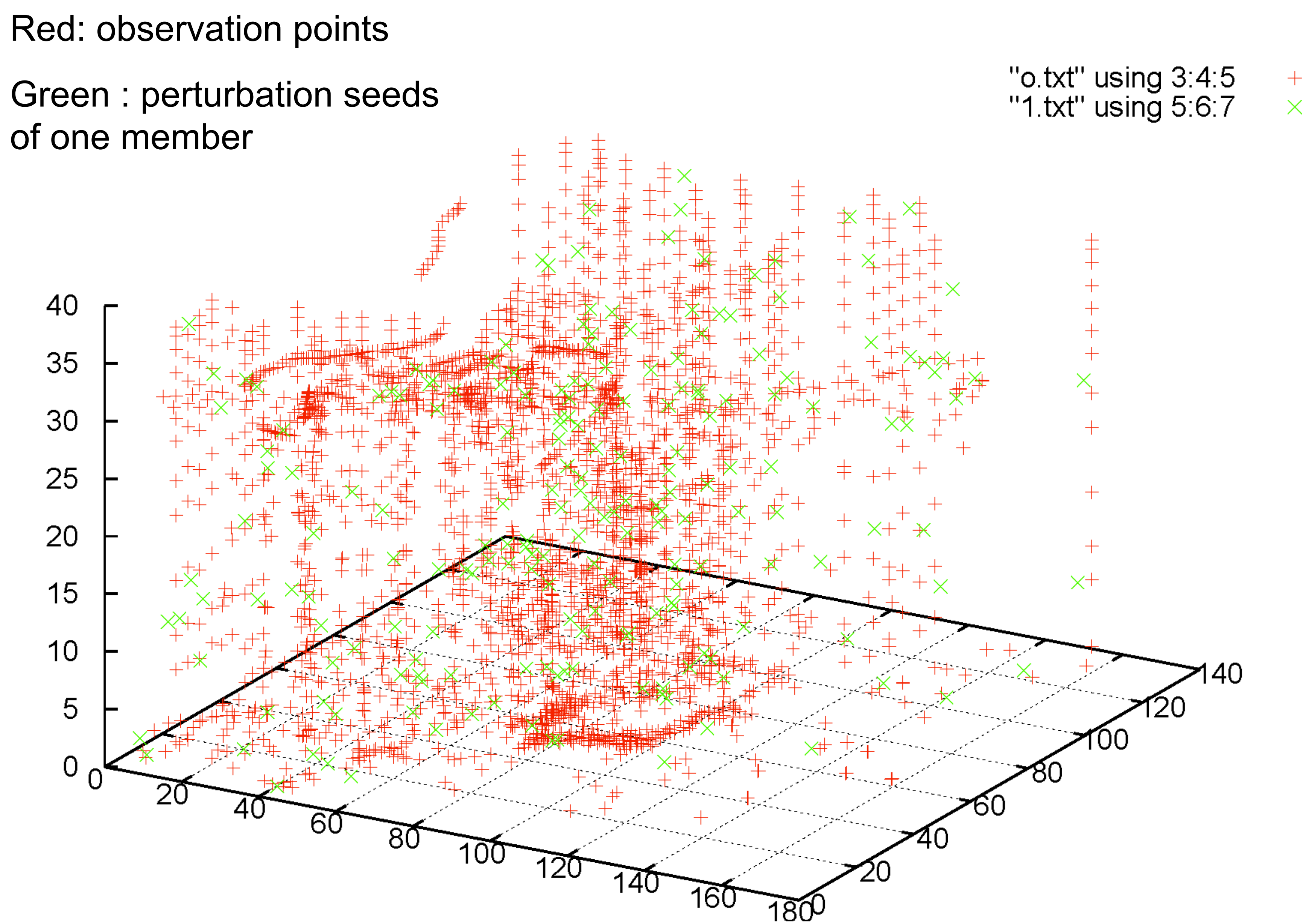
$$\mathbf{v}^{(l)} = \mathbf{B}^{1/2}\mathbf{w}^{(l)}$$ correct formulation, but not balanced

$$v_i^{(l)} = \sum_j \left\langle (\Delta x_i)(\Delta x_j / \sigma_{x_j})^T \right\rangle w_j^{(l)}$$

Procedure to generate perturbation

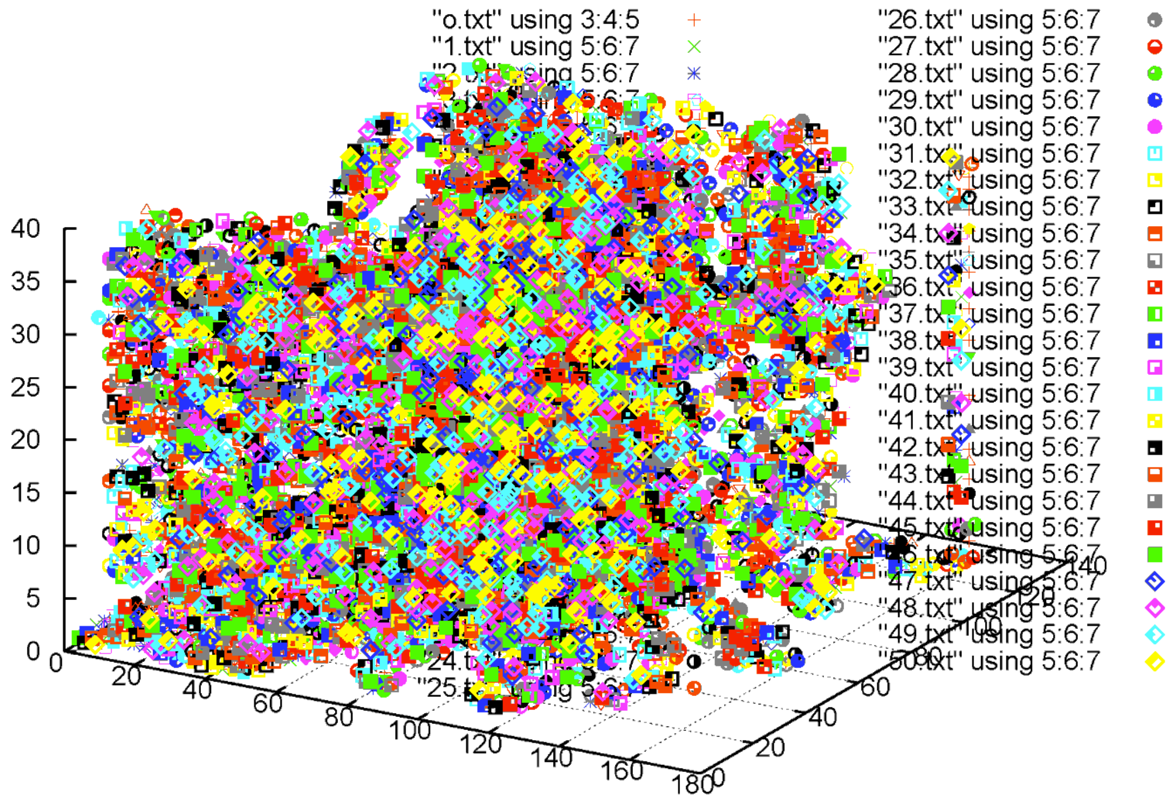
1. Check observation distribution
2. Select grid points near obs.(apply thinning)
3. Distribute selected grid points to ensemble members
4. Put +1, -1, +1, -1 . . . .(seeds) on selected grid points.
5. Apply B

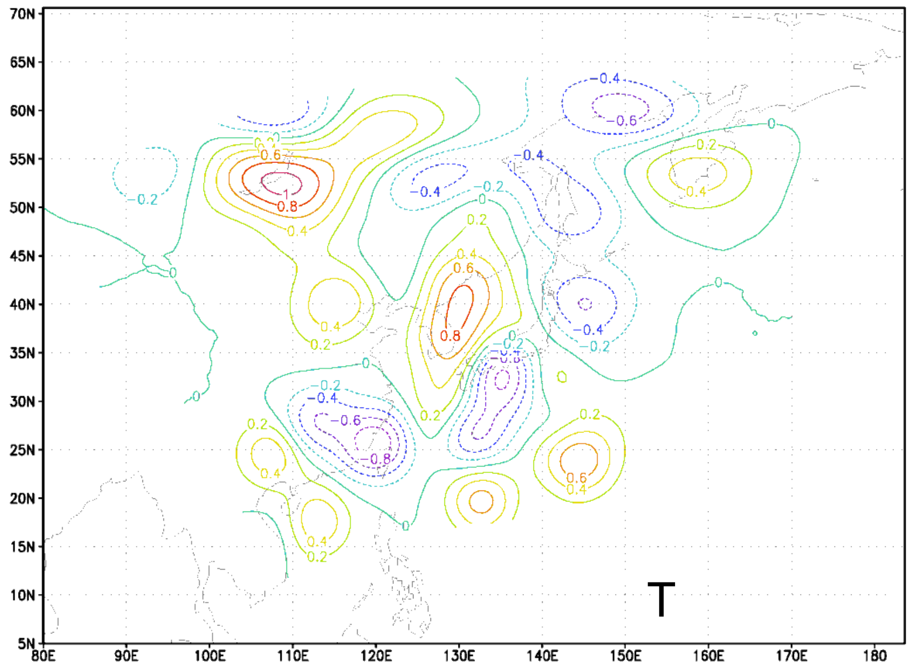
LETKF pert distribution of seeds of the perturbations

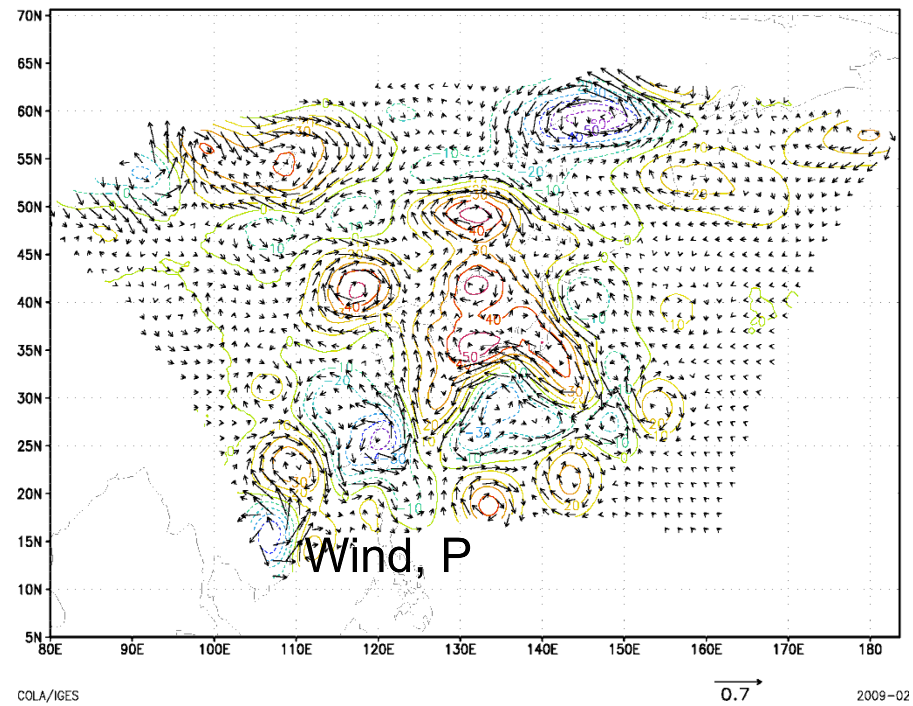


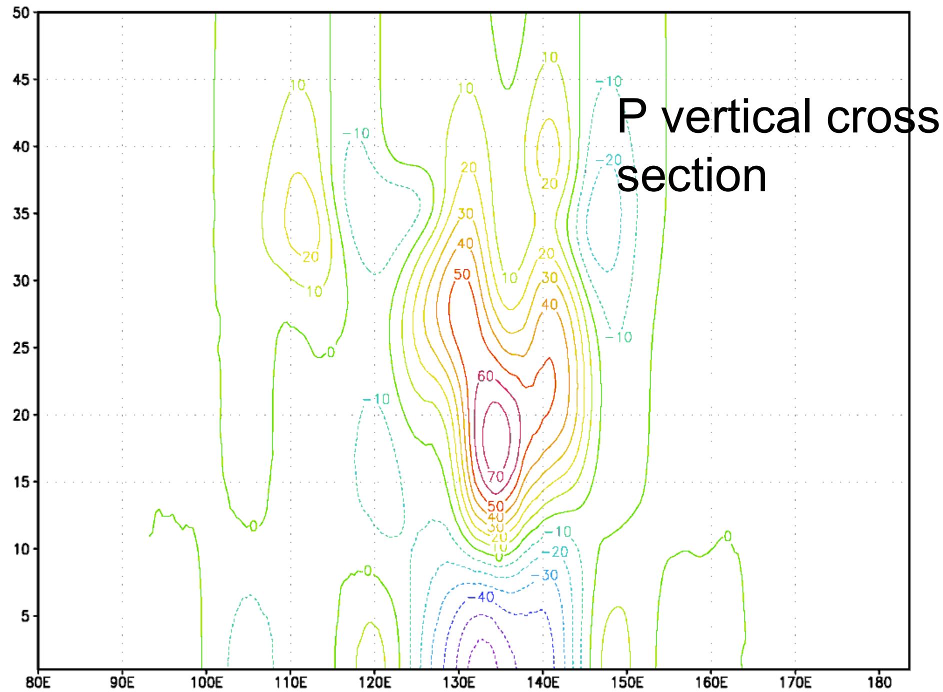
Distribution of perturbation seeds

(color indicates member)





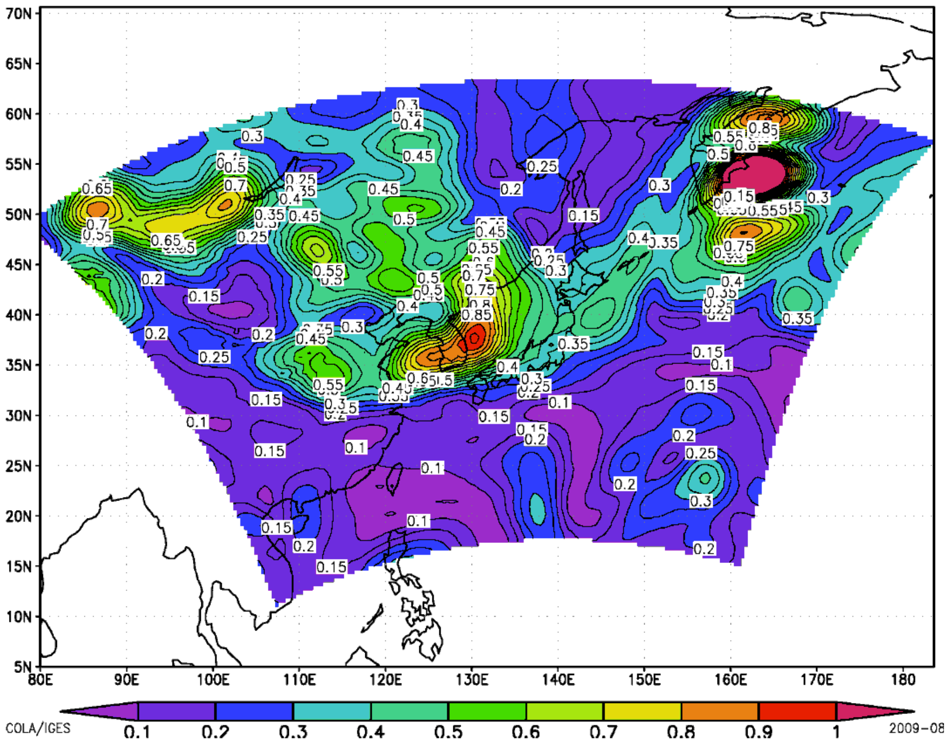




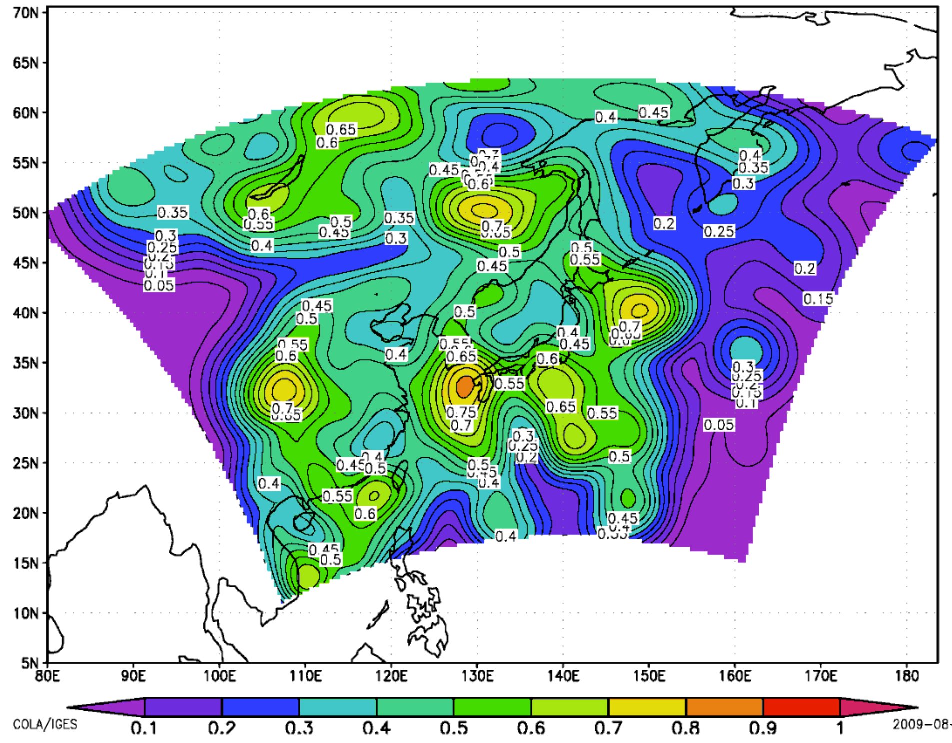
Perturbation of one member (25th level) FT=0

T spread 25th level

Operational global ensemble forecast 50 members



Generated perturbation



4DVAR (hydro static, (outer model non-hydrostatic))

Control variables u_u, v_u, T_v, P_S, q

Incremental method (inner 40km, outer 20km)

LETKF pert

LETKF using the generated Var. perturbations

u_u, v_u, T_v perturbation (seeded around observation points)

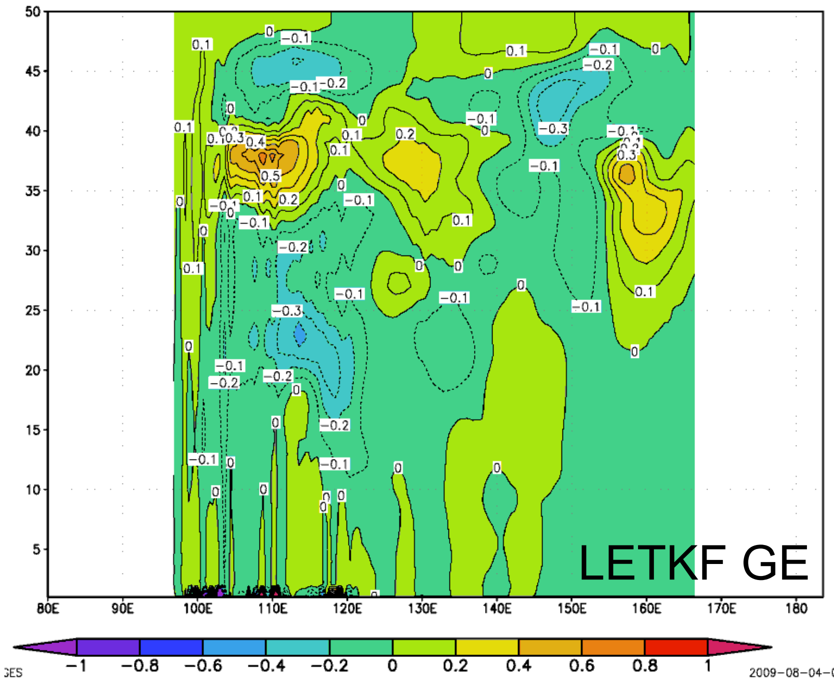
±7 grid points, every 2 grid points
±5 vertical levels, every 3 levels
seeds distributed different members (25 members for each element) => 75 members

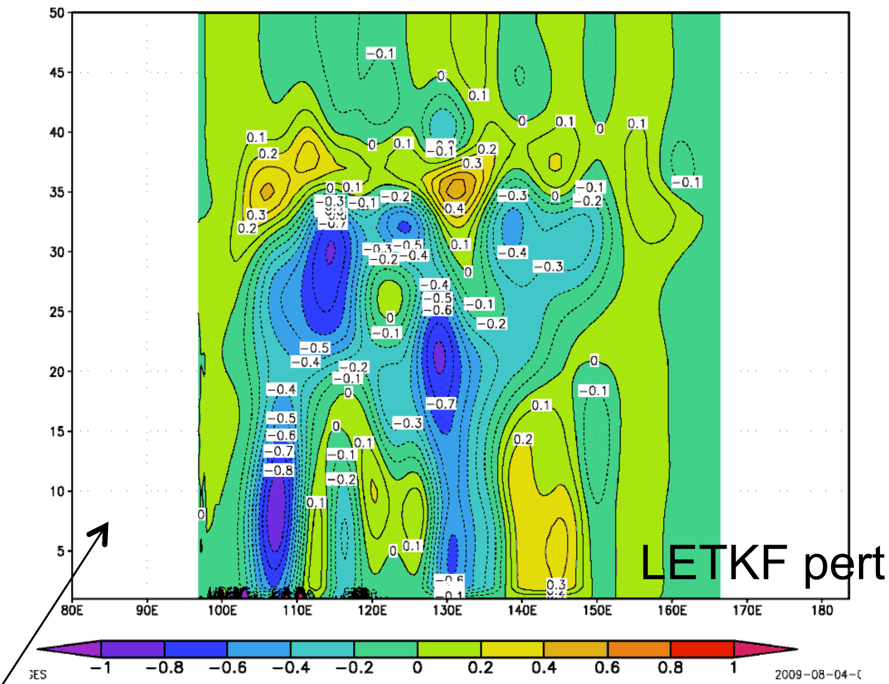
Incremental method (40km ensemble + 20km control)

Localization scale: horrizontal 10 grid points, 8 vertical levels

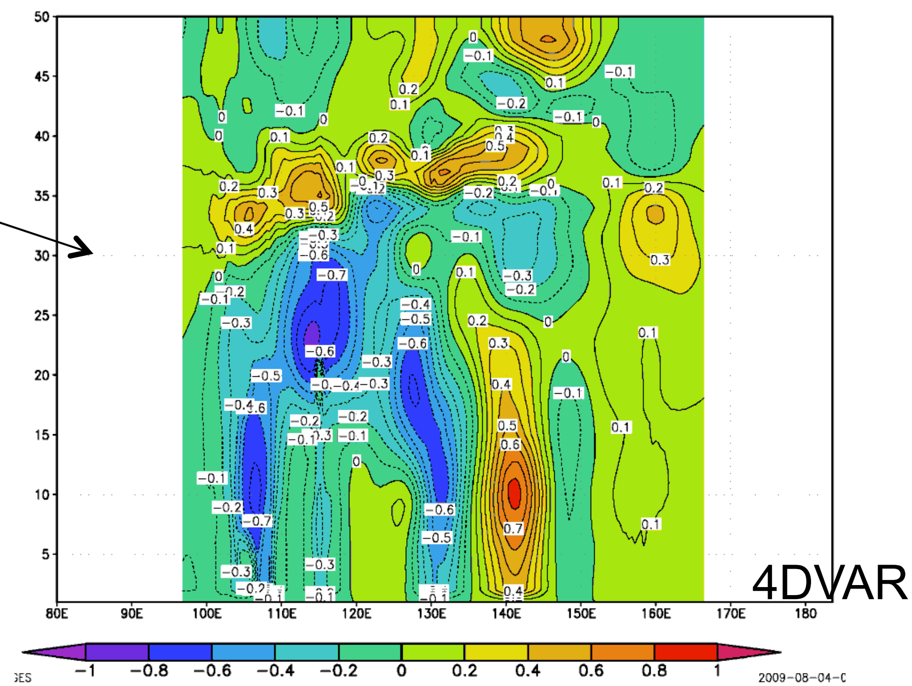
LETKF GE

LETKF using perturbations from operational global ensemble forecast (SV, 50 members)

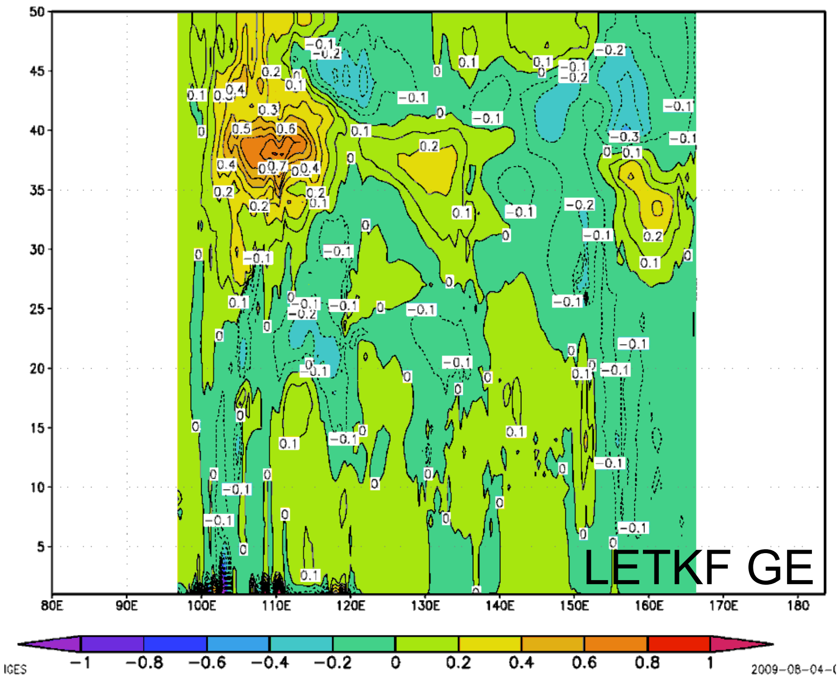


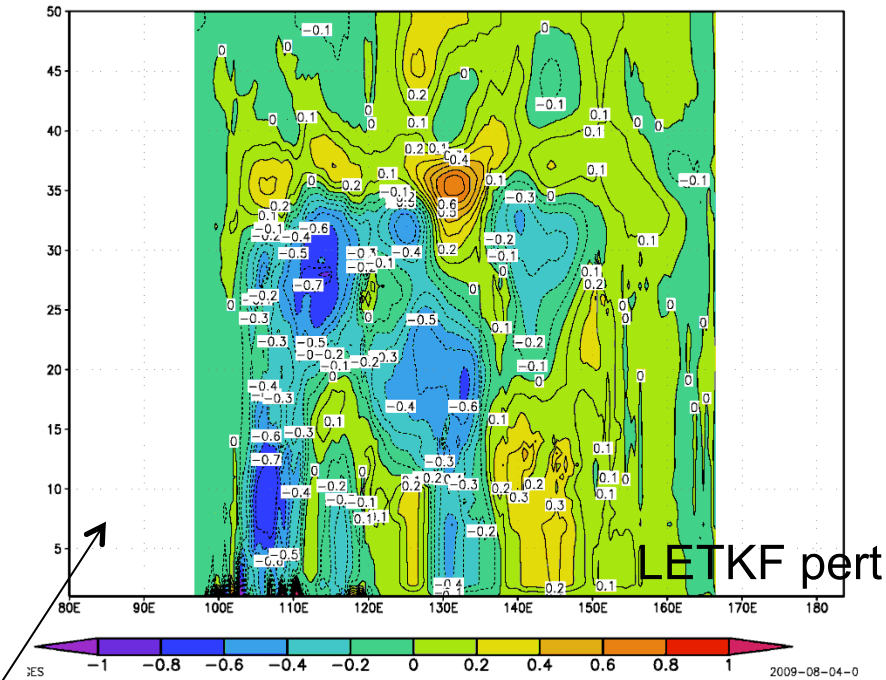


Similar pattern

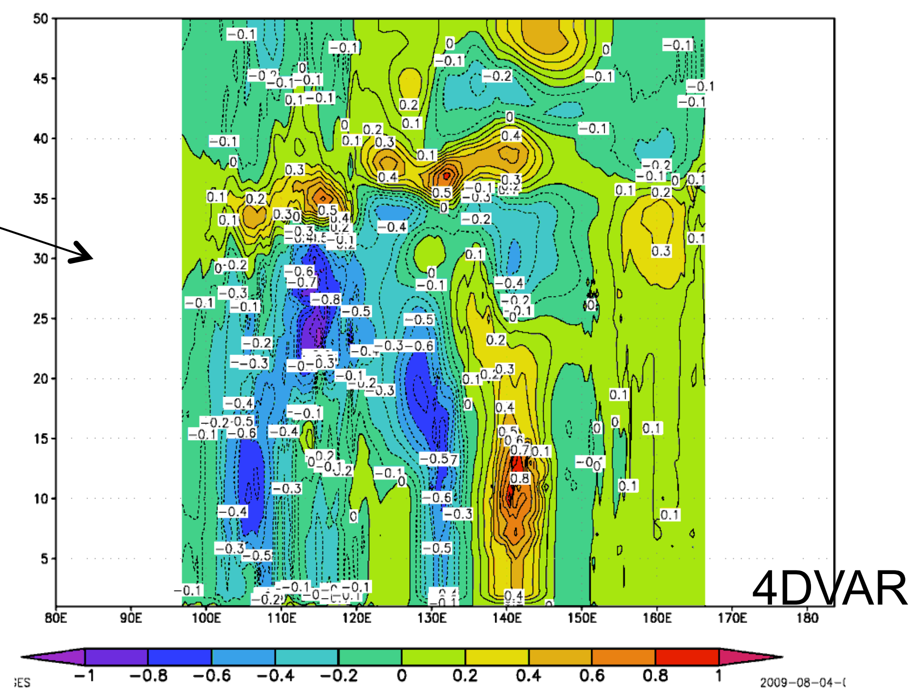


Lat=30N
T increment vertical cross section
FT=0

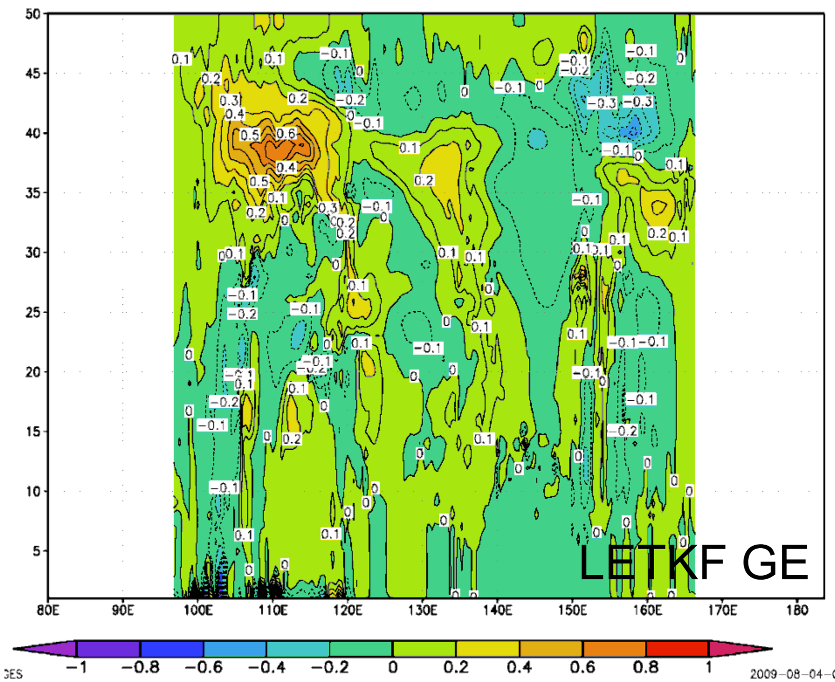


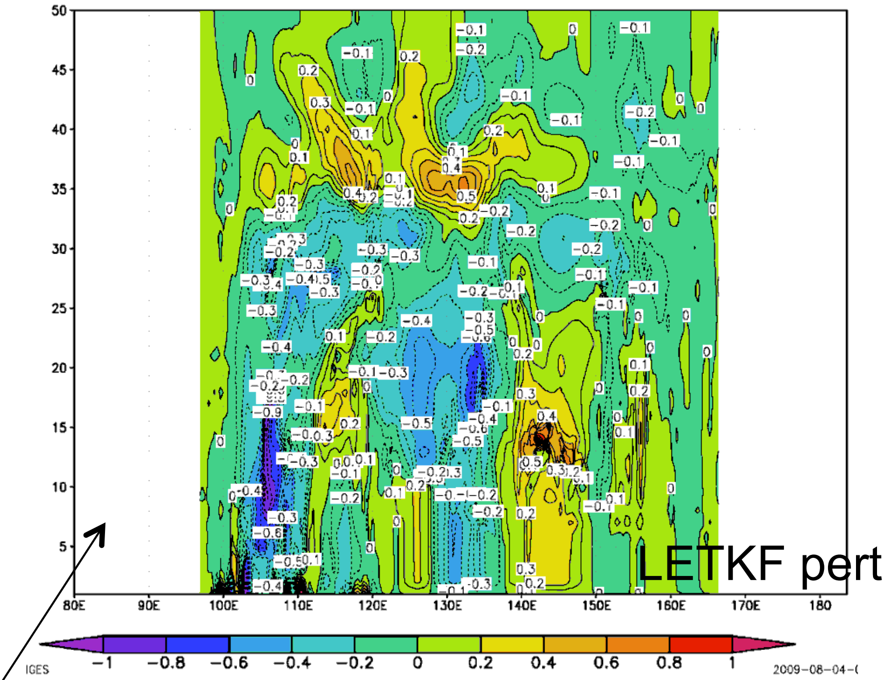


Similar pattern

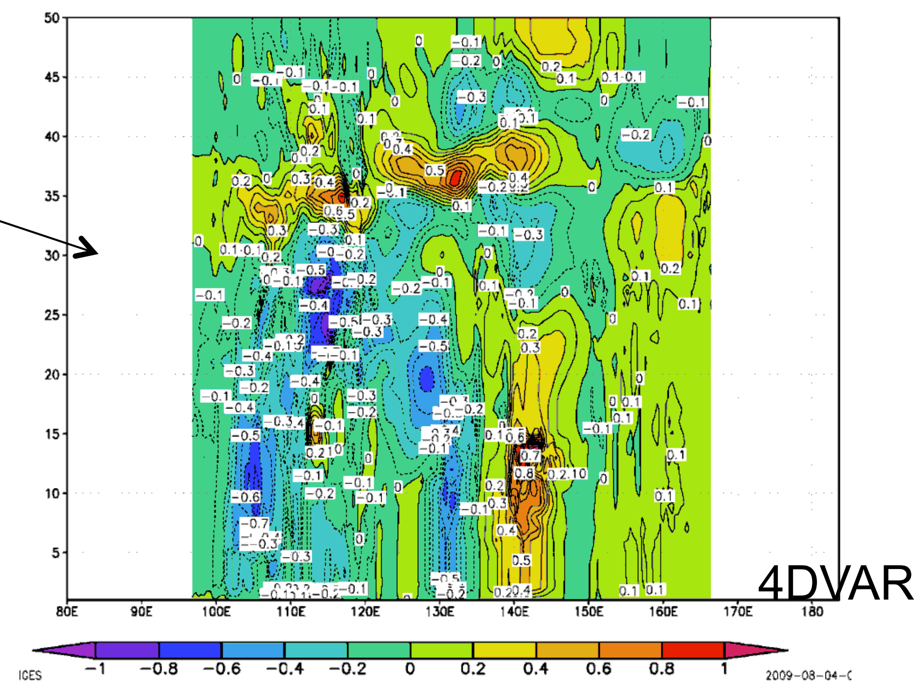


Lat=30N
T increment vertical cross section
FT=1

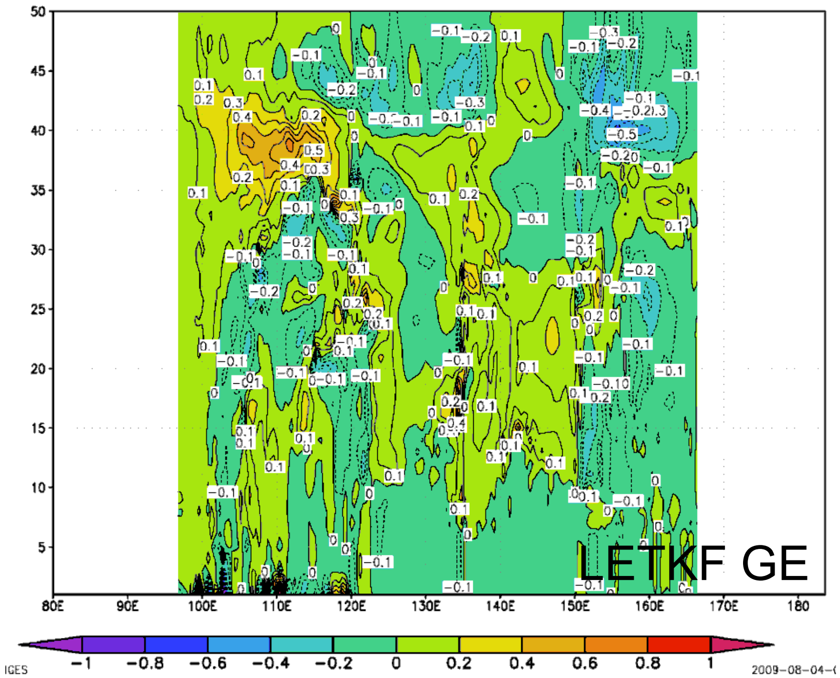


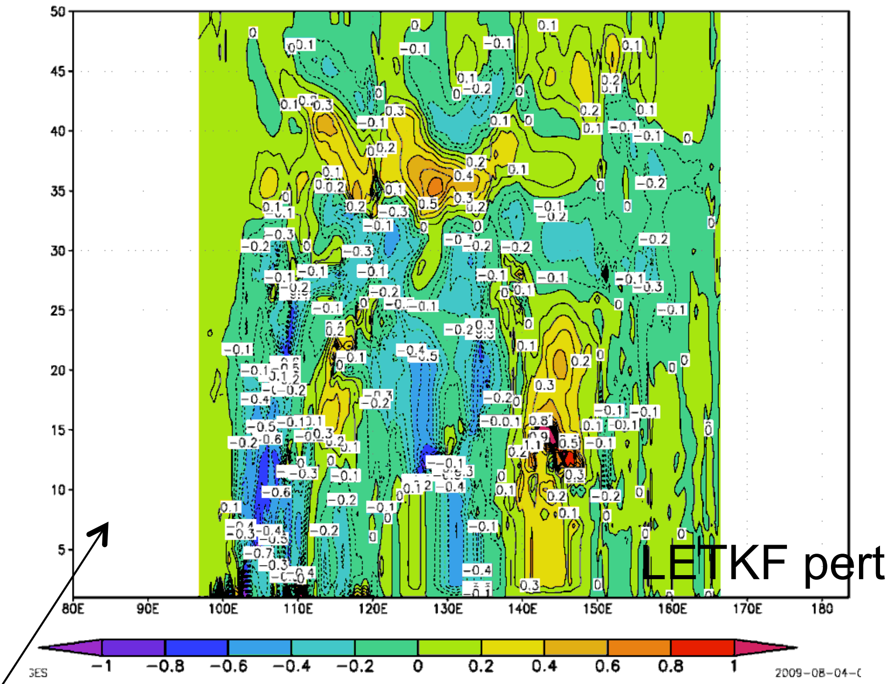


Similar pattern

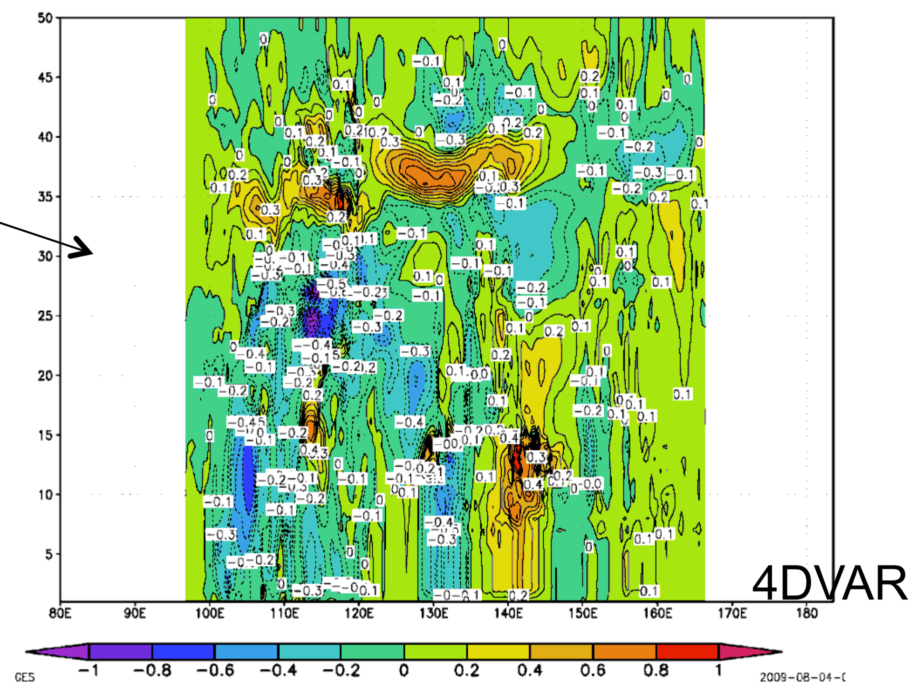


Lat=30N
T increment vertical cross section
FT=2





Similar pattern

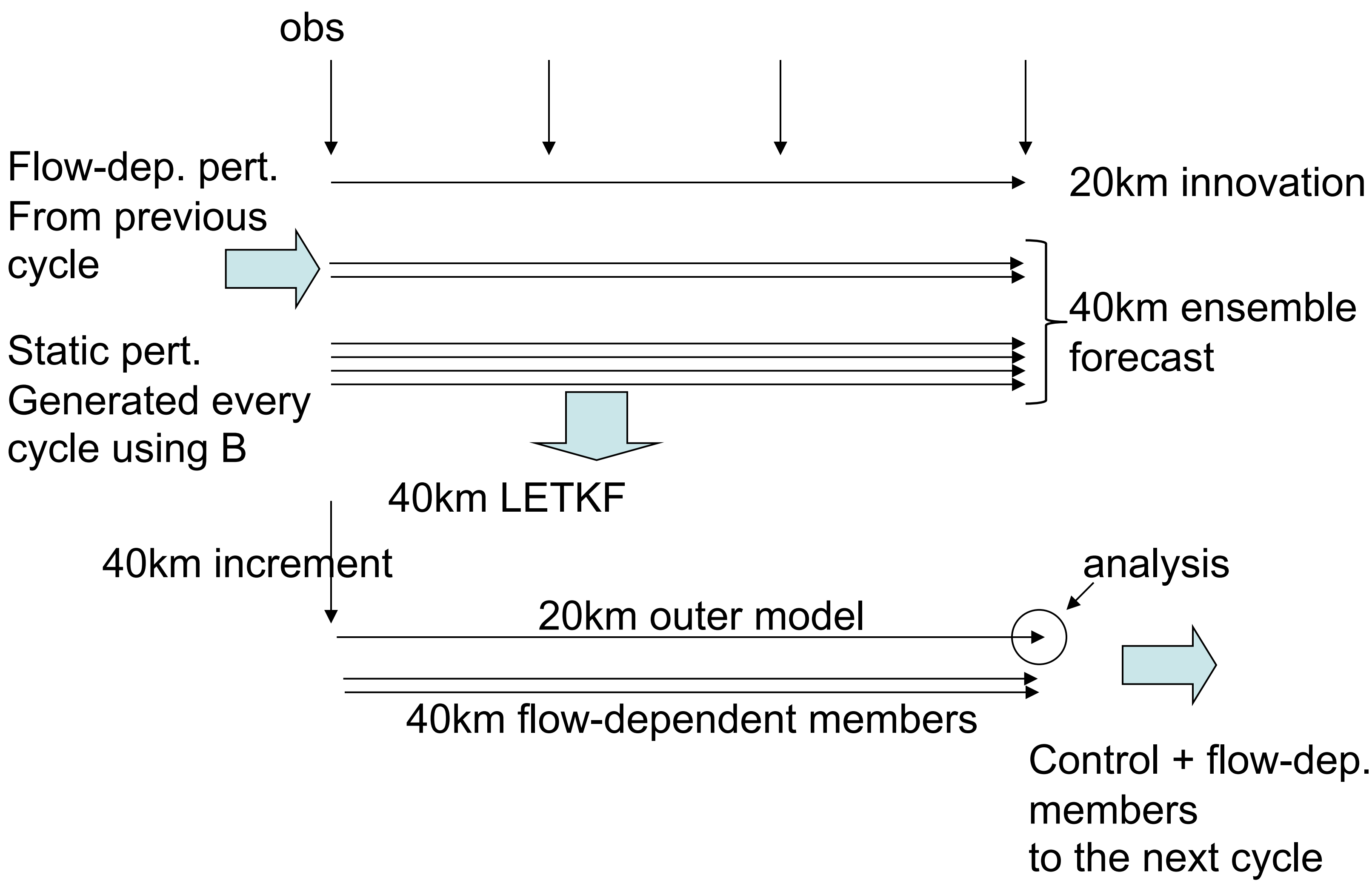


Lat=30N

T increment vertical cross section

FT=3

Possible design of a system using flow-dependent and static perturbations



Using perturbations with different scales in ensemble data assimilation (test with variational method, displacement perturbations)

test to handle errors in different scales in data assimilation.

Variational framework

Using ensemble perturbations in variational method

Hamill and Snyder, 2000
Lorenc, 2003
Buehner et al., 2004
Wang et al., 2008

$$J = \frac{1}{2}\mathbf{v}_0^T\mathbf{v}_0 + \frac{1}{2}\mathbf{v}_{pert}^T\mathbf{v}_{pert} + \frac{1}{2}(\mathbf{y} - H(\mathbf{x}^b + \Delta\mathbf{x}))^T\mathbf{R}^{-1}(\mathbf{y} - H(\mathbf{x}^b + \Delta\mathbf{x}))$$

$$\Delta\mathbf{x} = \underbrace{\beta^{1/2}\mathbf{B}_0^{1/2}\mathbf{v}_0}_{\text{static}} + \underbrace{\sqrt{1-\beta}\,\mathbf{B}_{pert}^{1/2}\mathbf{v}_{pert}}_{\text{ensemble}}$$

Localization (allow to specify localization of each member)

$$\mathbf{B}_{pert}^{1/2} = \frac{1}{\sqrt{M-1}}(\mathbf{D}_1\mathbf{L}_1^{1/2}\ \mathbf{D}_2\mathbf{L}_2^{1/2}\ \cdots\mathbf{D}_M\mathbf{L}_M^{1/2})$$

v_pert : NxM dimensional vector
(weight of each member on each grid point)

$$\mathbf{D}_m = \begin{pmatrix} \mathbf{D}_m^1 \\ \mathbf{D}_m^2 \\ \vdots \\ \mathbf{D}_m^L \end{pmatrix}$$

$$\mathbf{D}_m^l = \begin{pmatrix} \delta x_{m(l,1)} & & & \\ & \delta x_{m(l,2)} & & \\ & & \ddots & \\ & & & \delta x_{m(l,N_{space})} \end{pmatrix}$$

Simple example of perturbation
horizontal displacement perturbation (scale selective)

Apply smoothing: Pick up information of specified scale

$$\overline{\mathbf{x}}_{\Delta}(i,j,k)=\frac{1}{(2\Delta+1)^2}\sum_{i'=-\Delta}^{\Delta}\sum_{j'=-\Delta}^{\Delta}\mathbf{x}(i+i',j+j',k)$$

Generate perturbations from x- and y- displacement
Consider only uncertainties from horizontal displacement error

$$\delta\mathbf{x}_x^{\Delta}(i,j,k)=\overline{\mathbf{x}}_{\Delta}(i+\Delta/2,j,k)-\overline{\mathbf{x}}_{\Delta}(i-\Delta/2,j,k)$$

$$\delta\mathbf{x}_y^{\Delta}(i,j,k)=\overline{\mathbf{x}}_{\Delta}(i,j+\Delta/2,k)-\overline{\mathbf{x}}_{\Delta}(i,j-\Delta/2,k)$$

*Smooth with scale delta to pick up displacement error in the specified scale.
*use several deltas (error correlation in different scales)
* x- and y- perturbations (independent 2 directions) represent horizontal displacement in every direction.
* Assign larger localization scale for larger scale error (correlation signal reaches over longer distance)

cf. Aonashi and Eito, J. Meteor. Soc. Japan 2010

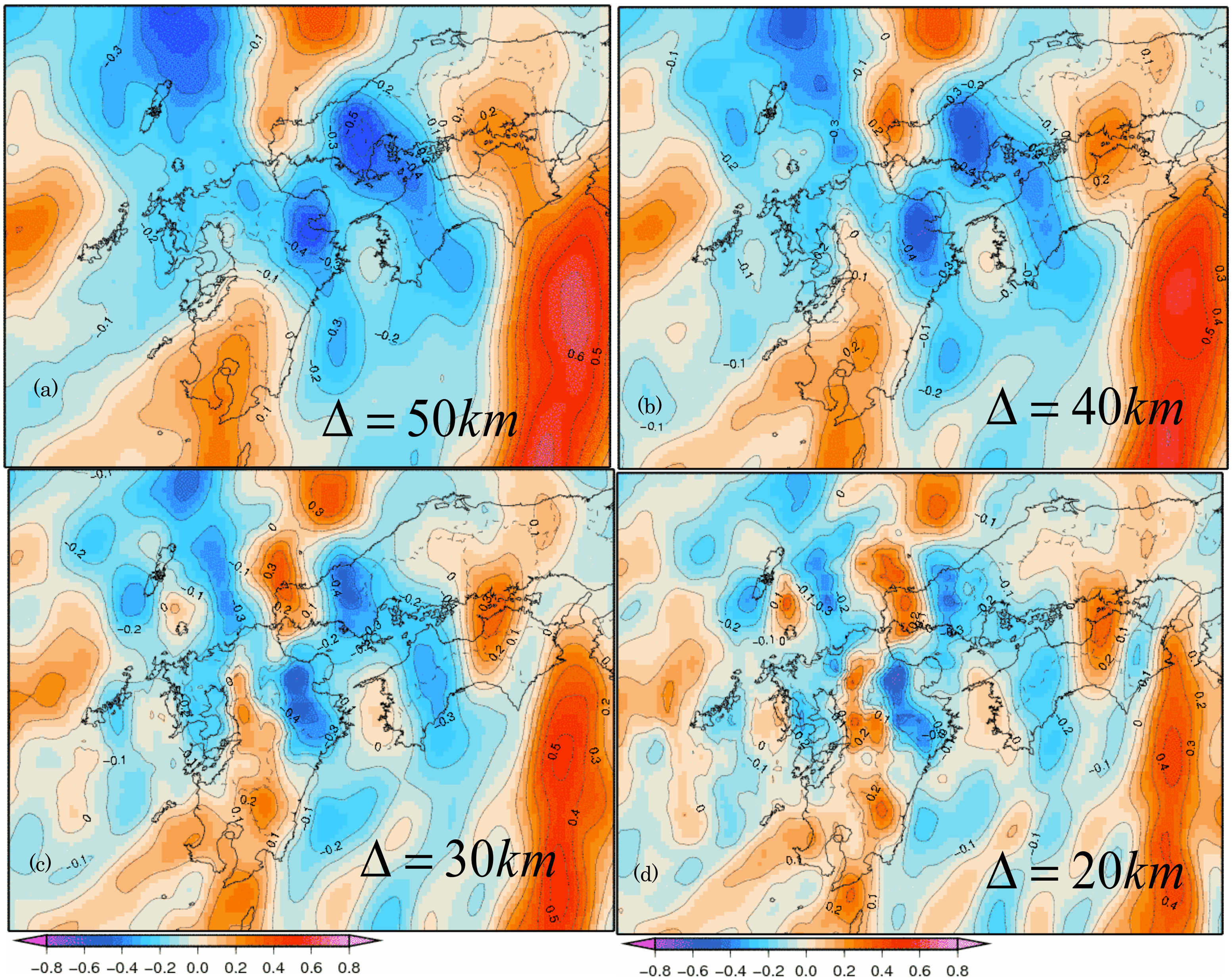
Example (5km grid spacing)

using 4 scales =>
x- and y- directions x 4 scales = 8 members

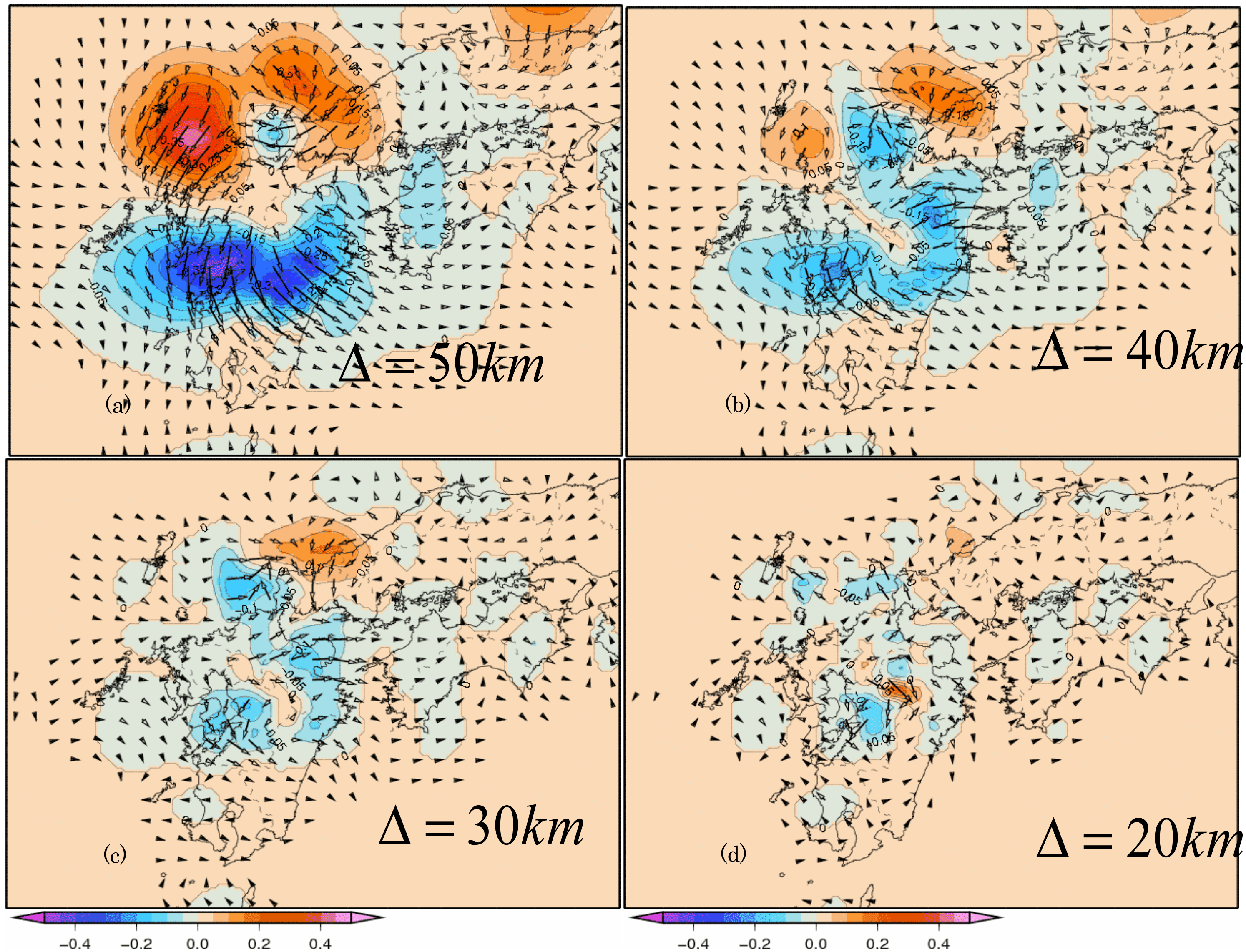
Assign independent degrees of freedom of control variable
to each scale and each direction at each grid point
=> v_pert : 8 x N_space dimensional vector

$\delta \mathbf{x}_x^{\Delta}$

Potential temperature x-displacement perturbation
25^{th} level (~ 500hPa)



Potential temperature increment, displacement vector
25^{th} level (~ 500hPa)



4 dimensional generalization of the formulation

$$J = \frac{1}{2}\mathbf{v}_0^T\mathbf{v}_0 + \frac{1}{2}\mathbf{v}_{pert}^T\mathbf{v}_{pert}$$

Liu et al. MWR 2008, 2009
Buehner et al. MWR 2009

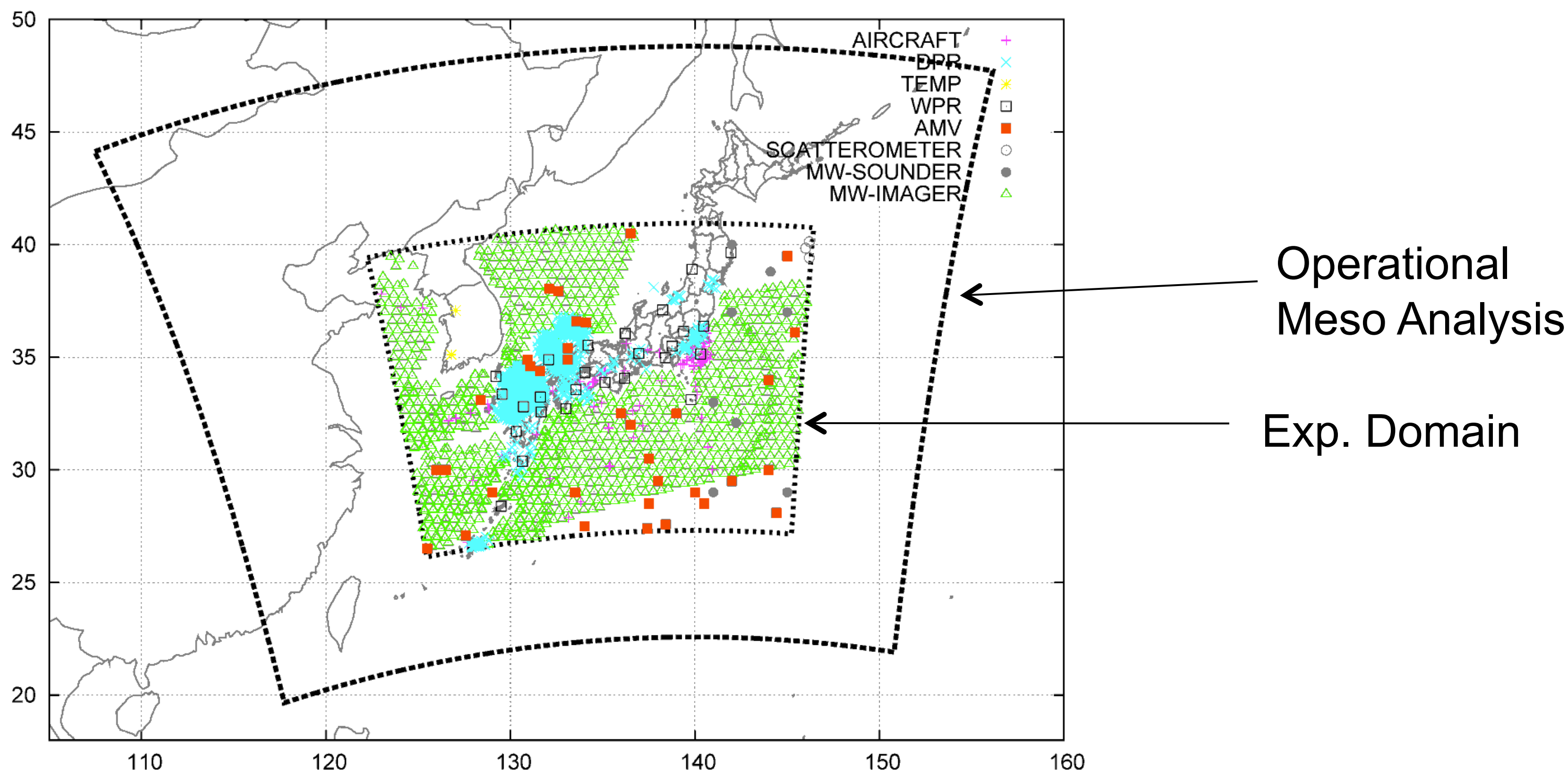
$$+\frac{1}{2}(\mathbf{y} - H(\mathbf{x}^b + \Delta\mathbf{x}))^T\mathbf{R}^{-1}(\mathbf{y} - H(\mathbf{x}^b + \Delta\mathbf{x}))$$

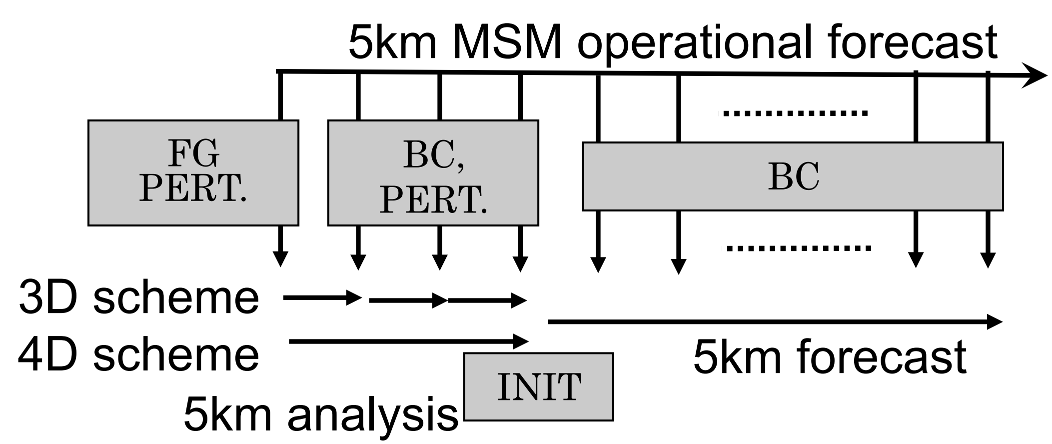
HM (replacing each H)

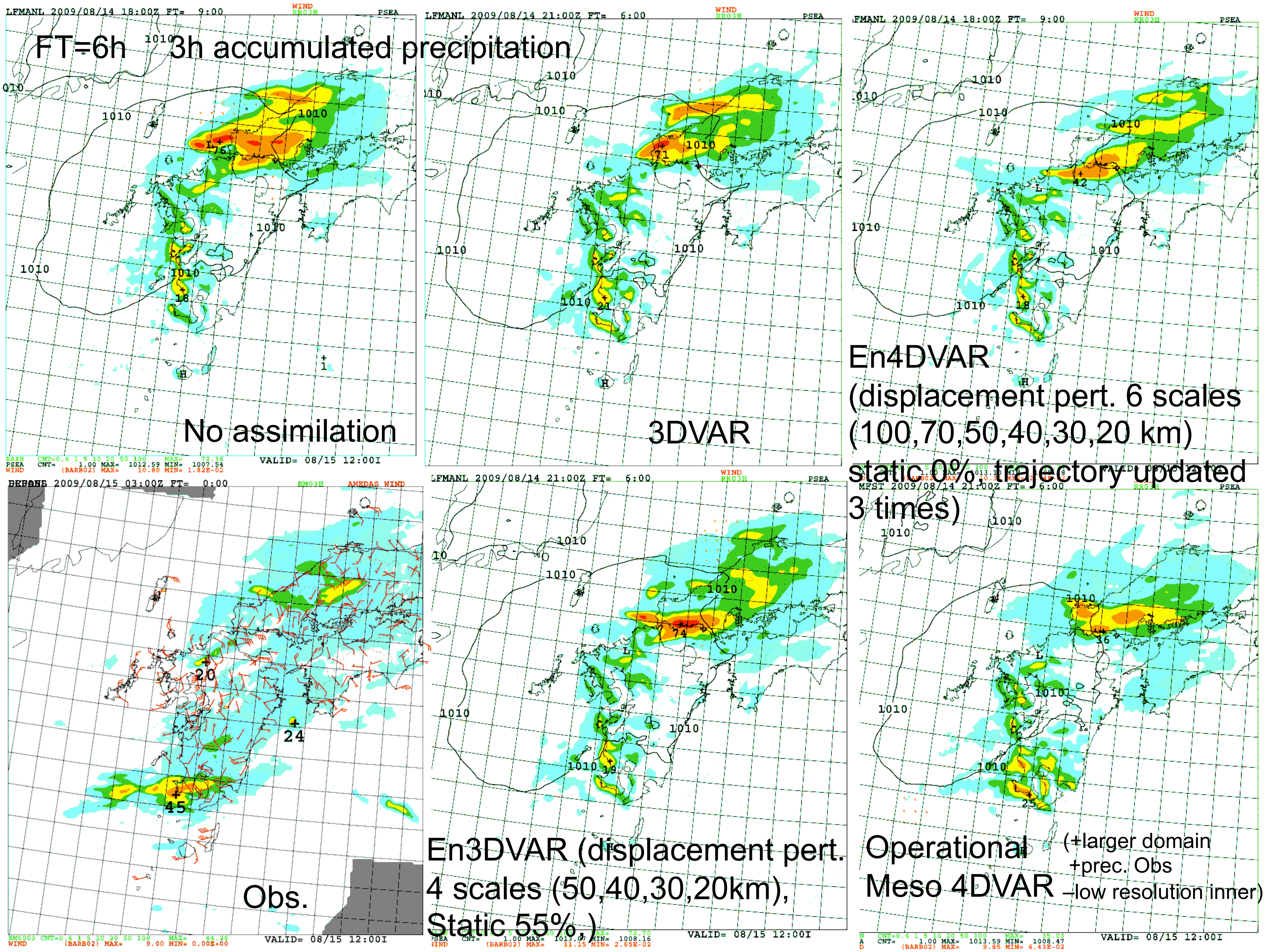
$$\mathbf{x}^b \Rightarrow M\mathbf{x}^b$$

$$\delta\mathbf{x}_x^{\Delta}(i,j,k) \Rightarrow \overline{M\mathbf{x}}_{\Delta}(i+\Delta/2,j,k) - \overline{M\mathbf{x}}_{\Delta}(i-\Delta/2,j,k)$$

Use time correlation of perturbations
Instead of tangent linear and adjoint models


AIRCRAFT
DPR
TEMP
WPR
AMV
SCATTEROMETER
MW-SOUNDER
MW-IMAGER
50
45
40
35
30
25
20
110
120
130
140
150
160
Operational
Meso Analysis
Exp. Domain


5km MSM operational forecast
FG
PERT.
BC,
PERT.
BC
3D scheme
4D scheme
5km analysis
INIT
5km forecast


FT=6h
3h accumulated precipitation
No assimilation
3DVAR
En4DVAR
(displacement pert. 6 scales
(100,70,50,40,30,20 km)
static 0%, trajectory updated
3 times)
Obs.
En3DVAR (displacement pert.
4 scales (50,40,30,20km),
Static 55%,)
Operational
Meso 4DVAR
(+larger domain
+prec. Obs
–low resolution inner)

Summary

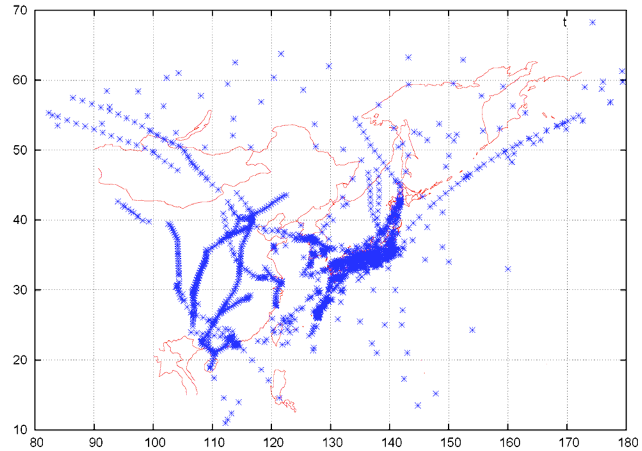
Meso scale LETKF analysis cycle system is developed. A cycle analysis experiment is performed.

Perturbations based on static B from Var. are tested in LETKF.
May work to make analysis similar to 4DVAR.
(may help spin-up of analysis cycle,
may mitigate influence of model error)

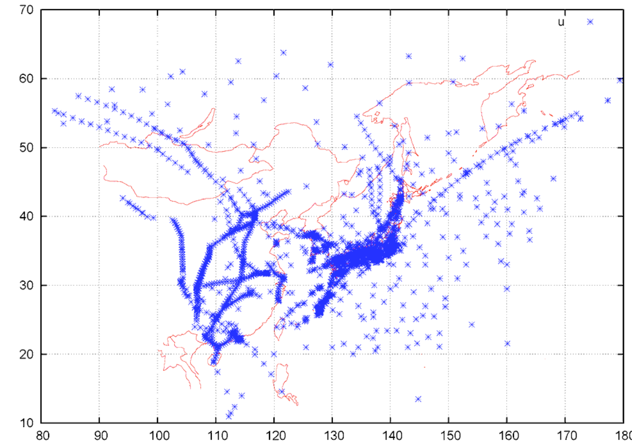
Property of ensemble perturbations is important in LETKF.
possibility of designing perturbations with different features (static/ flow-dep., different scales)

25 Aug. 2008 00-03UTC observations

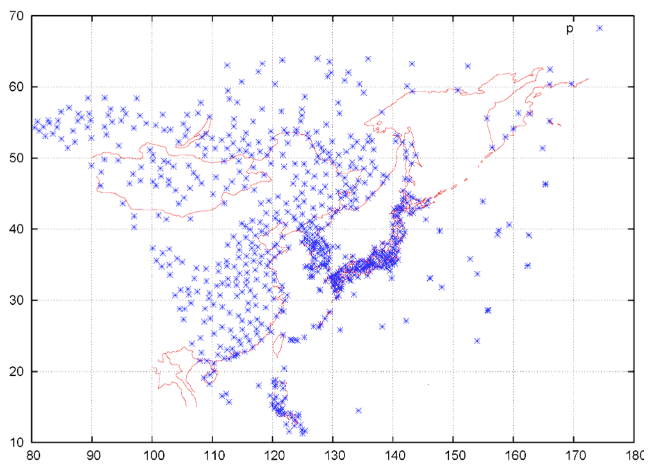
T



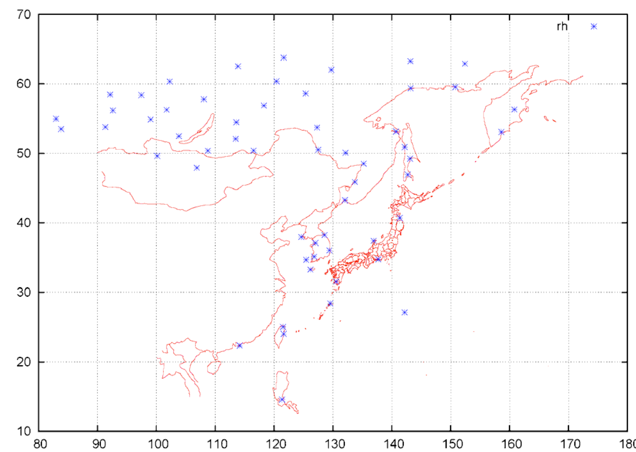
U



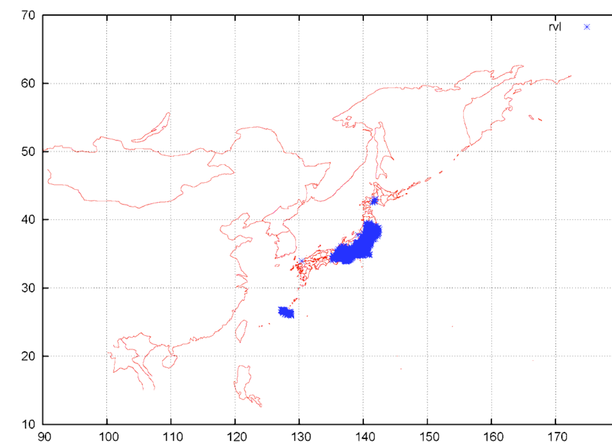
P

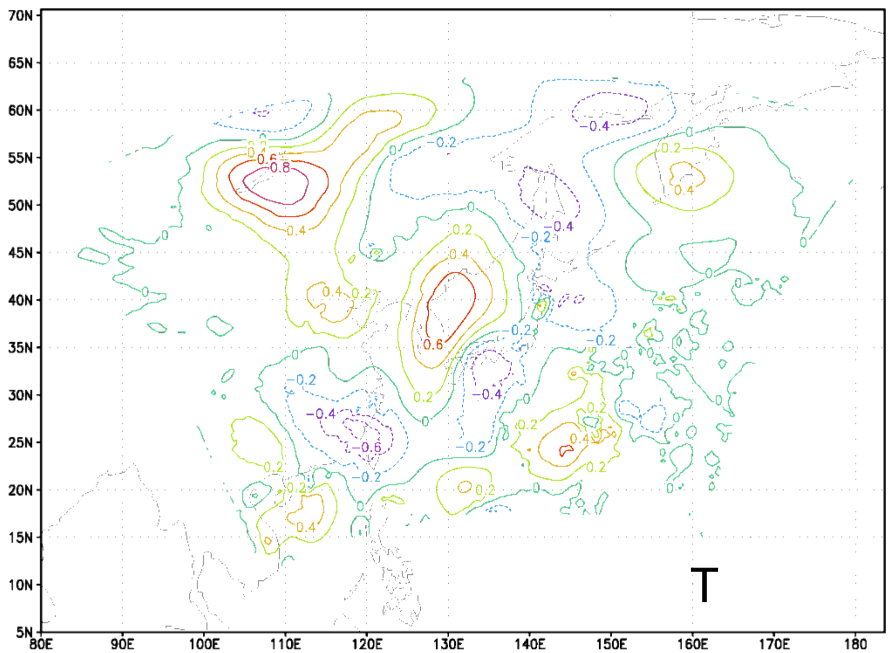


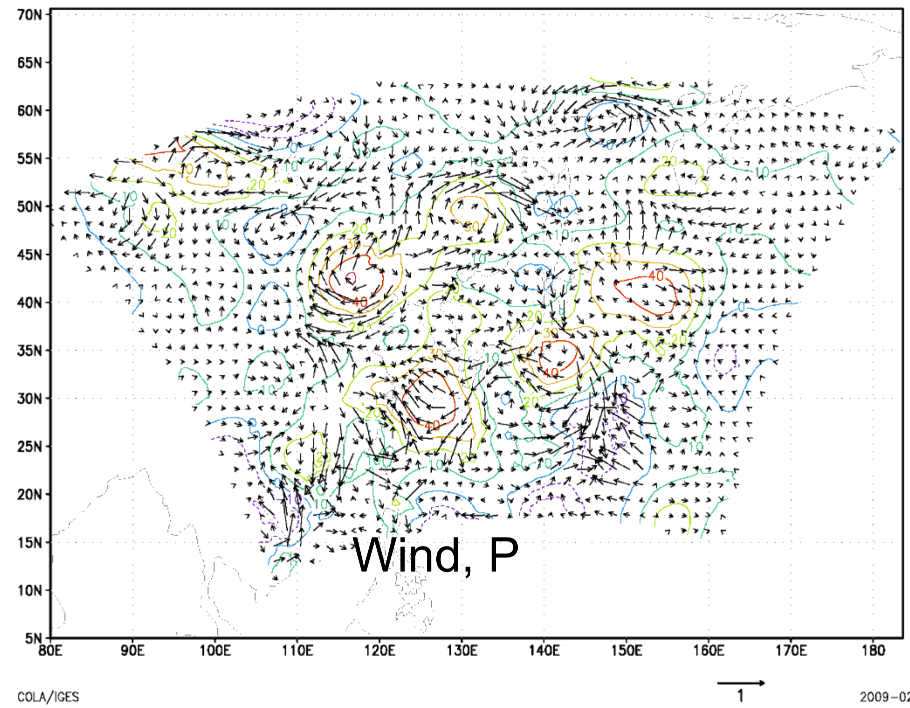
RH

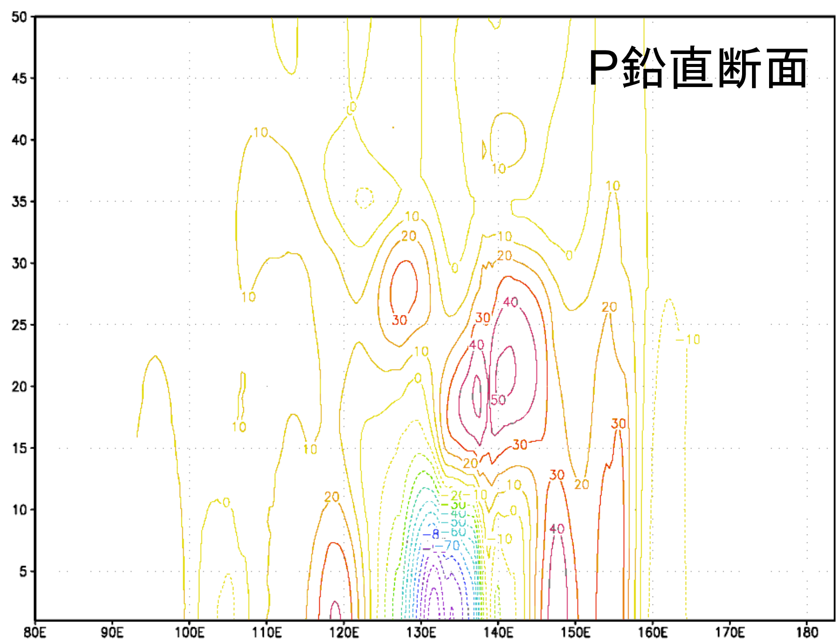


RVL



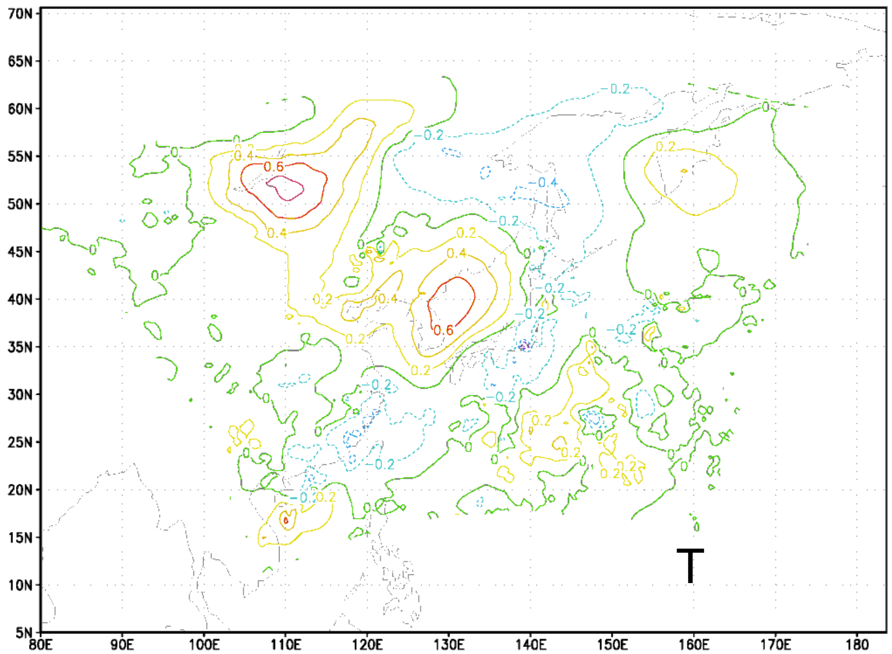


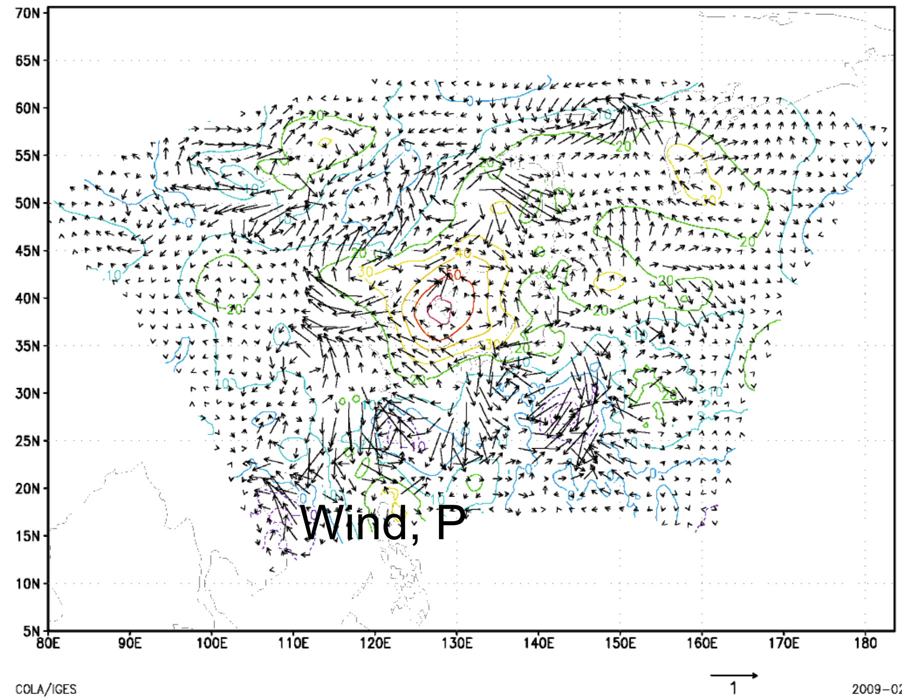


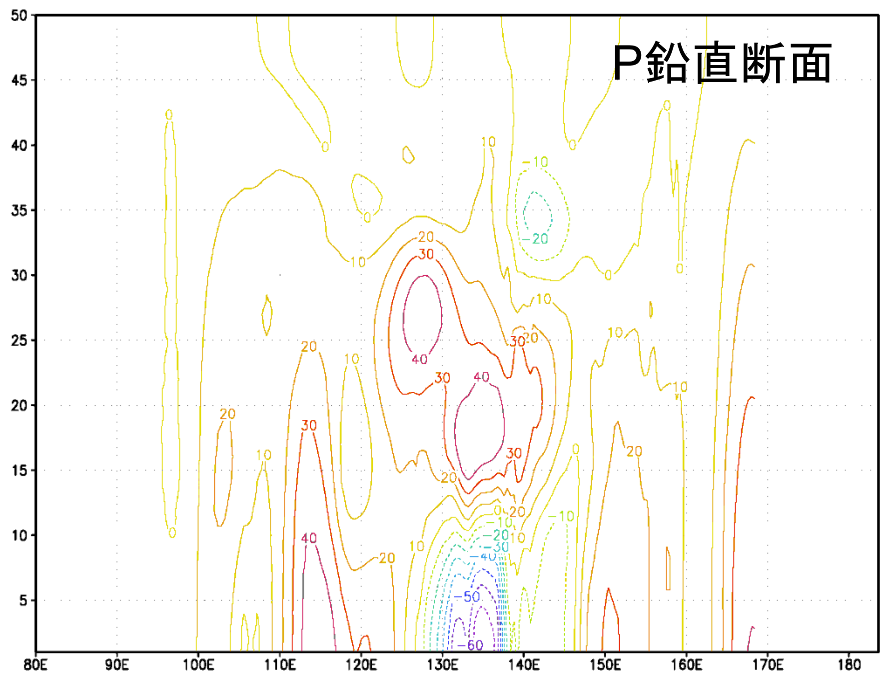


あるメンバーの摂動の時間発展（25層）

FT=1

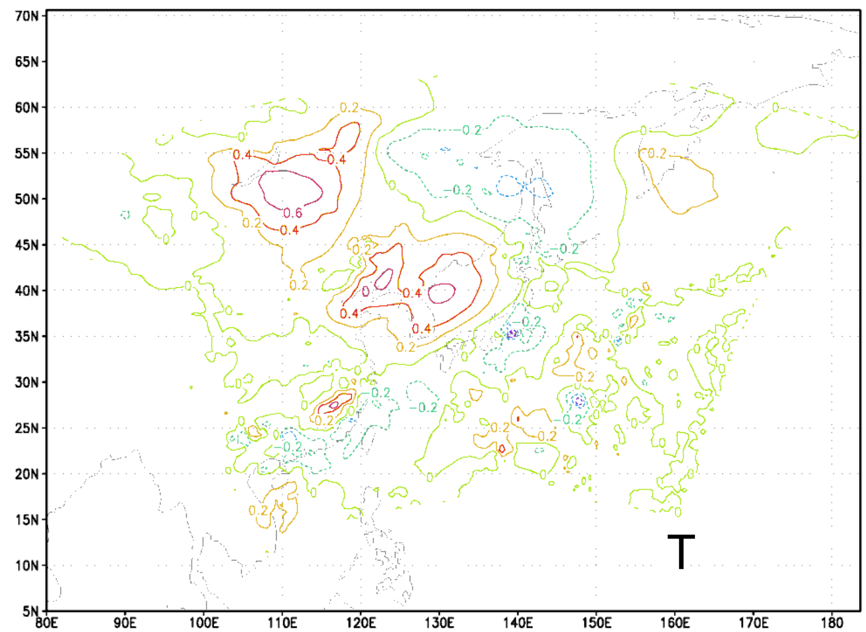


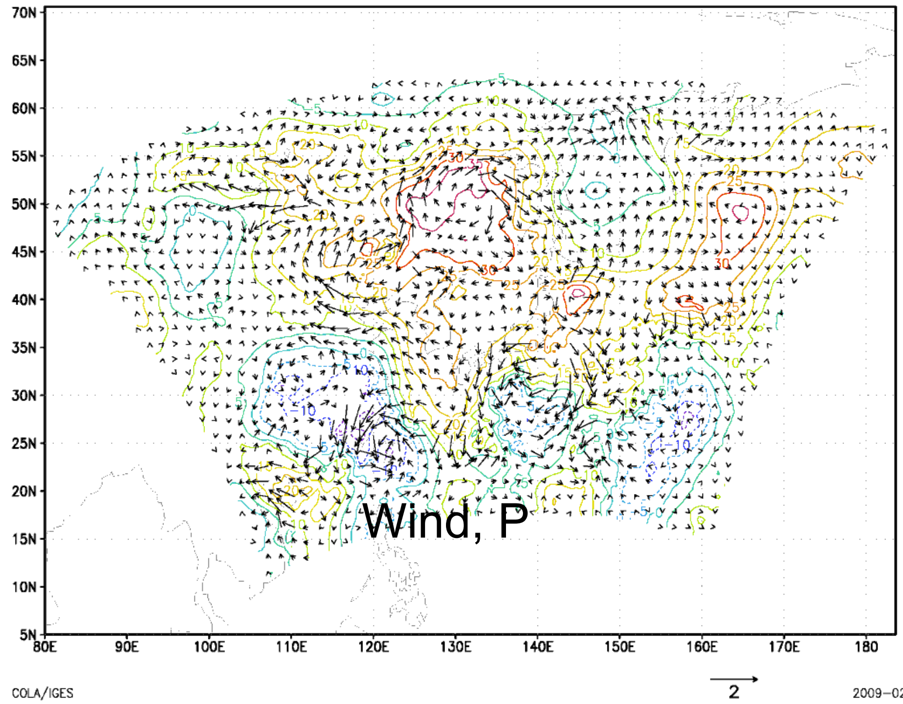


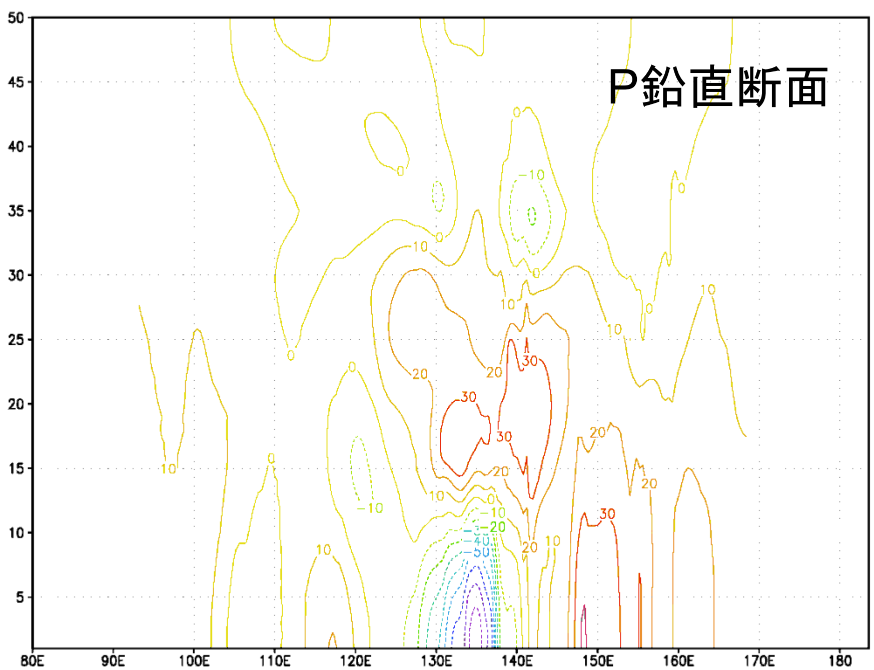


あるメンバーの摂動の時間発展（25層）

FT=2







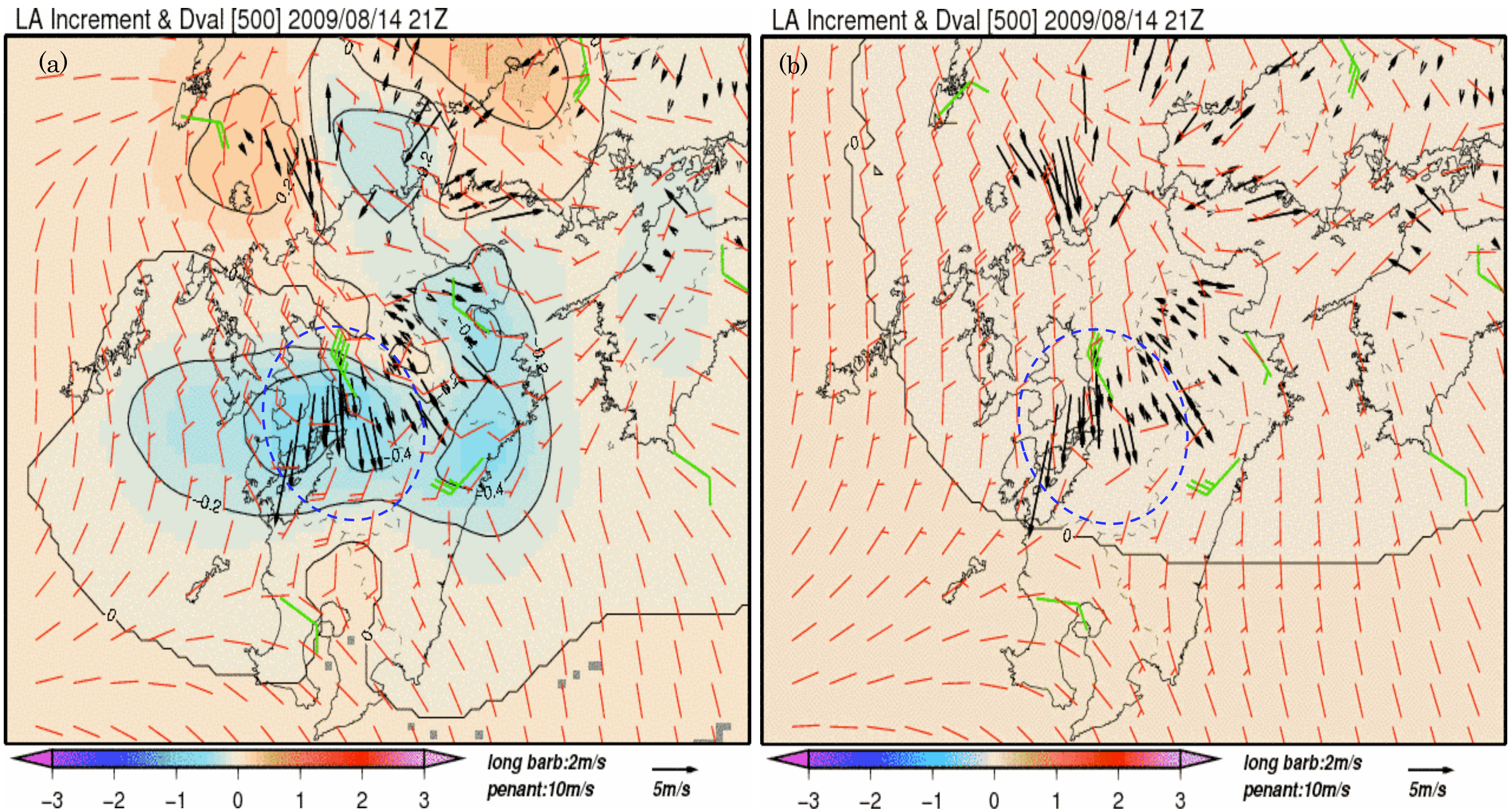
あるメンバーの摂動の時間発展（25層）

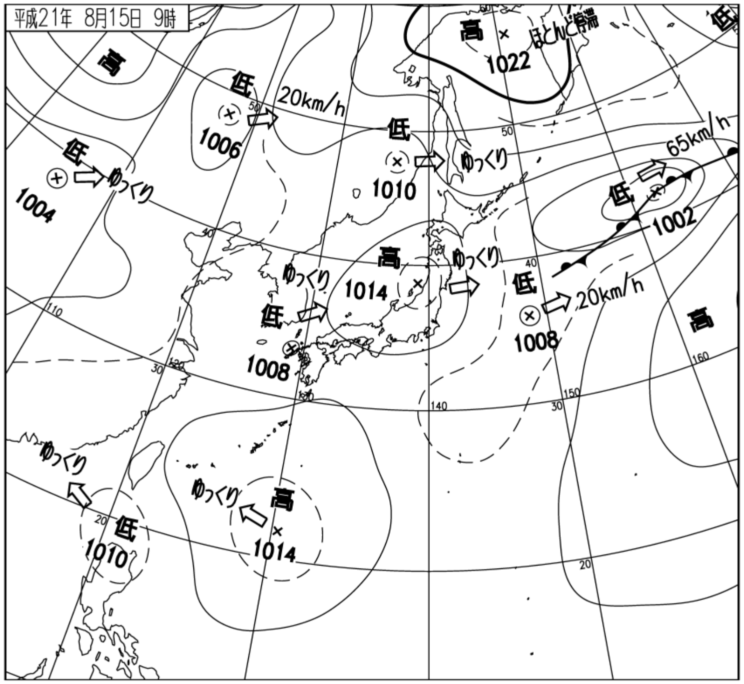
FT=3

Temperature and wind analysis increment (500hPa)

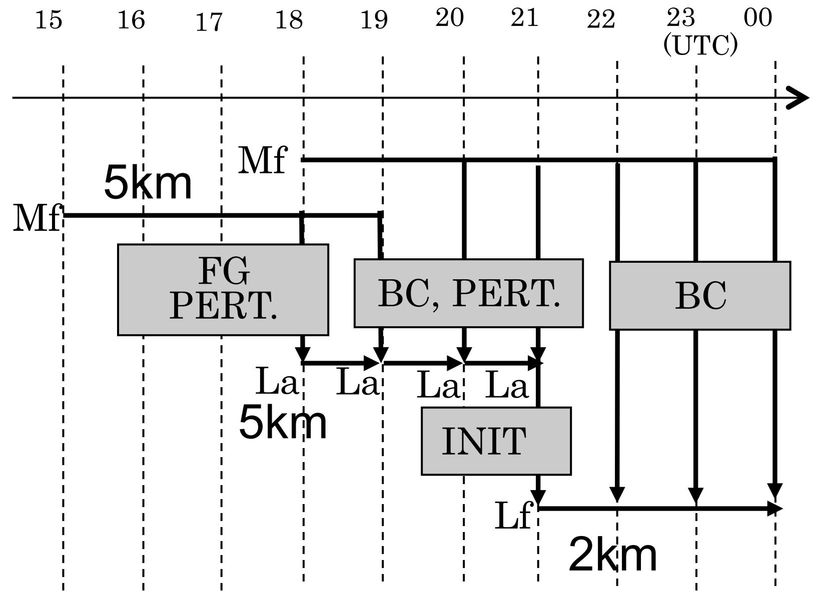
3DVAR
With perturbation

3DVAR
Without perturbation





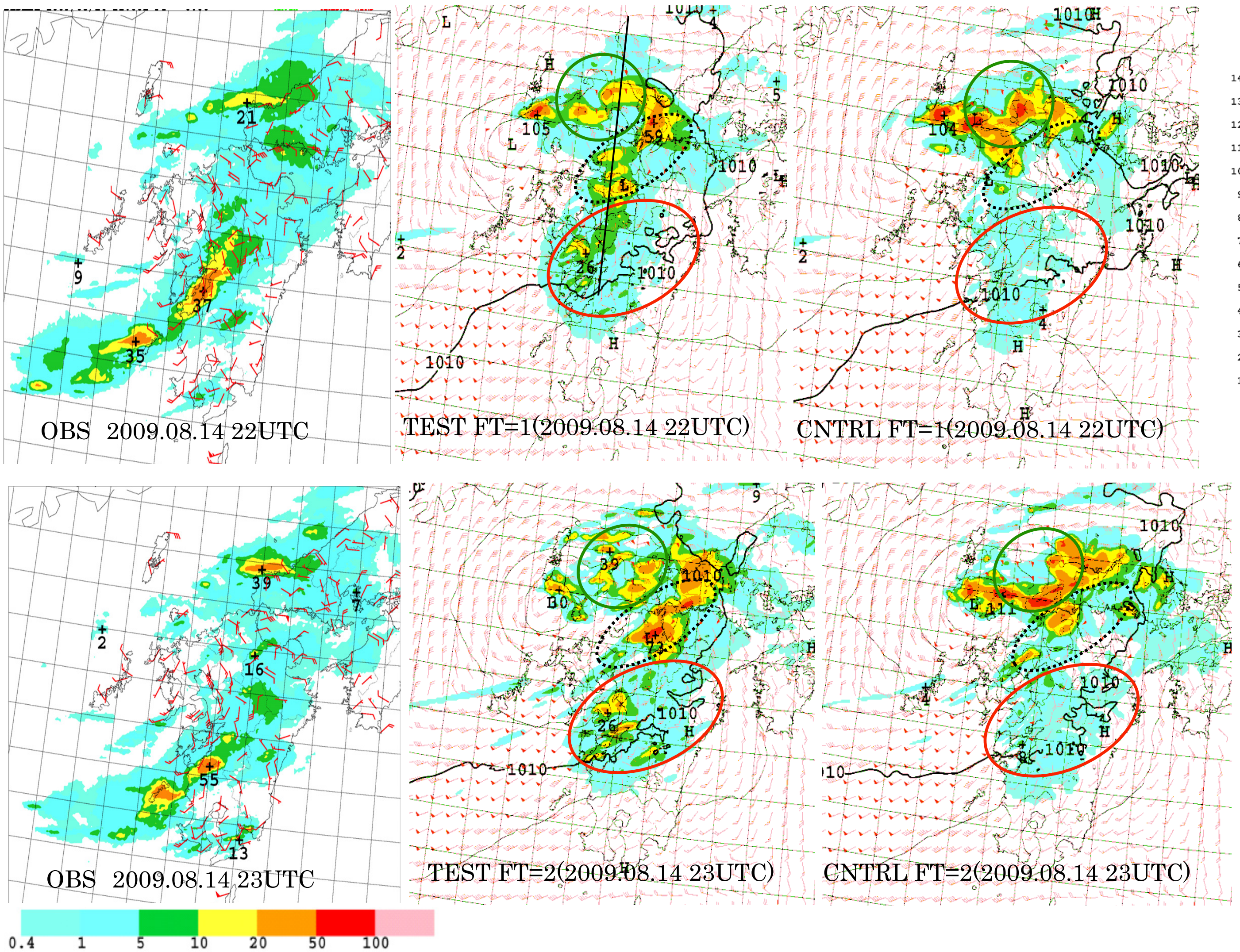
15 Aug. 2009, 00UTC

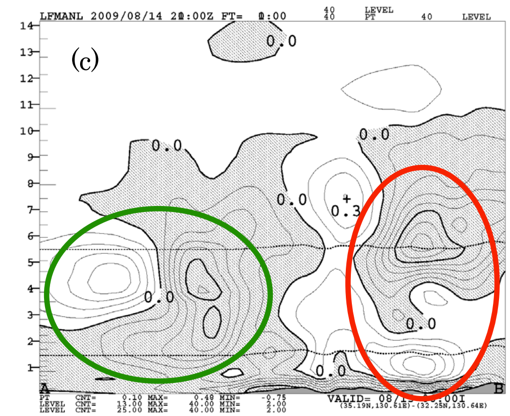


2km forecast from the analysis (1h precipitation)

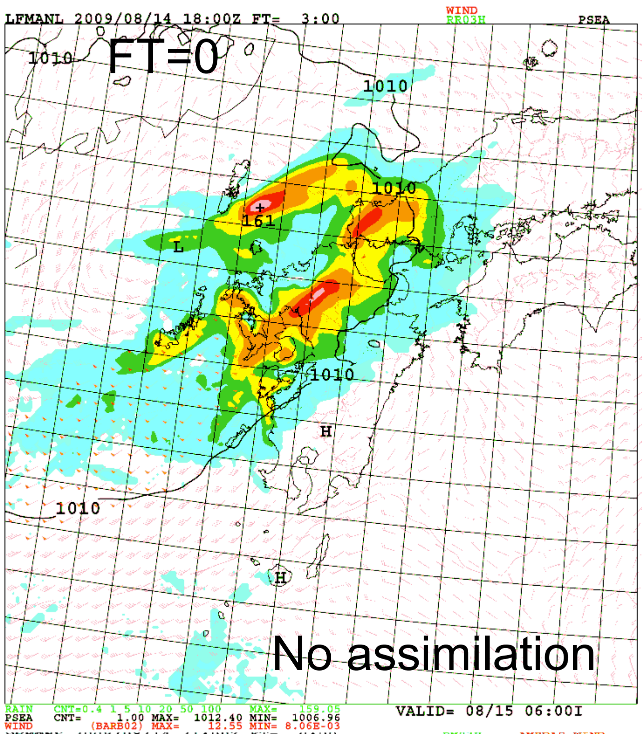
With perturbation

w/o perturbation

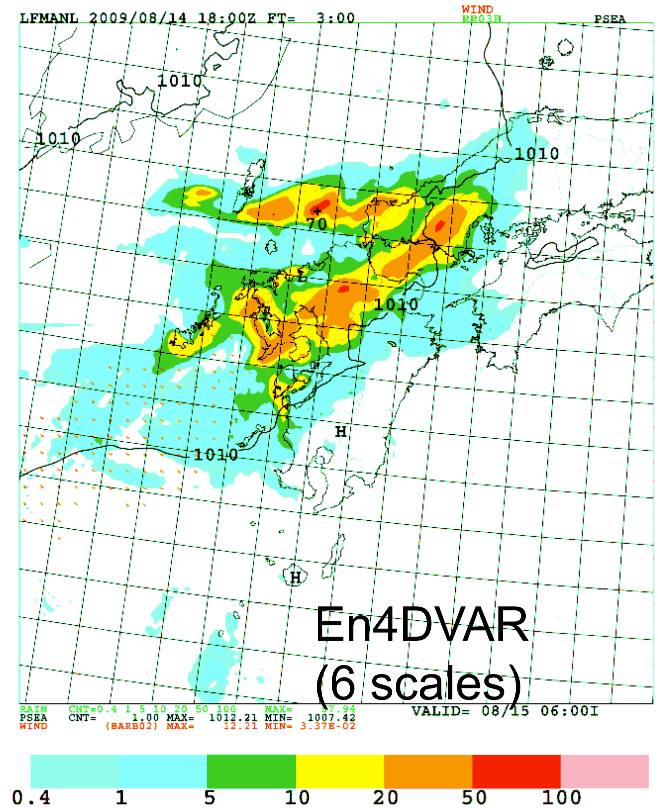


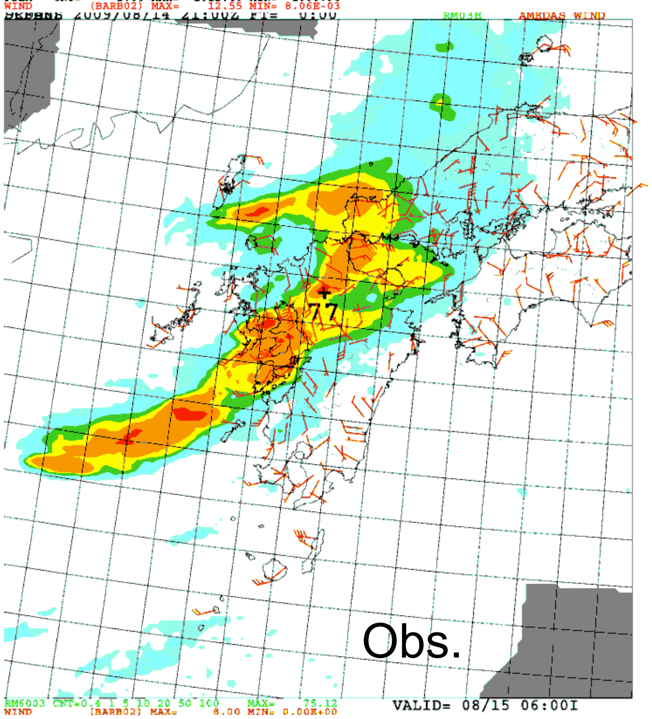


Potential temperature increment vertical cross section
(contoured every 0.1K, Shaded: negative)



3DVAR

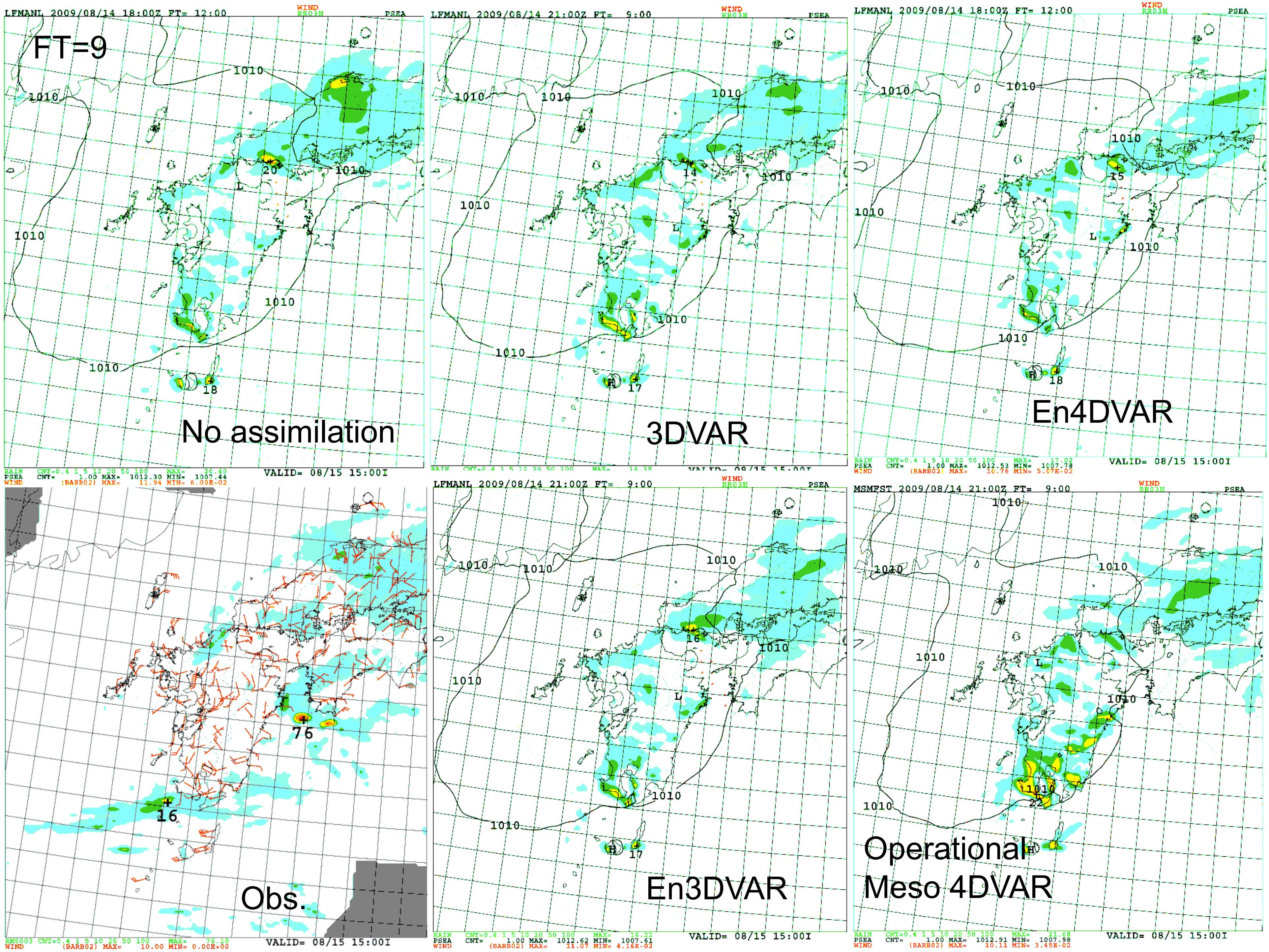




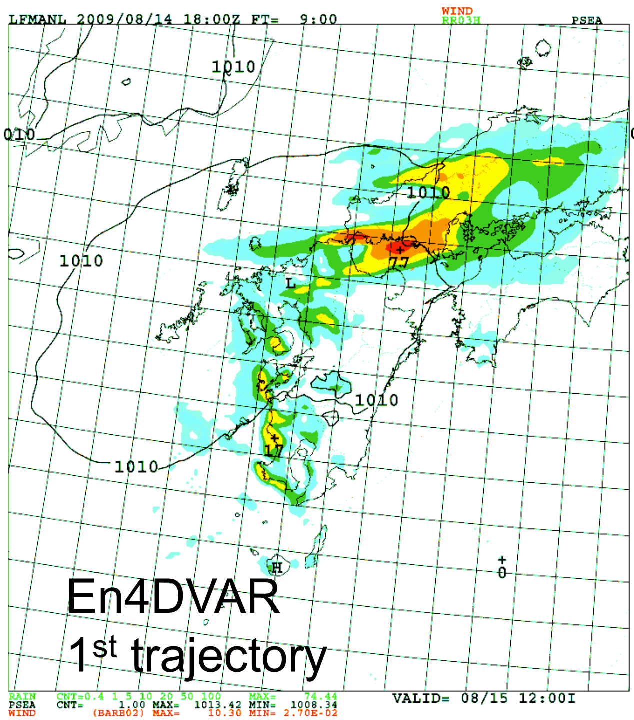
En3DVAR
Static 55%,
4 scales

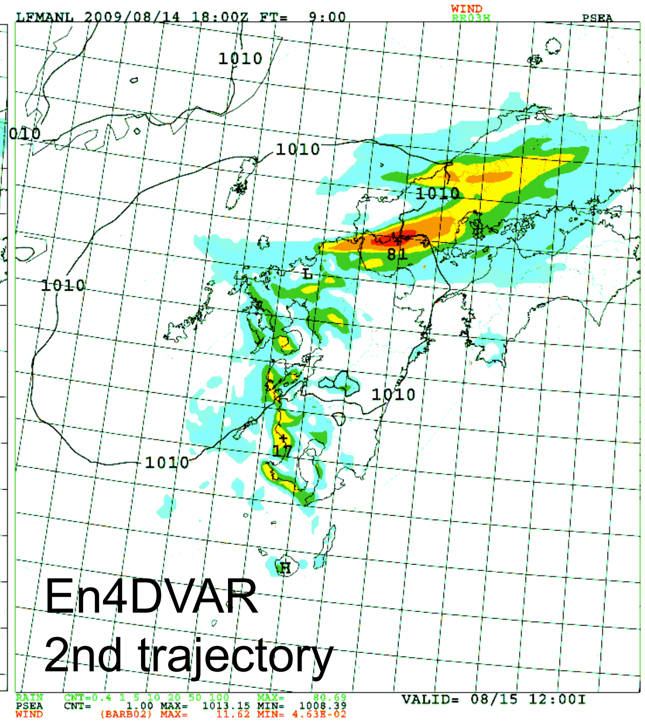
Operational
Meso 4DVAR

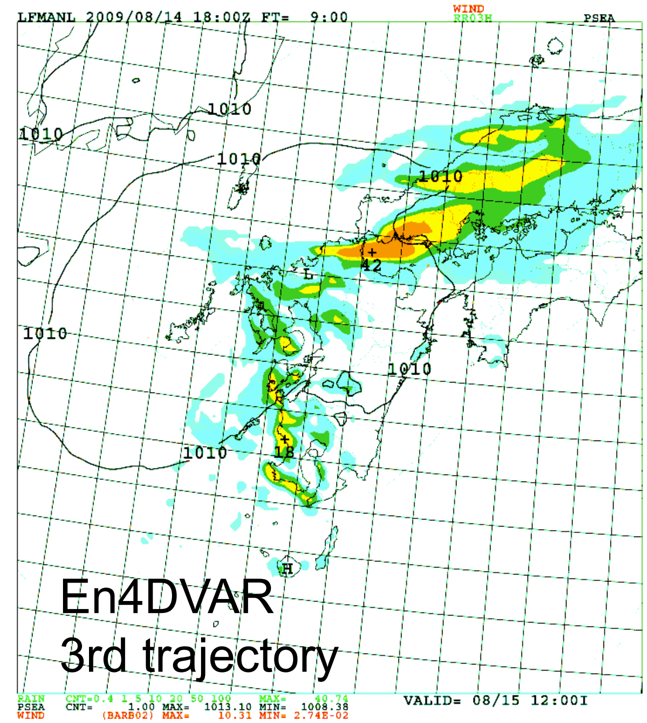
(+larger domain
+prec., Ps Obs
–low resolution inner)



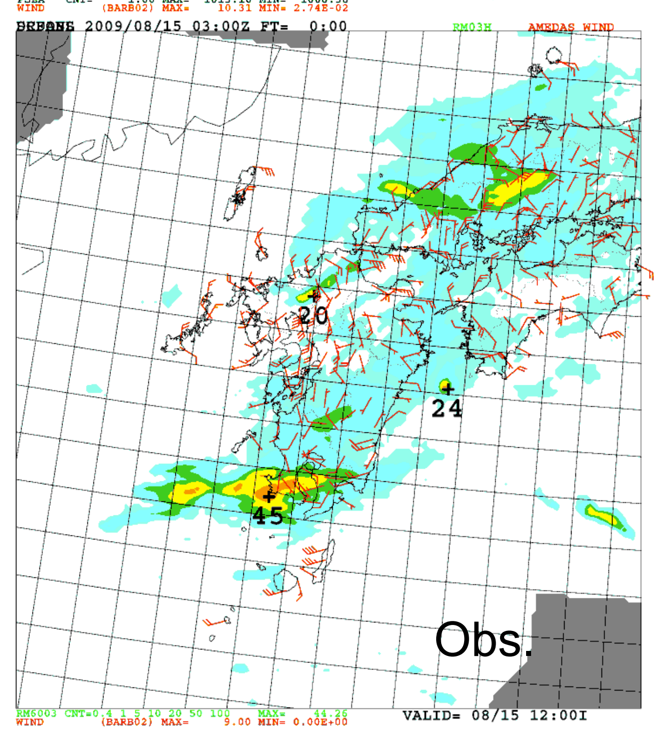
FT=9
LFMANL 2009/08/14 18:00Z FT= 12:00
No assimilation
LFMANL 2009/08/14 21:00Z FT= 9:00
3DVAR
LFMANL 2009/08/14 18:00Z FT= 12:00
En4DVAR
Obs.
LFMANL 2009/08/14 21:00Z FT= 9:00
En3DVAR
MSMFST 2009/08/14 21:00Z FT= 9:00
Operational
Meso 4DVAR
VALID= 08/15 15:00I

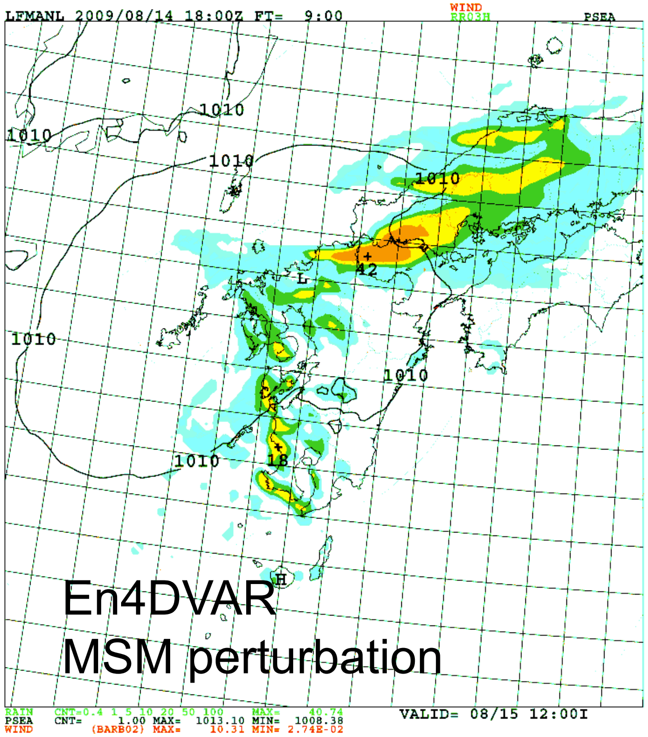


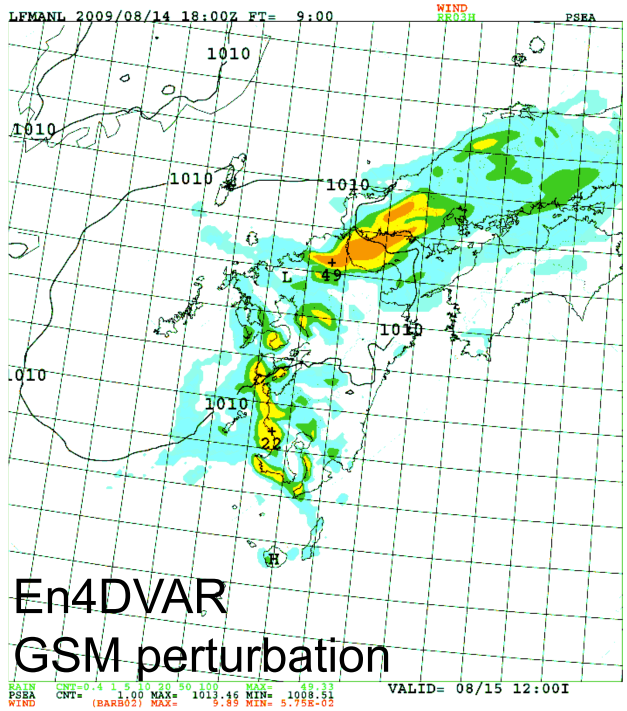


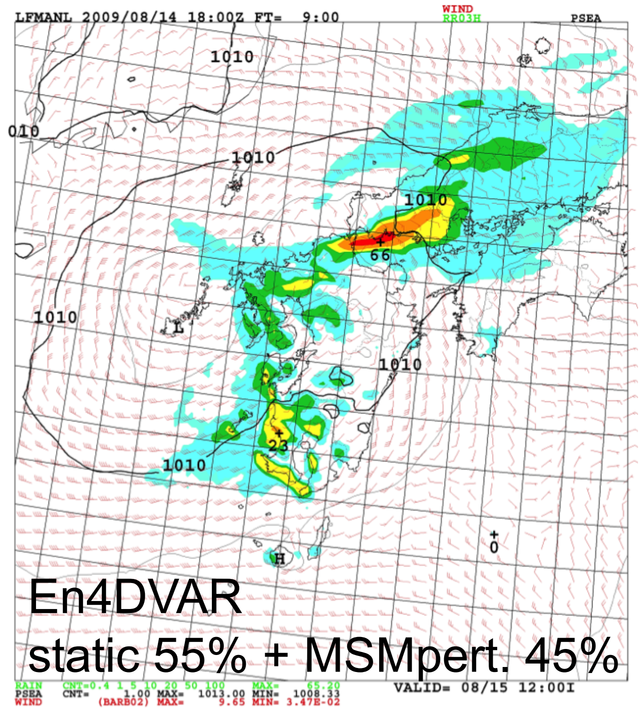


Effect of updating trajectory



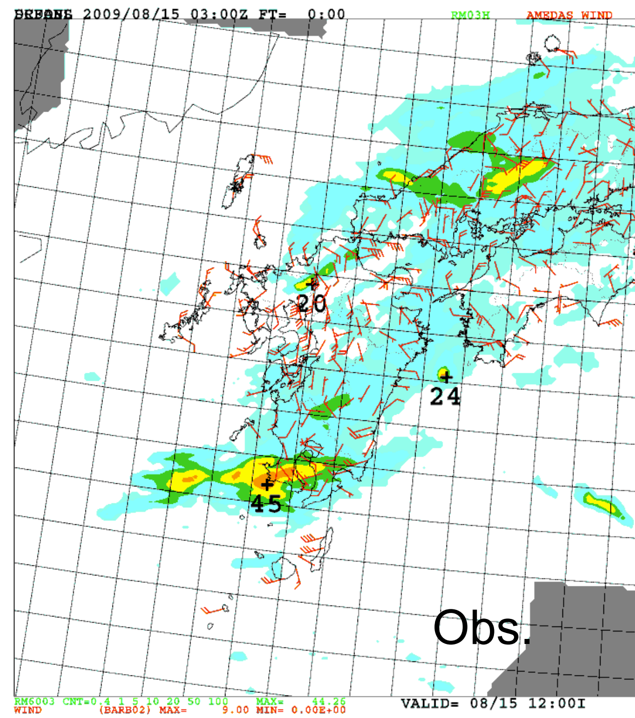






Using different perturbations

MSM: operational mesoscale model (JMANHM)
GSM: operational global model



summary

Perturbations with information of uncertainties in different scales are tried in variational method.
3d and 4d versions are implemented.
Independent control variable is assigned to each scale.
Localization scale is specified according to the displacement scale of each perturbation.

Perturbations are designed to represent displacement error.
Low cost method to represent flow-dependent background error with small ensemble size.

Possibility of construct an ensemble with En4DVARs with different perturbation design. (different trajectories, different weights on static B, etc.)