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Fall Colloquium on the Physics of Weather and Climate: Regional Weather Predictability and Modelling

29 September - 10 October, 2008

Maximum Likelihood Ensemble Filter. II

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Lecture 2: Maximum Likelihood Ensemble Filter

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Fall Colloquium on the Physics of Weather and Climate: Regional Weather Predictability and Modelling
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OUTLINE

Lecture 2:

- Maximum Likelihood Ensemble Filter (MLEF)
- Discussions of the results from the Lab exercises
- Results of more complex data assimilation experiemnts

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MLEF equations ⇒ results

Analysis step:

Analysis solution x_a obtained by minimizing the cost function

$$J = \frac{1}{2}[\boldsymbol{x} - \boldsymbol{x}_b]^T \boldsymbol{P}_f^{-1}[\boldsymbol{x} - \boldsymbol{x}_b] + \frac{1}{2}[H(\boldsymbol{x}) - \boldsymbol{y}]^T \boldsymbol{R}^{-1}[H(\boldsymbol{x}) - \boldsymbol{y}]$$

../MLEF_test/current/totcost.${icycle}

Analysis error covariance in ensemble subspace:

$$\left(\boldsymbol{P}_a\right)^{1/2} = \boldsymbol{P}_f^{1/2}\left[\boldsymbol{I} + \left(\boldsymbol{Z}(\boldsymbol{x}_a)\right)^T \boldsymbol{Z}(\boldsymbol{x}_a)\right]^{-1/2}$$

$$\boldsymbol{Z}(\boldsymbol{x}) = \left[\boldsymbol{z}_1(\boldsymbol{x}) \quad \boldsymbol{z}_2(\boldsymbol{x}) \quad \cdot \quad \cdot \quad \boldsymbol{z}_{Nens}(\boldsymbol{x})\right] \; ; \; \boldsymbol{z}_i(\boldsymbol{x}) = \boldsymbol{R}^{-1/2}\left[H(\boldsymbol{x} + \boldsymbol{p}_i^f) - H(\boldsymbol{x})\right]$$

$$\boldsymbol{P}_a = \left(\boldsymbol{P}_a\right)^{1/2}\left[\left(\boldsymbol{P}_a\right)^{1/2}\right]^T$$

../MLEF_test/cycle${icycle}/covPa.gif

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MLEF equations ⇒ results

Forecast step:

Ensemble forecasts employing a **non-linear** model M

$$\boldsymbol{x}_n^j = M_{n,n-1}(\boldsymbol{x}_{n-1}^j)$$

Non-linear ensemble forecast perturbations

$$p_f^i = M(\boldsymbol{x}_a + p_a^i) - M(\boldsymbol{x}_a)$$

Forecast error covariance calculated using ensemble perturbations:

$$\left(\boldsymbol{P}_f\right)^{1/2} = \left[p_f^1 \quad p_f^2 \quad . \quad p_f^{Nens} \right]$$

$$\boldsymbol{P}_f = \left(\boldsymbol{P}_f\right)^{1/2} \left[\left(\boldsymbol{P}_f\right)^{1/2} \right]^{\boldsymbol{T}}$$

← ../MLEF_test/cycle${icycle}/covPf.gif

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MLEF equations ⇒ results

$$Z(x) = \left[z_1(x) \quad z_2(x) \quad \cdot \quad \cdot \quad z_{Nens}(x) \right] \; ; \; z_i(x) = R^{-1/2} \left[H(x + p_i^f) - H(x) \right]$$

$$A = Z^T Z$$

A - information matrix in ensemble subspace of dim *Nens* x *Nens*

Degrees of freedom (DOF) for signal (*Rodgers 2000, Zupanski et al. 2007*):

$$d_s = tr[(I + \mathbf{A})^{-1} \mathbf{A}] = \sum_i \frac{\lambda_i^2}{(1 + \lambda_i^2)}$$

λ_i^2 - eigenvalues of A

../MLEF_test/current/entropy_A.${icycle}

Errors are assumed Gaussian in these measures.

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Where to find more results

../MLEF_test/work - this is the directory where MLEF works
(files are not saved here)

You can do the following in this directory:
ls -ltr *.err (to see if there are error files with some error messages)

Also, you can see the outputs of each executable. These outputs have names like this:
name_of_executable.out

Where to find more results

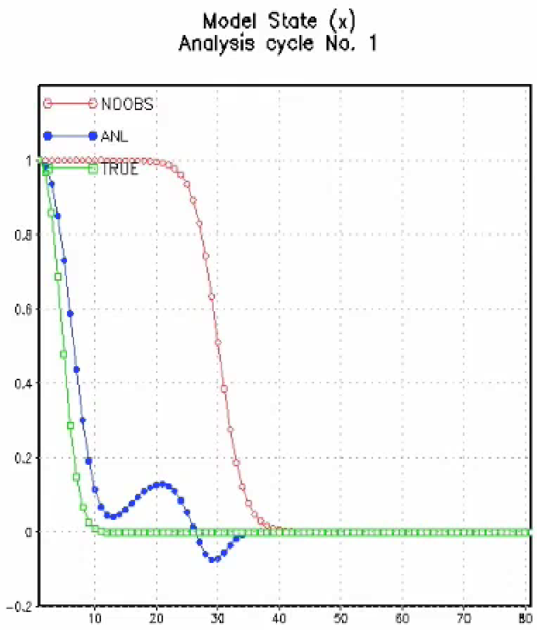
../MLEF_test - this is the directory where MLEF results are saved

Subdirectory **current** includes some summary results. Check these files:
rms_analysis (analysis errors, listed for all cycles)
rms_background (background errors of all cycles)
rms_noobs (rms errors of the experiment without data assimilation)
These rms errors are also plotted in the file **rms.gif**
evd_A.${icycle} (eigenvalues of the information matrix A)

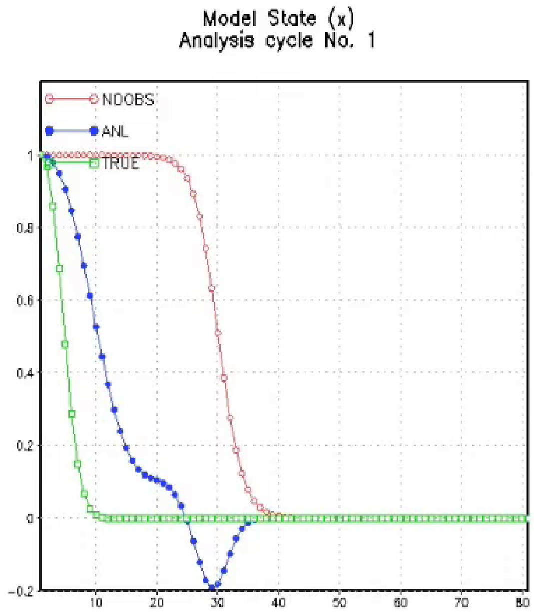
Subdirectories **cycle${icycle}** include results of specific data assimilation cycles. Check these files:
covPa.gif (analysis error covariance)
covPa.gif (forecast error covariance)
state.gif (x_a, x_b and x_{noobs} plotted in each grid point. There are 81 grid points)
state_error.gif (errors of x_a, x_b and x_{noobs} in each grid point)

MLEF vs 3d-var
model state x_{true} , x_a, and x_{noobs}
(Burgers model results from the Lab exercise)

MLEF



3d-var

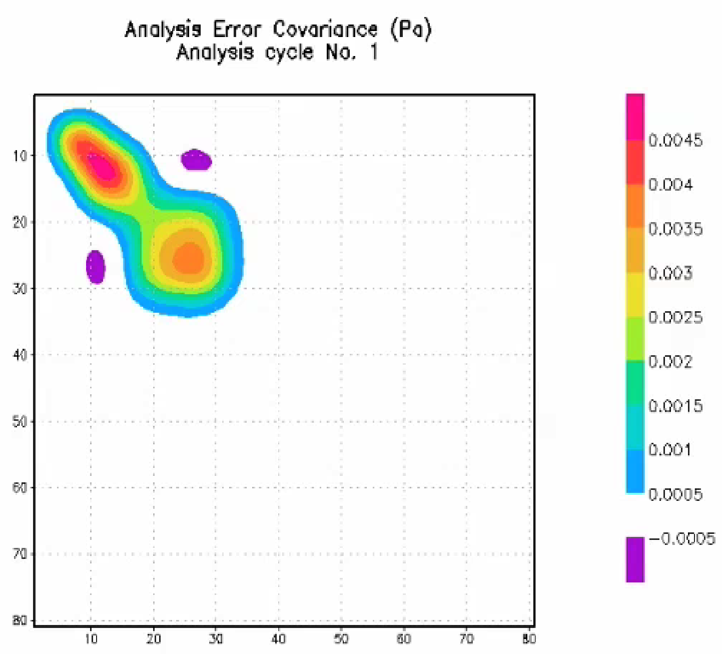


MLEF analysis becomes almost identical to the truth after first several cycles!

3d-var analysis does not improve with time.

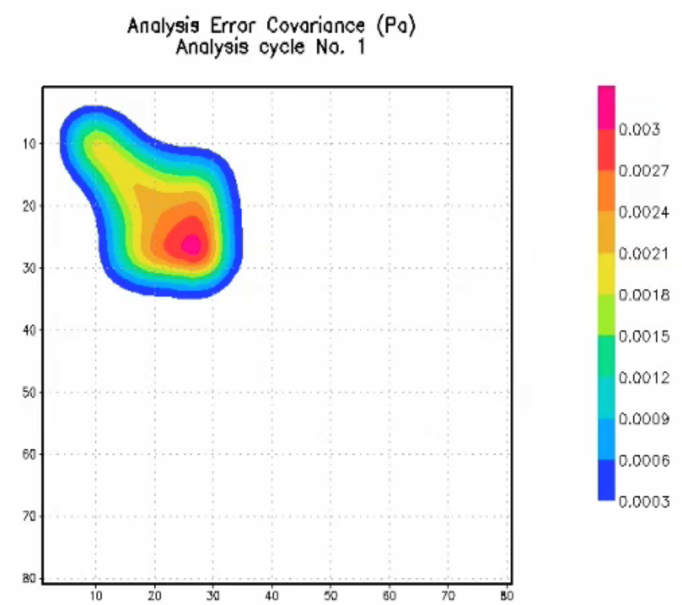
MLEF vs 3d-var
(P_a)

MLEF



P_a is flow-dependent

3d-var



P_a is NOT flow-dependent

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Applications of the MLEF

- **Low-dimensional models (state vector dimension up to 10^4)**
  - *Korteweg de Vries - Burgers (KdVB) model* - solitons
  - ***Burgers model* - shock wave, advection, diffusion (our lab exercise)**
  - *Shallow-water models* - Rossby-Haurwitz, mountain interaction, gravity waves
  - *NASA GEOS-5 Single-Column Model* - precipitation, moisture
  - *Lorenz models* (*3-variable* (1963) and *40-variable* (1996)) - nonlinear/chaotic regimes
- **High-dimensional, complex, multi-scale models (state vector dimension of 10^5-10^7)**
  - *Weather Research and Forecasting (WRF) regional model* - hurricanes, precipitation, clouds
  - *NASA GEOS-5 Atmospheric Global Circulation Model* - precipitation, moisture (*Smoother*)
  - *NASA Global Cumulus Ensemble (GCE) model* - cloud microphysics
  - *NCEP GFS global atmospheric model* (NOAA operational weather model)
  - *RAMS (Colorado State University) as a Large Eddy Simulation (LES) regional model* - arctic boundary layer clouds
  - *Parameterized Chemistry Transport Model (PCTM)* - carbon
- **Observations**
  - *NOAA NCEP operational meteorological observations* (conventional, satellite, radar)
  - *NASA forward operators for TRMM and future Global Precipitation Mission (GPM) satellites*
  - *NCAR upper-air and surface observations*
  - *Ice and liquid water path* - SHEEBA experiment in Arctic
- **We have not applied the MLEF to the Eta model yet, but we plan to do it in the near future**

Some results from complex MLEF applications

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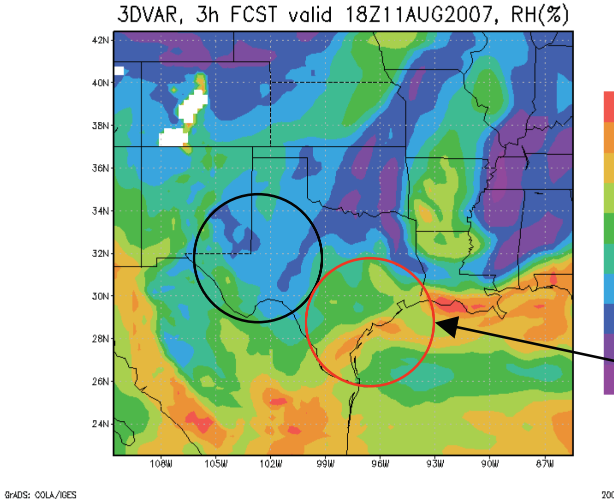
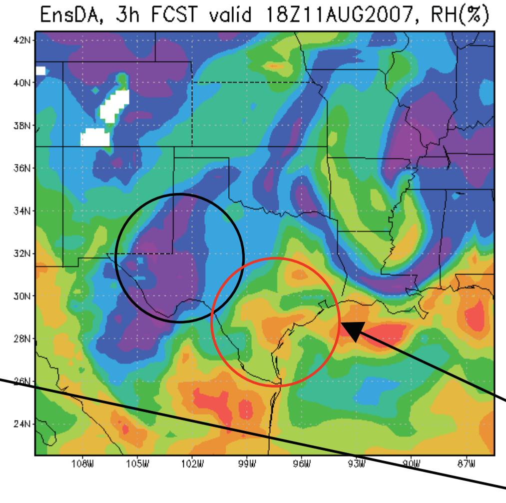
Assimilation of NCEP conventional observations
MLEF+WRF

Comparison between the MLEF and the GSI (Gridpoint Statistical Interpolation). Results of 3-h forecasts after data assimilation (valid at 1800 Z 11 AUG 2007) are shown for relative humidity.

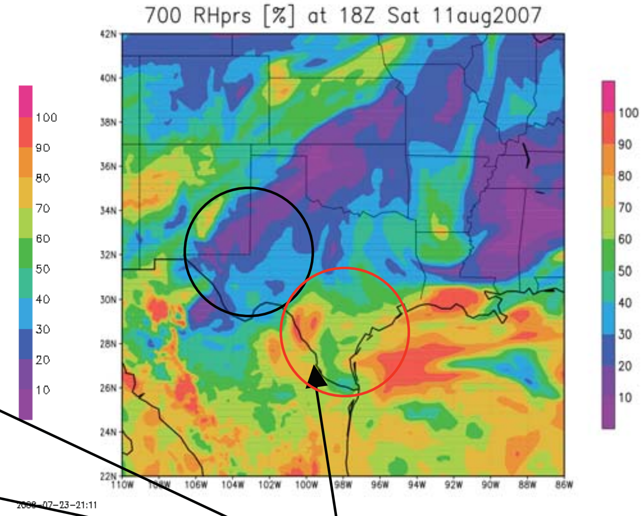
GSI + 3h FCST (30km) CONTROL



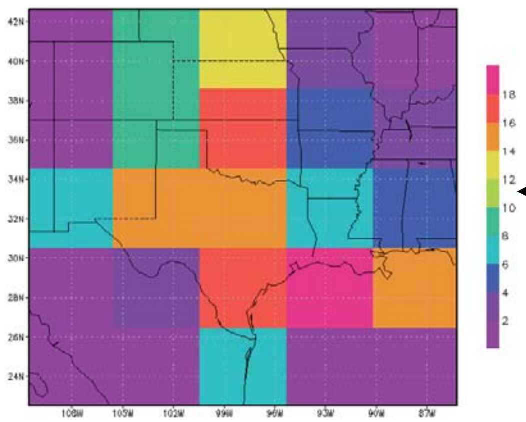
MLEF + 3h FCST (30km)



VERIFICATION (12km)



Deg. of Freedom for Signal

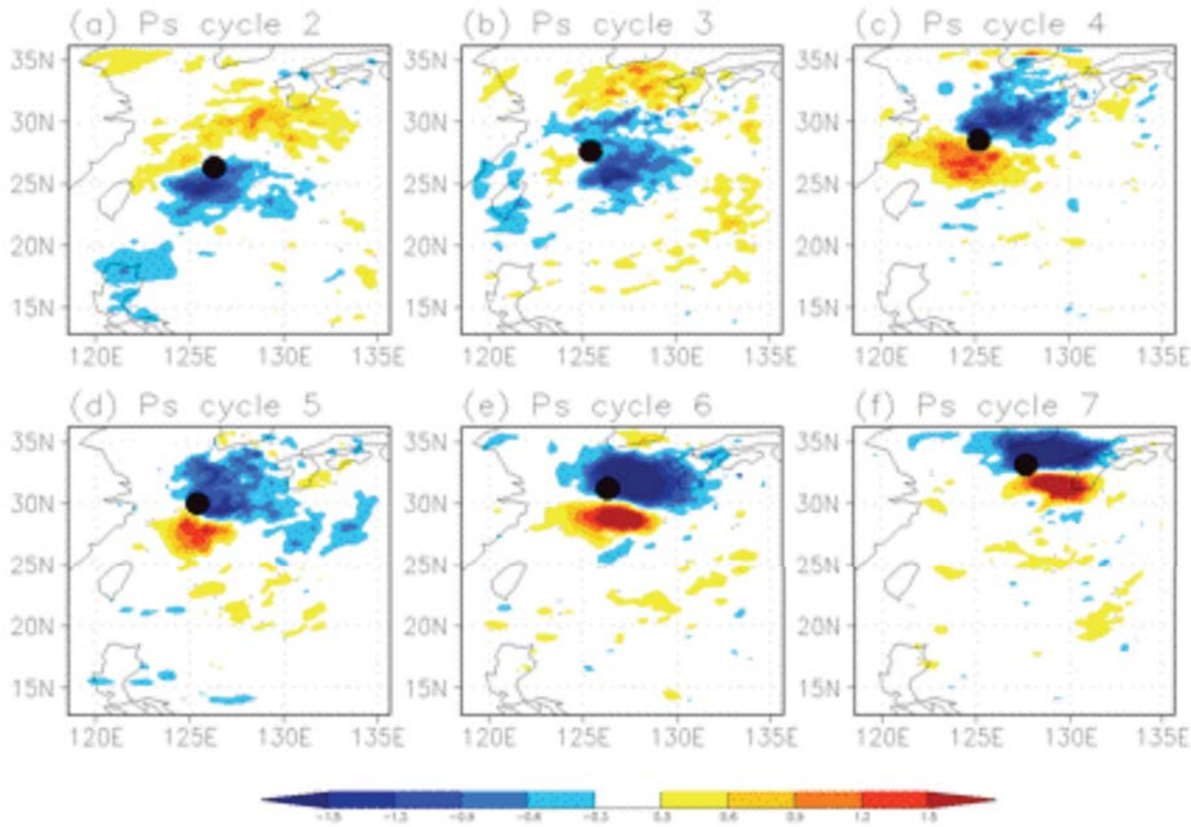


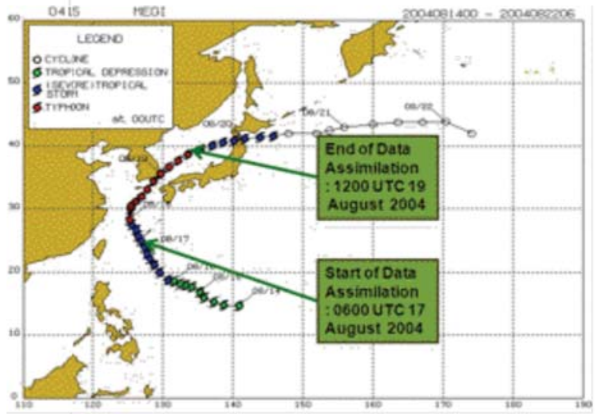
Flow-dependent information measure indicates more information over Texas, Oklahoma and the Gulf of Mexico, where there is more disagreement between different forecasts.

Generally, MLEF is in better agreement with the verification (high resolution NCEP operational analysis) than the CONTROL GSI. There is a slight degradation at the north-eastern corner of the domain.

Assimilation of conventional observations for typhoon Megi
MLEF+WRF

Differences in surface pressure (in hPa) between the experiments with and without data assimilation. Results for data assimilation cycles 2-7 are shown (from 1200 UTC 17 Aug 2004 to 1800 UTC 18 Aug 2004). Black circle indicates typhoon location.





Typhoon is always located in the area where the pressure was reduced due to data assimilation (blue). Note switch in the blue/red dipole in cycle 4, when Megi makes a turn towards east.

Courtesy of Hyun Hee Kim

More results will be presented by Stephane Vannitsem at the Conference (on Friday)

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References for further reading

Anderson, J. L., 2001: An ensemble adjustment filter for data assimilation. *Mon. Wea. Rev.,* **129**, 2884–2903.

Carrio, G. G., W. R. Cotton, D. Zupanski, and M. Zupanski, 2008: Development of an aerosol retrieval method: Description and preliminary tests. *J. Appl. Meteor*. *Climate* (in press).

Fletcher, S.J., and M. Zupanski, 2006: A data assimilation method for lognormally distributed observational errors. *Q. J. Roy. Meteor. Soc*. **132**, 2505-2519.

Evensen, G., 1994: Sequential data assimilation with a nonlinear quasi-geostrophic model using Monte Carlo methods to forecast error statistics. *J. Geophys. Res.*, **99**, (C5),. 10143-10162.

Evensen, G., 2003: The ensemble Kalman filter: theoretical formulation and practical implementation. *Ocean Dynamics*. **53**, 343-367.

Hamill, T. M., and C. Snyder, 2000: A hybrid ensemble Kalman filter/3D-variational analysis scheme. *Mon. Wea. Rev.,* **128**, 2905–2919.

Houtekamer, Peter L., Herschel L. Mitchell, 1998: Data Assimilation Using an Ensemble Kalman Filter Technique. *Mon. Wea. Rev.,* **126**, 796-811.

Houtekamer, P. L., H. L. Mitchell, G. Pellerin, M. Buehner, M. Charron, L. Spacek, and B. Hansen, 2005: Atmospheric data assimilation with an ensemble Kalman filter: Results with real observations. *Mon. Wea. Rev.,* **133**, 604-620.

Hunt, B. R., E. J. Kostelich, and I. Szunyogh, 2007: Efficient data assimilation for spatiotemporal chaos: A local ensemble transform Kalman filter. *Physica D*, **230**, 112-126.

Jazwinski, A.H., 1970: *Stochastic Processes and Filtering Theory*. Academic Press: San Diego.

References for further reading (continued)

Ott, E., and Coauthors, 2004: A local ensemble Kalman filter for atmospheric data assimilation. *Tellus.,* **56A**, 415–428.

Tippett, M. K., J. L. Anderson, C. H. Bishop, T. M. Hamill, and J. S. Whitaker, 2003: Ensemble square root filters. *Mon. Wea. Rev.,* **131**, 1485–1490.

Pham D.T., Verron J., and Roubaud M.C.,1998: A singular evolutive extended Kalman filter for data assimilation in oceanography. *J. Marine Sys.* **16**, 323-340.

Peters, W., J. B. Miller, J. Whitaker, A. S. Denning, A. Hirsch, M. C. Krol, D. Zupanski, L. Bruhwiler, and P. P. Tans, 2005: An ensemble data assimilation system to estimate CO2 surface fluxes from atmospheric trace gas observations, *J. Geophys. Res*., **110,** D24304, doi:10.1029/2005JD006157.

Torn, R. D., and G. J. Hakim, 2008: Performance characteristics of pseudo-operational ensemble Kalman filter, *Mon. Wea. Rev.,* (in press)

Zupanski, D., A. S. Denning, M. Uliasz, M. Zupanski, A. E. Schuh, P. J. Rayner, W. Peters and K. D. Corbin, 2007: Carbon flux bias estimation employing Maximum Likelihood Ensemble Filter (MLEF). *J. Geophys. Res.*, **112**, D17107, doi:10.1029/2006JD008371.

Zupanski D. and M. Zupanski, 2006: Model error estimation employing an ensemble data assimilation approach. *Mon. Wea. Rev*. **134**, 1337-1354.

Zupanski, D., A. Y. Hou, S. Q. Zhang, M. Zupanski, C. D. Kummerow, and S. H. Cheung, 2007: Applications of information theory In ensemble data assimilation. *Q. J. R. Meteorol. Soc*., **133**, 1533-1545.

Zupanski, M., 2005: Maximum likelihood ensemble filter: Theoretical aspects. *Mon. Wea. Rev.*, **133**, 1710–1726.

Zupanski, M., I. M. Navon, and D. Zupanski, 2008: The maximum likelihood ensemble filter as a non-differentiable minimization algorithm. *Quart. J. Roy. Meteor. Soc*. **134**, 1039-1050.