Ocean state and uncertainty forecasts using HYCOM with Local Ensemble Transfer Kalman Filter (LETKF)

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Introduction

An ensemble forecast system based on the US Navy's operational HYCOM model using Local Ensemble Transfer Kalman Filter (LETKF) technology has been developed for ocean state and uncertainty forecasts. One of the advantages is that the best possible initial analysis states for the HYCOM forecasts are provided by the LETKF which assimilates the Navy's operational observations using ensemble method. The background covariance during this assimilation process is provided with the ensemble, avoiding the difficulty of developing tangent linear and adjoint models from the complicated hybrid isopycnal vertical coordinate in HYCOM for 4D-VAR.

Another advantage is that the computationally efficient LETKF based ensemble system provides the valuable uncertainty estimate corresponding to every ocean state forecast. Uncertainty forecasts have been proven to be critical for the downstream users and managers to make more scientifically sound decisions.

LETKF formulation for HYCOM ensemble Prediction System

In Local Ensemble Transform Kalman Filter (LETKF), the analysis is obtained at each grid point using the observations around it within a defined radius (Hunt et al. 2007, Miyoshi and Yamane 2007, Penny 2014, Penny et al. 2015). If an matrix is defined as:

$$\mathbf{Y}^b = [\mathbf{H}\mathbf{x}^b{}_1 - \overline{\mathbf{y}}^b,\ \mathbf{H}\mathbf{x}^b{}_2 - \overline{\mathbf{y}}^b, \ldots..,\ \mathbf{H}\mathbf{x}^b{}_k - \overline{\mathbf{y}}^b]$$

Then, the analysis error covariance in ensemble space is

$$\tilde{\mathbf{P}}^a = [(k-1)\mathbf{I} + (\mathbf{Y}^b)^T \mathbf{R}^{-1}\mathbf{Y}^b]^{-1}$$

The analysis perturbations in model space are $\mathbf{X}^a = \mathbf{X}^b\mathbf{W}^a$

where $\mathbf{W}^a = [(k-1)\tilde{\mathbf{P}}^a]^{1/2}$ is the square root of $\tilde{\mathbf{P}}^a$, the analysis mean can be derived as $\overline{\mathbf{x}}^a = \overline{\mathbf{x}}^b + \mathbf{X}^b\mathbf{w}^a$

and $\mathbf{w}^a = \tilde{\mathbf{P}}^a(\mathbf{Y}^b)^T\mathbf{R}^{-1}(\mathbf{y}^0 - \overline{\mathbf{y}}^b)$

The final ensemble of analysis states can be generated by adding the analysis perturbations to the analysis mean, i.e.

$$\mathbf{x}^{a(j)} = \overline{\mathbf{x}}^a + \mathbf{X}^{a(j)} = \overline{\mathbf{x}}^b + \mathbf{X}^b\mathbf{w}^a + \mathbf{X}^{a(j)}$$

with $j = 1, 2, \ldots. k$, indicating different ensemble members.

Ensemble experiment configuration

HYCOM (Hybrid Coordinate Ocean Model) grid resolution: 1/25° ~ 3.5km (mid-lat)
Vertical levels: 34 hybrid levels
Number of ensemble members: 30
Domain: Gulf of Mexixo
DA: LETKF every 24 hours at 12Z using Navy's operational observations
Forecast length:15 days starting from 12 Z each day.
Experiment period: Jan 5 – Feb 10, 2012
Horizontal covariance localization scale: Rossby radius of deformation in the GOM (~ 50km)

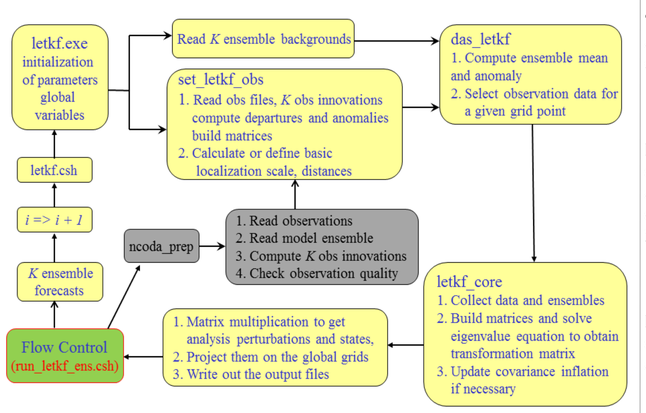
the *Relaxation to the Prior Perturbations* (RTPP) (Zhang et al. 2004) approach is used to improve the ensemble spread such as:

$$\mathbf{X}_{new}{}^a \leftarrow \alpha\,\mathbf{X}^b + (1-\alpha)\mathbf{X}^a$$

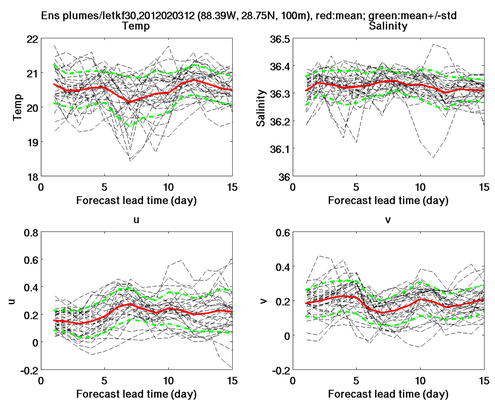
where $0.0 \le \alpha \le 1.0$ is the coefficient used to relax the analysis perturbations to the prior perturbations. α=0.9 is chosen to relax the analysis perturbations more efficiently. The selection is based on the vast past experiences with ensemble Kalman filter systems in both atmospheric and ocean systems.

Ensemble System Flow Chart

HYCOM LETKF for Global Ensemble Forecast System

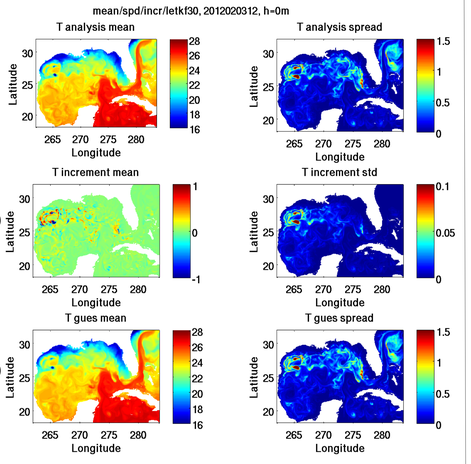


Ensemble Plume



The 15-day ensemble forecast plumes from Feb 3, 2012 at Deep Water Horizon location at 100m for T (deg C), S (psu), u (m/s), v (m/s), ensemble mean (red) and mean plus/minus STD (green)

Surface temperature spread at 12Z Feb. 3, 2012

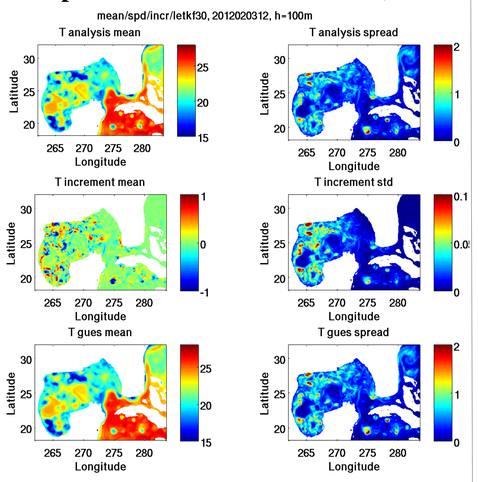


Top panel: ensemble analysis mean (left), spread (right)

Middle panel: ensemble mean (left) and standard deviation of increments (right),

Bottom panel: prior ensemble mean (left) and spread (right)

Temperature spread at 100m at 12Z Feb. 3, 2012

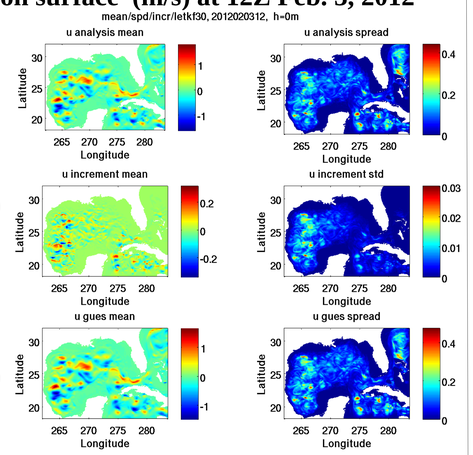


Top panel: ensemble analysis mean (left), spread (right)

Middle panel: ensemble mean (left) and standard deviation of increments (right),

Bottom panel: prior ensemble mean (left) and spread (right)

u spread on surface (m/s) at 12Z Feb. 3, 2012



Top panel: ensemble analysis mean (left), spread (right)

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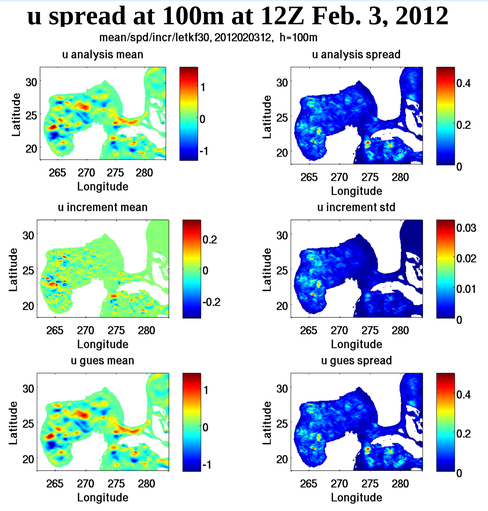
u spread at 100m at 12Z Feb. 3, 2012

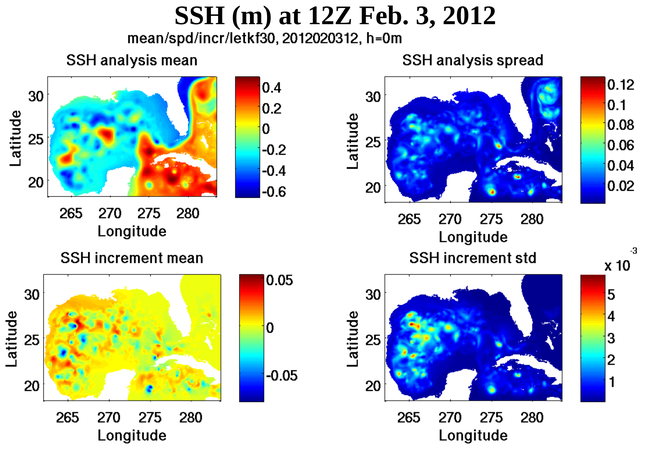


Top panel: ensemble analysis mean (left), spread (right)

Middle panel: ensemble mean (left) and standard deviation of increments (right)

Bottom panel: prior ensemble mean (left) and spread (right)

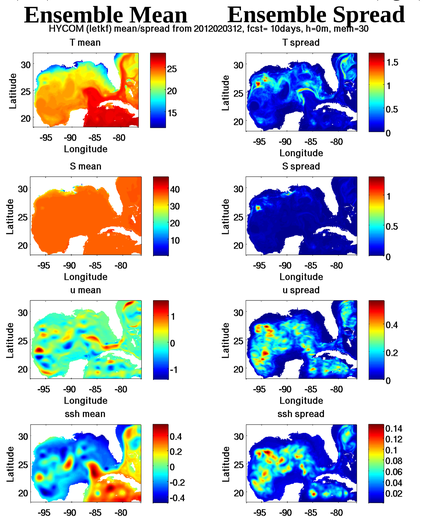
SSH (m) at 12Z Feb. 3, 2012



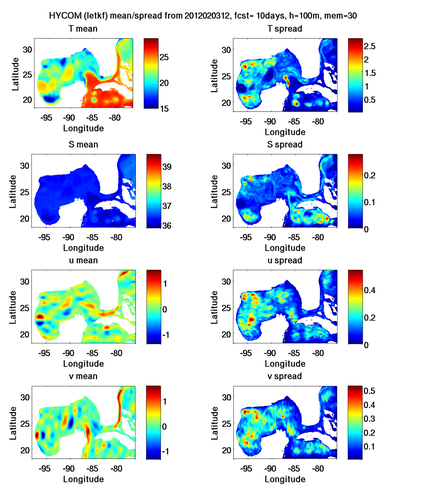
Top: ensemble analysis mean (left), spread (right).
Bottom: ensemble mean (left) and standard deviation of increments (right)

Ensemble Mean Ensemble Spread

Ensemble forecast on surface after 10 days from 12Z Feb. 3, 2012.

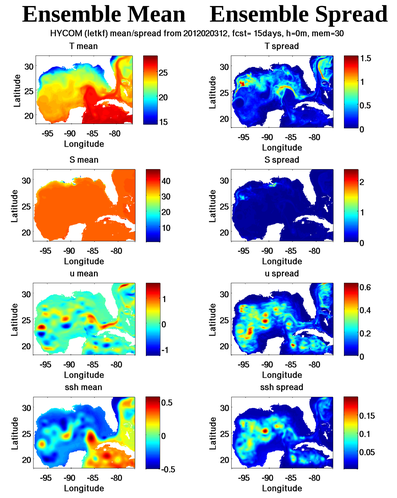


Ensemble forecast at 100m after 10 days from 12Z Feb. 3, 20



Ensemble Mean Ensemble Spread

Ensemble forecast on surface after 15 days from 12Z Feb. 3, 2012.

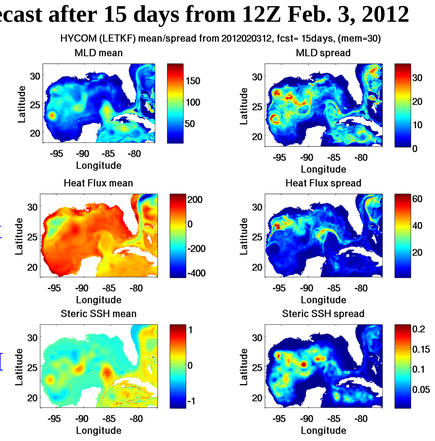


Ensemble forecast after 15 days from 12Z Feb. 3, 2012

MLD

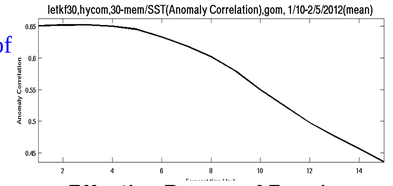
Heat Flux

Steric SSH



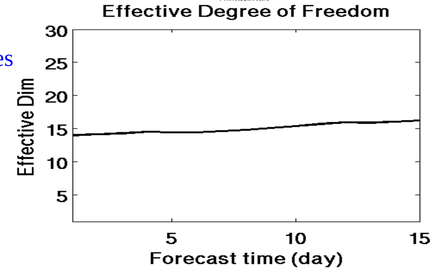
Anomaly Correlation of SST as a function of forecast time ave over

1/10-2/5/2012



The effective degrees of freedom in ensemble space for SST, ave over

1/10-2/5/2012.



Summary

- A 30-member ensemble forecast system based on the LETKF has been developed using the Navy's HYCOM with full operational observational data, experimented over the Gulf of Mexico for Jan 4 to Feb 10, 2012.
- The benefits of an ensemble include simultaneous probabilistic forecasts with uncertainty info provided by ensemble spread, in addition to superior forecasts provided by ensemble mean.
- It is found that the LETKF based ensemble is under-dispersive due to the lack of model-related uncertainty representation. The spread can be effectively enhanced by using the RTPP (relaxation to the prior perturbation) technique.
- The number of effective degrees of freedom in the 30-member ensemble subspace is about 15, indicating that the ensemble subspace is collapsing to certain extent.
- The horizontal covariance localization is based on the Rossby radius of deformation, however, the vertical covariance localization has not been implemented.
- Other development underway includes (1) how to account for the model-related uncertainties in HYCOM, which will increase ensemble spread, (2) how to overcome the computing cost and extend the ensemble system to cover the global oceans.