Impact of Atmospheric and Model Physics Perturbations On a High-Resolution Ensemble Data Assimilation System of the Red Sea

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Objective

✓ To demonstrate the importance of accounting various sources of uncertainty in ocean data assimilation systems.

✓ To provide improved high-resolution ocean reanalysis for the Red Sea (RS), which in turn help to improve ocean forecasts of the basin on a range of time scales.
Quick look at the basic concept(s) related to the present study
What are the Sources of **forecast errors** in Ocean models?

- Uncertainties/errors in
  - Ocean initial conditions
  - Atmospheric forcing
  - Model Physics
  - Open Ocean boundary conditions (more relevant for the regional models)
  - Bathymetry (more relevant near coast)

This information of uncertainty is an important input for ocean data assimilation.
Data Assimilation: What does it do?

Data Assimilation corrects the model trajectory based on sparse observations.

\[
X^a = X^b + BH^T [HBH^T + R]^{-1} [Y - HX^b]
\]

- **No Assimilation**
- **Assimilation**

\[
\begin{align*}
X^a &\quad \rightarrow \quad \text{Analysis} & X^b &\quad \rightarrow \quad \text{Forecast} \\
Y &\quad \rightarrow \quad \text{Observations} & H &\quad \rightarrow \quad \text{Transformation/Interpolation operator} \\
B &\quad \rightarrow \quad \text{Forecast error covariance} & R &\quad \rightarrow \quad \text{Observations error covariance}
\end{align*}
\]
What is the Role of Forecast Error Covariance (B)?

\[
X^a = X^b + BH^T [HBH^T + R]^{-1} [Y - HX^b]
\]

\[B=\begin{bmatrix}
B_{11} & B_{12} & \cdots & B_{19} \\
B_{21} & B_{22} & \cdots & B_{29} \\
B_{31} & B_{32} & B_{33} & \cdots \\
\vdots & \vdots & \cdots & \vdots \\
B_{91} & B_{92} & \cdots & B_{99}
\end{bmatrix}\]

\[
\begin{pmatrix}
x_1^a \\
x_2^a \\
x_3^a \\
\vdots \\
x_9^a
\end{pmatrix} = \begin{pmatrix}
x_1^b \\
x_2^b \\
x_3^b \\
\vdots \\
x_9^b
\end{pmatrix} + \begin{pmatrix}
B_{13} \\
B_{23} \\
B_{33} \\
\vdots \\
B_{93}
\end{pmatrix}\frac{(y_0 - x_3^b)}{(B_{33} + \sigma_o^2)}
\]

Model Grid

Observation location

\[X^b = \begin{bmatrix}
x_1^b \\
x_2^b \\
x_3^b \\
\vdots \\
x_9^b
\end{bmatrix} \quad Y = \begin{bmatrix} y_0 \end{bmatrix} \quad R = \begin{bmatrix} \sigma_o^2 \end{bmatrix}
\]

\[H = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}\]

B propagates observations information from one grid/location/variable to another.
Brief description about the assimilation system and Experiments conducted
Configuration of Red Sea Data Assimilation System

- Model: 4km-MITgcm
- Assimilation: DART with Ensemble Adjustment Kalman Filter (EAKF)
- Ensemble members: 50
- Localization: ~300 km in the horizontal; No vertical localization
- Inflation: 1.1 (10%)

Observations assimilated:
- Satellite Level-4 Reynolds SST. Observation error used is between 0.1 to 0.6 degC
- Satellite Level-3 altimeter SLA (merged). Observation error used is 4cm.
- In situ T & S profiles from EN4 dataset (fully QC’d). Observation error used for T & S profiles is 0.5 degC and 0.2 psu respectively

Initial conditions: 1st Jan, 2011
- Free model: WRF5km evolved simulation
- MITDART: 50 ensembles prepared based on hind casts re-centered on 1st Jan, 2011

Forcing
- Free model: Ensemble (50) mean of ECMWF 0.5 x 0.5 perturbed forcing
- MITDART: ECMWF 0.5 x 0.5 perturbed forcing (50 members)

OBCS: Daily averaged ocean state from 25km-resolution GLORYS ocean reanalysis
- Length of Experiments: 1 year starting from 1st Jan, 2011
## Configuration of Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Initial condition</th>
<th>Atm. Forcing</th>
<th>Physics</th>
<th>Assimilation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(F_{exp})</td>
<td>Single. 1(^{st}) Jan, 2011</td>
<td>Ensemble mean</td>
<td>STANDARD</td>
<td>No</td>
</tr>
<tr>
<td>(I_{exp})</td>
<td>50-member ensemble based on hindcasts recentered for 1(^{st}) Jan, 2011.</td>
<td>Ensemble mean</td>
<td>STANDARD</td>
<td>Yes</td>
</tr>
<tr>
<td>(I_{Aexp})</td>
<td>50-member ensemble based on hindcasts recentered for 1(^{st}) Jan, 2011.</td>
<td>50-member ensemble</td>
<td>STANDARD</td>
<td>Yes</td>
</tr>
<tr>
<td>(I_{APexp})</td>
<td>50-member ensemble based on hindcasts recentered for 1(^{st}) Jan, 2011.</td>
<td>50-member ensemble</td>
<td>RANDOM across members (multi-model monthly OBCS were used)</td>
<td>Yes</td>
</tr>
</tbody>
</table>

\(I_{exp}\) → Uncertainties accounted only from Initial conditions
\(I_{Aexp}\) → Uncertainties accounted from Initial conditions and atmospheric forcing
\(I_{APexp}\) → Uncertainties accounted from Initial conditions, atmospheric forcing, and model physics
Results highlighting the improvements in \textit{IAPexp} compared to other experiments
Anomaly correlations within Ensemble on 1st October, 2011

Too Noisy correlations in $l_{exp}$ become more organized in $IAP_{exp}$. 
Comparisons with in-situ SST and SSS observations during WHOI/KAUST cruise

Noisy and too anomalous
Slightly Noisy
Less Noisy and more organized
Subsurface Temperature comparisons during WHOI/KAUST cruise

Maximum Vertical Velocity in the ocean column along RS axis

Improved biases in the deep layers with IAPexp
SSH Comparisons with along-track observations

\(I\text{APexp}\) is better than interpolated level-4 product of AVISO.

Also, It represents the basin scale eddies better than any other experiment.
Conclusions

- The old “perturbing initial conditions alone” strategy yields minimal SST improvements and creates large imbalances within the ocean state.

- Admitting additional source of uncertainty, atmospheric forcing, yields substantial improvements.

- Admitting the uncertainties in model physics, atmospheric forcing, and initial conditions not only yield substantial improvements but obtains more dynamically balanced solutions. It improves basin scale eddy features too.