Ocean Modeling: Bias correction through stochastic forcing.

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8 May 2015
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Motivation: Large scale models

Most **low resolution** models suffer important errors due to poorly represented processes. This leads to a **systematic error** with a non-zero mean: bias.

Bias is considered to be the **main source** of errors in climatic model. It allows only to study the variation of a model, not its absolute results. (Zunz, 2012)

Both off-line and on-line methods aim at correcting the bias during the assimilation procedure. The **source** of bias remains.
Bias correction: Innovative approach

How to correct bias with data assimilation?

- Estimate the model’s bias and its source in the model’s equations.
- Create an ensemble of stochastic forcing directly added into the model’s equations.
- Run the model for each forcing field separately.
- Consider this stochastic forcing as a control variable for data assimilation.
- Adjust the forcing field with data assimilation to correct the bias.
- Rerun the model with the new forcing field.
- Validate the bias correction with external and independent data.

⇒ This method allows a **continuous correction** for bias during the model run, since the source of bias itself is corrected.
Lorenz ’96 model: Mean Model State

Modified Lorenz ’96 model equation:

\[
\frac{dX_k}{dt} = -X_{k-2}X_{k-1} + X_{k-1}X_{k+1} - X_k + F_k
\]  \hspace{1cm} (1)

Model is run with classic configuration:

- \(0 < F_k < 10\), where \(k = 1, \ldots, 40\)
- 1000 time step of \(t = 0.05\)

However, we do not look at the variables at a specific point in time, but rather at the model’s spatial and temporal mean.

- 15 different initial condition \(X_k\) for each \(0 < F_k < 10\).
- Temporal average from 200\(th\) time step, average over the \(i = 15\) initial conditions

**Model Mean State:** \(X_k = \overline{X}_{k,i,t}\)
Lorenz ’96 model: Mean Model State

Model Mean State: 30 evenly distributed different $0 < F_k < 10$, with 450 different initial conditions for each mean $F$:

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure1.png}
\caption{Lorenz ’96 model mean state compared to a constant forcing parameter $F$.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure2.png}
\caption{Lorenz ’96 model mean state compared to a mean spatially variable forcing parameter $F_k$, with a mean $F$ and standard deviation of $F_{\text{std}} = 1$.}
\end{figure}
Lorenz ’96 model: Twin Experiment

We tested our innovative approach with a Twin Experiment with the Lorenz ’96 model:

- $F_{\text{tru}} = 4$, with spatially correlated perturbation
  \[ F_k = F_{k,\text{tru}} + z \quad \text{(2)} \]
  \[ z \sim N(0, P) \quad \text{(3)} \]
- One run is considered as reality.
- Observations are extracted: spatial model mean $\bar{X}_{k,\text{tru}}$
- Ensemble is built with 100 runs with different $F_{k,\text{ens}}$.

Perturbation is considered as bias, we intend to find it and correct the model:

- State vector consists of $F_{k,\text{ens}}$ and $\bar{X}_{k,\text{ens}}$
- We assimilate $\bar{X}_{k,\text{tru}}$, and correct our ensemble
Lorenz ’96 Twin Experiment Results

**Figure**: Lorenz ’96 model $F_k$ parameter of the truth, ensemble mean and assimilated ensemble mean runs.

**Figure**: Lorenz ’96 model $X_k$ temporal mean of the truth, ensemble mean and assimilated ensemble mean runs.
This method is currently being applied to the NEMO-LIM model.

- Global and **low resolution** (2°) coupled model with long time steps allowing simulations over several decades.
- Used in the PredAntar project (Belspo), which aims at understanding and predicting the Antarctic sea ice variability at the decadal timescale.

Because of this low resolution, **ocean currents** are poorly represented and have been identified as a possible source of bias. They have a direct impact on heat transportation in the ocean, thus also on the sea surface temperature bias.
Forcing the model

Current investigation: poorly located currents in NEMO-LIM model. We apply the forcing terms directly into the **momentum equations** of ocean dynamics in NEMO.

\[
\frac{du}{dt} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + f v + \frac{1}{\rho} \frac{\partial \tau_x}{\partial z} + F_u \tag{4}
\]

\[
\frac{dv}{dt} = -\frac{1}{\rho} \frac{\partial p}{\partial y} - f u + \frac{1}{\rho} \frac{\partial \tau_y}{\partial z} + F_v \tag{5}
\]
Random field is created with Diva-ND (Barth et al., 2013). It allows to apply constraints by using a cost function:

1. Penalizes abrupt variations
2. Uses a given correlation length
3. Decouples disconnected areas based on topography

\[ J(\Psi) = \int_{\Omega} \alpha_2 (\nabla^2 \Psi)^2 + \alpha_1 (\nabla \Psi)^2 + \alpha_0 \Psi \, dx \]  \hspace{1cm} (6)
Constructing the forcing term: Diva-ND

However, in order not to create currents perpendicular to the coasts, we tried different additional constraints on the stream function:

1. Constraining the stream function to be zero at the coasts. Too restrictive.
2. Constraining the gradient of the stream function along the coast. We use a strong constraint: forced to be zero.

\[ J'(\Psi) = J(\Psi) + \lim_{\sigma \to 0} \frac{1}{\sigma} \int_{\Delta \Omega} (\nabla \Psi \cdot \hat{t})^2 ds \quad (7) \]

Additionnal filtering to smoothen the first derivative, for a higher model stability.
We use this field as a stream function to construct zonal and meridional currents. The condition of zero divergence resulting from flow incompressibility gives us:

\[ u = -\frac{\partial \Psi'}{\partial y} \quad (8) \]
\[ v = \frac{\partial \Psi'}{\partial x} \quad (9) \]

The zonal and meridional currents are then dampened towards depths depending on the yearly mean turbocline \( T(x, y) \), in order to keep surface currents, defined as the ocean mixed layer thickness.

\[ F_u(x, y, z) = \frac{u(x, y)}{1 + \exp \left( \frac{z-T(x,y)}{L} \right)} \]
\[ F_v(x, y, z) = \frac{v(x, y)}{1 + \exp \left( \frac{z-T(x,y)}{L} \right)} \quad (11) \]
With forcings on the meridional and zonal currents, we are able to obtain an internal variability of the **Sea Surface Height** (SSH) of about 28 cm, which can be compared with the RMS between a NEMO free run and the CNES Mean Dynamic Topography, of 20 cm.

We build a Twin Experiment similarly to the Lorenz ’96 case:

- Ensemble of forcings on zonal and meridional currents
- The yearly mean SSH is considered as observation and control variable
- We build and ensemble of forcings, and assimilate observations from a truth run
Local assimilation correlation length: 2000 km.

Figure: SSH NEMO Ensemble Mean before assimilation (in m)

Figure: SSH NEMO Twin True run (in m)
Local assimilation correlation length: 2000 km.

**Figure:** SSH NEMO Ensemble Mean after assimilation (in m)

**Figure:** SSH NEMO Twin True run (in m)
**Figure**: RMS on SSH from Ensemble Mean before and after analysis, with True Run
Background estimate of $F_u \approx 0$.

**Figure:** NEMO Ensemble mean after analysis, Zonal Forcing

**Figure:** NEMO True Run, Zonal Forcing
Background estimate of $F_v \approx 0$.

Figure: NEMO Ensemble mean after analysis, Meridional Forcing

Figure: NEMO True Run Meridional Forcing
Figure: RMS on Zonal Forcing from Ensemble mean before and after Analysis, with True Run

Figure: RMS on Meridional Forcing from Ensemble mean before and after Analysis, with True Run
NEMO Rerun, with the assimilated U and V forcings.

Figure: SSH NEMO Rerun (in m)

Figure: SSH NEMO Twin True run (in m)
Figure: RMS on SSH from Ensemble Mean before and after analysis, and from Rerun, with True Run
Conclusion and perspectives

- Results with Lorenz ’96 model were encouraging enough to start testing this method on NEMO model.
- Model stability problems with forcing have been handled.
- Variability on SSH from forcing is large enough to correct the estimated bias from the model.
- Local assimilation procedure gives encouraging results.
- Rerun of the model with analysed forcings ongoing.
- Real data and observations (CNES MDT) will be used to correct the model after the Twin Experiment.
Thank you!