Coupled Physical-Acoustical Data Assimilation in MAB/Shelfbreak PRIMER and First Comparison of the SCS and MAB Frontal Systems

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http://www.deas.harvard.edu/~pierrel
http://www.deas.harvard.edu/~robinson
PHYSICAL-ACOUSTICAL FILTERING IN A SHELFBREAK ENVIRONMENT:
Ocean Physics as Simulated 2 Years Ago
Evaluation based on SST

July 18
Evaluation based on SST

July 20
Evaluation based on SST

July 22
30m Temperature: 8 July – 7 August 1996
Importance and Effects of Atmospheric Forcings and Uncertainties

Best Run

No Atmos. Forcing

- Oceanic frontal instabilities occur from sub-mesoscales to mesoscales
- Atmospheric forcing impose certain scales on multi-scale oceanic frontal instability
- Deeper surface boundary layer and increased SBL mixing deepens large frontal meander but does not lead to much stronger surface signal
Quick-Look evaluations of 50m Temperature: July 26, 1996

Gawarkiewicz, et al. 50m potential temperature for 26 July, 29 July and 31 July, objectively analyzed from Seasoar data

50m temperature in HOPS simulation with data assimilation for the same dates

26 July 29 July 31 July
50m Temperature: 8 July – 7 August 1996
50m Temperature: July 26, 1996

No DA

18 day predictions

With DA

18 day predictions, with DA of July 26 data
ESSE: Uncertainty Predictions and Data Assimilation

1. Dynamics: \[ dx = M(x) dt + d\eta \] \[ \eta \sim N(0, Q) \]
2. Measurement: \[ y = H(x) + \varepsilon \] \[ \varepsilon \sim N(0, R) \]

3. Non-lin. Err. Cov. evolution: \[ P(0) = P_0 \]
   \[ \frac{dP}{dt} = <(x - \hat{x})(M(x) - M(\hat{x}))^T > + <(M(x) - M(\hat{x}))(x - \hat{x})^T > + Q \]

4. Error reduction by DA:
   \[ P(+) = (I - KH)P(-) \]
   where \( K \) is the reduced Kalman Gain

- ESSE retains and nonlinearly evolves uncertainties that matter, combining,
  i. Proper Orthogonal Decompositions (PODs) or Karhunen-Loeve (KL) expansions
  \[ u = \sum_{i=1}^{M} \phi_u(x, y, z) a_i(t) \]
  \[ \frac{d a_i(t)}{dt} = f(a) \]
  ii. Time-varying basis functions, and,
  iii. Multi-scale initialisation and Stochastic ensemble predictions
  to obtain a dynamic low-dimensional representation of the error space.

- Linked to Polynomial chaos, but
  with time-varying error KL basis:
  \[ x(x, t, \theta) = \bar{x}(x, t) + \sum_{i=1}^{M} \sqrt{\lambda_i} \phi_u^s(x, t) \zeta_i(\theta) \]
Sources of Uncertainty in Simulations of Ocean Physics

- Bathymetry
- Boundary conditions
  - Surface atmospheric forcing
  - Coastal-estuary and open-boundary fluxes
- Initial conditions
- Ocean physics data
- Model parameters and parameterized processes: sub-grid-scales, turbulence closures, un-resolved processes
  - e.g. tides and internal tides, internal waves and solitons, microstructure and turbulence
- Numerical errors: steep topographies/pressure gradient, non-convergence
NMFS–supplied CTD data, Jul 1 – Sep 30, 1996

WHOI PRIMER Seasoar data (Jul 26,27,28,29,30,31 and Aug 01)

WHOI Cross–shelf CTD data (Aug 05 – Aug 06)
Initial condition uncertainties: Positions and shapes of the tilted shelfbreak front

Outcropping of surface front
- Upstream positions relatively certain, with sharp ring-front interactions
- Downstream positions very uncertain:
  - Notice surface signature of advected shelf waters
  - SBF meandering and “old” weak warm core rings
  - Squirts of slope and shelf waters
IC uncertainties: Positions and shapes of the tilted SBF (cont.)
Uncertainties in Multiple Model Parameters:
Example of mixing layer depth (Ekman factor $E_k$)

- Similar uncertainties and fit for several other parameters
- Need for adaptive modeling (e.g. parameter values that evolve in time as a function of data)
- One reason: (sub)-mesoscale coastal variabilities and atmosphere-ocean interactions are not stationary at scales of days to a month
Stochastic Primitive Equation Model

The diagonal of time-decorrelations:

\[ \beta_a, \beta_v, \beta_T, \beta_S, \beta_\psi \text{ functions of } (x, y, z) \]

are here chosen \( \beta_X = \beta I \).

The diagonal of noise variances are chosen function of z only, of amplitude set to:

\[ \varepsilon \text{ * geostrophy} \]

\[ \Sigma_u = \Sigma_v = \sigma^2(z) I, \quad \Sigma_T = \sigma^2_T(z) I, \quad \Sigma_S = \sigma^2_S(z) I, \quad \Sigma_\psi = \sigma^2_\psi(z) I, \]

\[ \text{with } \sigma_U(z) = \varepsilon_U f_c U(z), \quad \sigma_T(z) = \varepsilon_T U(z) \frac{\Delta T(z)}{L(z)}, \quad \sigma_S(z) = \varepsilon_S U(z) \frac{\Delta S(z)}{L(z)}, \quad \sigma_\psi(z) = \varepsilon_\psi \frac{\nabla L(z)}{U(z)}. \]

\[ \text{Internal Baroclinic Zonal Mode} \]

\[ d\mathbf{u} = d\mathbf{u}' - d\mathbf{\bar{u}}', \]

\[ d\mathbf{u}' = \left(-I'(\mathbf{u}) + fv - \frac{\kappa}{\rho_0} \int_x^0 \rho_x \, dz + F_u + A_{uv} x \varepsilon \right) \, dt + B_u^{le} \, d\mathbf{\tilde{w}}^c_u, \]

with \( \mathbf{u} = \mathbf{\bar{u}} - \frac{1}{H} \psi_y \).

\[ d\mathbf{\tilde{w}}^c_u = -\beta_u \, d\mathbf{\bar{w}}^c_u \, dt + d\mathbf{w}^c_u, \]

with \( \mathbf{\bar{w}}^c_u(0) \sim (0, \Sigma_u) \) and \( \mathbf{w}_u^c \sim (0, 2\beta_u \Sigma_u) \).

\[ \text{Internal Baroclinic Meridional Mode} \]

\[ d\mathbf{v} = d\mathbf{v}' - d\mathbf{\bar{v}}', \]

\[ d\mathbf{v}' = \left(-I'(\mathbf{v}) - fu - \frac{\kappa}{\rho_0} \int_x^0 \rho_y \, dz + F_v + A_{vz} \varepsilon \right) \, dt + B_v^{le} \, d\mathbf{\tilde{w}}^c_v, \]

with \( \mathbf{v} = \mathbf{\bar{v}} + \frac{1}{H} \psi_x \).

\[ d\mathbf{\tilde{w}}^c_v = -\beta_v \, d\mathbf{\bar{w}}^c_v \, dt + d\mathbf{w}^c_v, \]

with \( \mathbf{\bar{w}}^c_v(0) \sim (0, \Sigma_v) \) and \( \mathbf{w}_v^c \sim (0, 2\beta_v \Sigma_v) \).

\[ \text{Thermal energy: Balance} \]

\[ dT = \left(-I'(T) + F_T + K_T x \varepsilon \right) \, dt + B_T^{le} \, d\mathbf{\tilde{w}}^c_T, \]

\[ d\mathbf{\tilde{w}}^c_T = -\beta_T \, d\mathbf{\bar{w}}^c_T \, dt + d\mathbf{w}^c_T, \]

with \( \mathbf{\bar{w}}^c_T(0) \sim (0, \Sigma_T) \) and \( \mathbf{w}_T^c \sim (0, 2\beta_T \Sigma_T) \).

\[ \text{Conservation of Salt} \]

\[ dS = \left(-I'(S) + F_S + K_S x \varepsilon \right) \, dt + B_S^{le} \, d\mathbf{\tilde{w}}^c_S, \]

\[ d\mathbf{\tilde{w}}^c_S = -\beta_S \, d\mathbf{\bar{w}}^c_S \, dt + d\mathbf{w}^c_S, \]

with \( \mathbf{\bar{w}}^c_S(0) \sim (0, \Sigma_S) \) and \( \mathbf{w}_S^c \sim (0, 2\beta_S \Sigma_S) \).

\[ \text{Barotropic Stream Function} \]

\[ \nabla_h \wedge [H^{-1} \nabla_h \wedge d\psi e_3] = -\nabla_h \wedge d\mathbf{\bar{u}} + B_{\psi}^{le} \, d\mathbf{\tilde{w}}^c_\psi, \]

\[ d\mathbf{\tilde{w}}^c_\psi = -\beta_\psi \, d\mathbf{\bar{w}}^c_\psi \, dt + d\mathbf{w}^c_\psi, \]

with \( \mathbf{\bar{w}}^c_\psi(0) \sim (0, \Sigma_\psi) \) and \( \mathbf{w}_\psi^c \sim (0, 2\beta_\psi \Sigma_\psi) \).
Evolution of Uncertainties:
Predicted Standard Deviation of Temperature Error at 10m
Acoustic Propagation Parameter: HOPS sound-sections at noon time

HOPS sections: 3 km grid (6-10 km scale)  
Seasoar + moored data (4 km cor. scale)
Coupled Physical-Acoustical Data Assimilation of real TL data: Eigenmodes of coupled normalized error covariance on Jul 26

**Sound-speed Component**

**Mode 1: C component**

**Mode 2: C component**

**Broadband TL Component**

**Mode 1: TL component**

**Mode 2: TL component**

*Shift in frontal shape (meander) and its acoustic TL counterpart above source and in cold channel*

*Opposition to mode 1 + surface thermocline tilt, leading to less (more) loss in cold channel (surface and bottom duct)*
Coupled Physical-Acoustical Data Assimilation of real TL data
## Comparison of PRIMER ’96 and ASIAEX ’00 Shelfbreak Fronts

<table>
<thead>
<tr>
<th></th>
<th>PRIMER</th>
<th>ASIAEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp. Range of Section</td>
<td>6.5 – 20°</td>
<td>13 – 26°</td>
</tr>
<tr>
<td>Salinity Range of Section</td>
<td>31.75 – 35.25 PSU</td>
<td>33.875 – 34.675 PSU</td>
</tr>
<tr>
<td>Salinity Difference across Front</td>
<td>~1.625 PSU</td>
<td>~0.2 PSU</td>
</tr>
<tr>
<td>Slope</td>
<td>.0020</td>
<td>.0023</td>
</tr>
<tr>
<td>Width</td>
<td>5 – 10 km</td>
<td>5 – 20 km</td>
</tr>
<tr>
<td>Foot</td>
<td>100m</td>
<td>110m</td>
</tr>
<tr>
<td>Notable</td>
<td>Strong surface heating</td>
<td>Front not always present (e.g. 2001)</td>
</tr>
</tbody>
</table>
Ensemble statistics for ASIAEX 2000
30m Salinity; 15 members

Mean

Standard Deviation

Kurtosis

Skewness
Ensemble statistics for PRIMER 1996
Surface Sound Speed; 80 members
CONCLUSIONS

• Achieved 1-month simulation of ocean physics and its uncertainties at accuracy useful for acoustic propagation predictions
  – Ocean prediction acoustically useful even at times where there is no physical data
  – Requires steep topographies and intensive parameter estimation/fit, but is feasible today

• Shelfbreak PRIMER oceanic processes:
  – Large meander captured (prior to data assimilation). Arises due to a combination of internal ocean instabilities and atmospheric forcing
  – (Sub)-mesoscale eddy field at the front important in summer conditions and similar to open ocean eddies

• Most multiple sources of physical uncertainties accounted and predicted using dominant error approach of ESSE: non-stationary error statistics

• Oceans physics/acoustics data assimilation via ESSE: carried-out with real data as a single multi-scale joint estimation for the first time, using higher-moments to characterize uncertainties
  – Corrects too lossy TL at depth (2 db) and two high in surface mixed layer
  – Leads to corrections in whole acoustic section within cold channel and to shift in sound-speed front above the source (slope water meander/eddy)
EXTRA VUGRAFS
Temperature along Western Acoustic Track
8 July – 7 August 1996
STOCHASTIC FORCINGS MODEL:
Sub-grid-scales

I. 0d Random Noise Exponentially Decorrelated in Time

\[ d\tilde{w} + \beta \tilde{w} \, dt = dw, \quad (76) \]

\[ \dot{p}_\tilde{w} = -2\beta \, p_\tilde{w} + q. \quad (77) \]

Setting \( \dot{p}_\tilde{w} \) to zero at all times yields \( p_\tilde{w}(0) = \sigma^2 = \frac{q}{2\beta} \). The process \( \tilde{w} \) is assumed to be of fixed fluctuation amplitude \( \sigma \) and autocorrelation time \( \frac{1}{\beta} \). The constant variance of the white noise \( w \) is thus set to \( q = 2\beta \sigma^2 \).
II. 3d Random Noise, Exponentially Decorrelated in Time and 2-Grid Point Decorrelated in Space

\[ d\psi^t = f^{PE}(\psi^t, t) \; dt + B^{fc}(t) \; dw^c . \]  
\[ dw^c = -\beta^c \tilde{w}^c \; dt + dw^c , \]  

where symbols denote the:

- discrete-space PE state vector: \( \psi = (\hat{u}, \hat{v}, T, S, p)^T \in \mathbb{R}^n \)
- coarse 3d white noise: \( w^c_k \)
- Coarse 3d Gauss-Markov process: \( \tilde{w}^c_k \),
  
  i.e. \( dw^c = (dw^c_{\hat{u}}, dw^c_{\hat{v}}, dw^c_T, dw^c_S, dw^c_p)^T \)
- PE dynamical model operator: \( f^{PE}(\cdot, t) \)
- linear extrapolation matrix, from coarse to fine state: \( B^{fc}(t) \)
Hurricane Bertha
23:00 Thu July 4, 1996 to 05:00 Sun July 14, 1996 EDT

Averaged wind-stress time-series

Day starting from Jul 1, 00EST, 1996

Average wind-stress (dynes/cm²)

July 5–6
July 10
July 13–14–15–16
July 19–20–21
July 30
Aug 1–2