Synthesis of Coastal Ocean Circulation Models and Satellite Altimetry: Opportunities & Challenges

Coastal Altimetry Workshop, Data Assimilation & Modeling and (DAM) Group: Aikman, Bouffard, Bulusu, Jacobs, Kurapov, Lozano, Liu, Madsen, Mooers, Patchen, Roblou, Wilkin
Dominant Physical Processes in the Coastal Ocean:

Scales of the processes: <100 km, hours (tides) – 1 month (larger scale eddies)

- Wind-driven currents and upwelling/downwelling
- Tides (barotropic, tidal fronts)
- Fronts, eddies, instabilities
- Coastally trapped waves
- Buoyancy currents (river input)
- Internal tides

Models to describe those processes: POM, ROMS, NCOM, HYCOM, MIT GCM, SYMPHONIE, … EFDC, CH3D, …, FVCOM; ELCIRC/SELF, …

- 3D, nonlinear, free surface
- Hydrostatic \( \frac{\partial p}{\partial z} = -\rho \ g \)
- Boussinesq (implies volume conservation instead of mass conservation, note: no SSH variation due to thermal expansion)
Model inputs / outputs / errors:

Ini Conditions
Boundary Conditions
Surf. Forcing
Internal Parameters

SSH
Velocity
Temperature
Salinity
Turbulent KE

(Biological fields)

(conservation of volume, momentum, internal energy, tracers, etc.)

(For 2-7 day forecasting in the coastal ocean, errors in atm. forcing can be as important as the errors in the initial conditions)
Synthesis of models and observations:

- **Model-data comparisons**: models provide time- and space-continuous information on the origin and evolution of dynamical structures apparent in the data.

- **Data Assimilation**: combine models and observations to:
  
  - *Improve accuracy of the model fields*
  
  - *Provide interpolation and synthesis of diverse and sparse data sets, replacing more traditional mapping tools based on statistical interpolation*
  
  - *Learn about model deficiencies*
Synthesis of SSH altimetry and Coastal Ocean Models:

Problems, Challenges, Questions…

- Dynamical processes are on smaller spatial scales than the distance between satellite tracks, shorter time scales than repeat cycles

- Ageostrophic processes: how to project surface observational information to 3D?

- How to match the models and satellite SSH?

- Tidal aliasing, storm surges influence on SSH

- Uncertainties in the geoid (esp. shelf break)

- Mean Dynamic Topography

- What SSH assimilation corrects the best? (Ini Cond., Forcing, etc.)
Details on DA:

**OI, 3DVAR** (e.g., Chao, Liu & Lozano):

\[ u^a = u^f + G(d-Hu^f) \quad G = G(P_f) \]

(+) low cost  
(-) Uses stationary forecast error covariance estimate \( P_f \)

**EnKF** (e.g, Lermusiaux, Chen & Rizzoli, also Roblou, De Mey):

(+) state dependent \( P_f \)  
?? Can 20-200 ensemble members span the error space ??

**Variational DA** (Wilkin, Kurapov, Ngodock, Moore): *Least squares fit to model & data over specified time interval*

(-) Requires adjoint code, minimiz. costly  
(+ state dependent \( P_f \),  
(+ Estimate both state and forcing  
(+ w/ asynchronous observations
Model vs coastal altimetry

Along track SLA variability

From Bouffard 2007 (PhD thesis)

Altimetric and Tide Gauge variabilities are twice more than the model one.
Why ? Because of the LF steric signal
Model vs coastal altimetry

Large scale LF signals (with a model steric correction)

Good agreement (both rms and mean)

The annual cycle is well represented

Time variability of the large spatial scale: TOPEX+Jason track 146 vs. SYMPHONIE

 Importance of the steric signals when compared sea level Obs./ Boussinesq model (that doesn't fully take into account the LF steric signal evolution)

SYMPHONIE [Marsaleix et al., 2007]
Boussinesq Model
On C grid with sigma generalized coordinate
Horizontal resolution : 3 km * 3 km
Boundary conditions : MFSTEP OGCM (Pinardi, 2003)

From Bouffard et al., 2008 (TAO in press)
- Good agreement with the Symphonie model on spatial scale greater than 50 km.
- Very small spatial scales (<13 km) are not reproduced by the model.
- Dynamics between 13 km and 60 km is only reproduced statistically.
Good agreements on instantaneous sea levels
Some disagreements close to the coast

Correlation - 2001
SYMPHONIE model elevations – altimetry
SLA: TOPEX + GFO

Correlation - 2002
SYMPHONIE model elevations – altimetry
SLA: Jason + GFO

Correlation - 2003
SYMPHONIE model elevations – altimetry
SLA: Jason + GFO + Envisat

From Bouffard et al., 2008 (TAO journal)
Model vs coastal altimetry
Problem at boundary condition

From Bouffard et al 2008 (TAO journal)

Problem at the OGCM forcing in the Corsica Chanel
This study emphasizes on:

- The importance of the LF steric signals in the altimetric sea level time series which are not fully simulated by Boussinesq models.
  
  ➔ Need of steric corrections for an altimetry/B. model homogeneity

- Problem of the model in terms
  - In terms of boundary conditions
  - In terms of mesoscale resolving

  ➔ Next of altimetry to diagnose and constrain the models
Application II: Data Assimilation in SSH on RTOFS (L. Liu et al./NOAA)

- SSHA: JASON-1, GFO, ENVISAT
- SSH=SSHA+MDT,
  - MDT from Rio, 2005
  - SSHA for depths < 1km is not employed.
  - QC: SSHA and SSH Innovations larger than 2.1 STD of SSHA are rejected.
- Algorithm: 2D Var in Horizontal, followed by 1D Var in Vertical
- HYCOM

(Potential for learning how SSH assimilation over deep ocean affects shelf areas)

- Latest Surface Height Forecast up to 120 Hours
Application III: Yi Chao et al.: 3DVAR / ROMS: Real-Time Forecasting Systems for SCCOOS and CeNCOOS
Using a 3-tier nested ROMS, we are developing a real-time forecasting system for Prince William Sound and nearby Alaska coastal waters.
Inhomogeneous and anisotropic 3D Global Error Covariance

Cross-shore and vertical section salinity correlation

SSH correlations

http://ourocean.jpl.nas.gov/MB06
**ROMS Analysis and Forecast Cycle:**
Incremental 3DVAR (feasible for real-time)

\[
\min_x J = \frac{1}{2} (x - x^f)^T B^{-1} (x - x^f) + \frac{1}{2} (Hx - y)^T R^{-1} (Hx - y)
\]

- **y:** observation
- **x:** model

\[x^a = x^f + \delta x^f\]
Incremental 3DVAR plus
Weak Geostrophic Constraint and Hydrostatic Balance

\[
x = \begin{pmatrix} \zeta \\ u \\ v \\ T \\ S \end{pmatrix} = \begin{pmatrix} x_\zeta \\ x_{uv} \\ x_{TS} \end{pmatrix} = \begin{pmatrix} x_\zeta^f + \Pi \delta x_{TS} + \delta x_{a\zeta} \\ x_{uv}^f + \Gamma \delta x_{TS} + \Phi_a \delta x_{a\psi \chi} \\ x_{TS}^f + \delta x_{TS} \end{pmatrix}
\]

(Li and Chao et al., JTech, submitted)

\[
\delta x_{uv} = \Gamma \delta x_{TS} + \Phi_a \delta x_{a\psi \chi}
\]

Geostrophic balance

\[
\delta x_{uv}^G = \Gamma \delta x_{TS}
\]

(Li and Chao et al., JGR, 2007)

\[
\delta x_\zeta = \Pi \delta x_{TS} + \delta x_{a\zeta}
\]

Vertical integral of the hydrostatic equation

\[
\delta x_\zeta^S = \Pi \delta x_{TS}
\]

(Li and Chao et al., MWR, 2006)

\[
\delta x_{a\psi \chi} \text{ ageostrophic streamfunction and velocity potential}
\]

Unique Features:
- Computational efficient to allow real-time forecasting
- Multiple sensors for the same variable with different errors
- Multiple variables
- In situ and remote sensing from satellite as well as land-based platforms
- Hydrographic measurements of temperature and salinity as well as velocity observations (e.g., HF radar)
Assimilated data sets included:
HF radar, gliders, SSH
(alongtrack)

SSH assimilation: larger effect in
away from the coast
Application IV: Oregon Shelf and Coastal Transition Zone (Kurapov et al.)

Dynamic regime: predominantly wind-driven on the shelf (Columbia R. plume and internal tides affect details of shelf transport), instabilities and coastal current separation in the ocean interior

3km ROMS nested into 9km NCOM-CCS (Kindle, NRL), COAMPS forcing

(Model analysis by Springer - NOPP):

SSH variability along satellite tracks is affected by separated currents and eddies

Real-time forecast model (CIOSS): http://www-hce.coas.oregonstate.edu/~orcoss/SSCforecast.html
SSH variation near coast associated with wind-driven upwelling:

COAST field experiment, summer 2001:
Moorings (ADP, T, S: Levine, Kosro, Boyd)
HF radars (Kosro)

Assimilation of moored velocities helps to improve variability in SSH prediction near coast (by dynamical adjustment) / 3DVAR implementation

SSH: obs, model only, DA (Lines N+S)

Model-data Corr.: 0.51 → 0.78, rmse: 5.4 → 3.8 cm

Kurapov et al. JGR (2005b)
Comparisons with mooring time-series (A. Koch CI OSS/GLOBEC):

- corr. coef = 0.86
- corr. coef = 0.76
- corr. coef = 0.61

(mooring data provided by P.M. Kosro, B. Hickey, S. Ramp)
Surface currents: long range HF radar (Kosro) and ROMS (Koch):

June, 2002

mean

July, 2002

StD ellipses
SST, GOES and ROMS (Koch):

Need better resolution (<3 km) to improve horizontal eddy fluxes of temperature and location of the temperature front?

Can assimilation of SSH improve the location of the temperature front, or more generally SST?
Different factors (e.g., Columbia R. plume) affect transports and the way the surface assimilated information would propagate to the ocean interior:

Columbia R. plume is advected southward with the coastal current. Cross-shore currents in the surface boundary layer x3 as fast as in the model case w/out Columbia R.

(Springer - NOPP, Fulton – NSF REU, CIOSS)
Possibilities for Assimilation off Oregon coast:

ALT tracks, 2003-2005

(array of HF radars, Kosro, 2003-present)

(figure courtesy P.T. Strub)
Representer-based variational DA
(w/ Egbert, Allen, Miller – ONR):

Inverse \( u(x,t) = \text{Prior} \ u(x,t) + \sum_k b_k \ r_k(x,t) \)

\( r_k(x,t) = [TL] \ C [ADJ] \ g_k \)

where \( g_k \) is the obs. functional (e.g., delta function at the obs. location)
C = error covariance for model input errors

How can we use the TL&ADJ tools?:

- Representer structure (3D + time): zones of influence of assimilated observations (or, multivariate model state error covariance)

- Array mode analysis: most stably observed combinations of representers (or model structures that can be best corrected)

- DA experiments

Illustrations here: use NL ROMS, TL&ADJ codes AVRORA (developed at OSU), along-shore uniform case (d .../dy=0), assume error in the wind stress
Representer (scaled by $-1 \text{ m}^{-1}$) for SSH measurement:

(Background ocean state: upwelling caused by $-0.12 \text{ N/m}^2$ wind stress for 3 days)

(Assume large cross-shore decorrelation length scale in alongshore wind stress, $l=50 \text{ km}$)

Representers are estimates of multivariate model state error covariances (between the model counterpart of obs. and all the other fields) – computed using TL&ADJ model and assumptions about errors in inputs.
(Assume small cross-shore decorrelation length scale in alongshore wind stress, \( l = 0.1 \) km)
Array mode analysis (array of surface alongshore velocity obs., all obs at t=3 d):

Sample all representers at all obs. locations ⇒ representer matrix \( R \). Do svd(\( R \))

Model error variance of array modes

Assumed data variance level \( = (0.05 \text{ m/s})^2 \)

Most stably observed combinations of \( r_k \)
Assumed data variance level $=(0.05 \text{ m})^2$

In this “2D” case (no alongshore variability): assimilation of surface currents may be more efficient than assimilation of SSH to correct for the error associated w/ wind stress

(still, we place high expectation for SSH assimilation to improve location of eddies and fronts, in the fully 3D case)
DA (twin experiment, or OSSE): assimilate alongshore surface currents, T=10 days

Prior: const wind stress (-0.12 N/m²)

True: wind stress is reduced inshore of the upwelling front (after N. Perlin et al. JPO 2007)

Assimilated data: sampled from the true solution (daily ave. alongshore velocities, days 2-10).

Time-ave RMS error is reduced:
Conclusions (for the “Oregon case”):

Variability in SSH associated with separation of coastal currents is found in alongtrack altimetry, matches model variability.

Variational DA: objective mapping of sparse and multivariate data sets using state dependent model error covariances.

Development of DA must be complemented with model improvements (resolution, physics).

Understanding of the source of model error is essential to effective DA.

In the coastal ocean, it would be beneficial to assimilate SSH together with other data (HF radar, glider, SST).

Adjoint-based tools: representers, array modes, observation array design, DA.
**Dynamic regime:** Boundary current separation region, large mesoscale eddies rapidly evolving mesoscale features strongly anisotropic variability

Similarities to Slope Sea and GS rings

<table>
<thead>
<tr>
<th>Resolution</th>
<th>0.25 x 0.25 degrees</th>
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<tbody>
<tr>
<td>$\Delta x$, $\Delta y$, $\Delta t$</td>
<td>$\sim 25$ km, 1080 sec</td>
</tr>
<tr>
<td>Bathymetry</td>
<td>16 to 4895 m</td>
</tr>
<tr>
<td>Open boundaries</td>
<td>Global NCOM (2001 and 2002)</td>
</tr>
<tr>
<td>Forcing</td>
<td>Global NOGAPS, daily</td>
</tr>
<tr>
<td>De-correlation scale</td>
<td>100 km, 150 m</td>
</tr>
<tr>
<td>N outer, N inner loops</td>
<td>10, 3</td>
</tr>
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</table>

$1/8^\circ$ resolution version simulates complex EOF “eddy” and “wave” modes of satellite SST and SSH in EAC separation:

EAC IS4DVAR

4DVar control variables are initial conditions of each interval

7-Day 4DVar Assimilation cycle

E1: SSH, SST Observations
E2: SSH, SST, XBT Observations
Ensemble Prediction: E2

White contours: Ensemble set
Color: Ensemble mean
Black contour: Observed SSH

1-day forecast
8-day forecast
15-day forecast
Synthetic XBT/CTD example:
Statistical projection of satellite SSH and SST using EOFs of subsurface $T(z)$, $S(z)$
Comparison between ROMS temperature *analysis (fit)* and *withheld observations* (all available XBTs); the XBT data were not assimilated – they are used here only to evaluate the quality of the reanalysis.

Similar results are obtained with *balance operator in background error covariance*.
Comparison between ROMS subsurface temperature *predictions* and all *XBT observations* in 2001-2002

<table>
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<tr>
<th>E3: SSH+SST+ Syn-CTD</th>
<th>correlation</th>
<th>RMS error (°C)</th>
</tr>
</thead>
</table>

Similar results are obtained with *balance operator in background error covariance*

- 0 lag – analysis skill
- 1 week lag – little loss of skill
- 2 week lag – forecast begins to deteriorate
- 3 week lag – forecast still better than …
- no assimilation
Application VI: U.S. East Coast (Wilkin)

**Dynamic regime:**

*Slope Sea*: Long-term mean gyre circulation; many GS rings and meander influences

*Gulf and Maine and Georges Bank*: Tidal mixing and tidal rectification; bathymetric steering

*Mid-Atlantic Bight shelf*: Large-scale flow on shelf influenced by seasonal winds, along- and across-shelf pressure gradients associated with low buoyancy shelf water and the Slope Sea gyre

Lessons from the EAC: IS4DVAR assimilation of gridded SSH with subsurface projection to $T(z),S(z)$ by statistical (data EOF or model covariance) or dynamical (balance operator) works because of low-mode geostrophic dynamics.

In the Slope Sea we anticipate similar methods would work.
Opportunities for altimetry DA in GoM and MAB:

Hierarchy of ROMS models:

NENA ... MABGOM ... ESPreSSO ... LaTTE
(12 km) ... (5 km) ... (1 km)

Pressure gradient (both barotropic and baroclinic) is fundamental to dynamic balance at all scales

• along-shelf p.g. to river plume

Slope Sea mesoscale (resolvable in altimetry) clearly impacts shelf circulation

Model shortcomings are typically:

• southwest mean flow is too weak, and

• Gulf Stream meander and ring influence is absent / misplaced

... both of which could be constrained by accurate altimetry
Difficulties for altimetry DA in GoM and MAB:

Inside the shelf/slope front the baroclinic pressure gradients can be associated with subsurface structures that are often seemingly decoupled from the surface geostrophic flow and SST
e.g. seasonal cold pool, salinity intrusions

Tides: $S_2$ is non-negligible especially in GoM (aliasing in Envisat)

How do we accommodate phase errors in tide model and ROMS w.r.t. altimeter?

Shelf/slope front is narrow and variable and located at a steep bathymetry change where, presumably, there is greatest uncertainty in the geoid
- are gravity data / geoid models useful at these scales?

Mean Dynamic Topography and 3-D climatological baroclinic density are not well mapped

Meteorology is downstream of the continent, therefore potential local influence in water vapor and wet troposphere correction term
Application VI: U.S. East Coast (Wilkin)

**Solving these difficulties in GoM and MAB:**

Dense complimentary integrated observational network

- velocity (CODAR, Oleander ADCP, MCC velocity, floats)
- repeat CTD (coastal and deep gliders, Argo, VOS)
- repeat and VOS XBT, NMFS surveys
- moorings, buoys (GoMOOS, NDBC) and cabled observatories (MVC0 and LEO)

Good tide models (WebTide, ADCIRC)

Good atmospheric analysis models (NCEP NAM, many regional WRF)

Some progress on climatological analysis of baroclinic circulation and dynamics
RU Endurance Line glider transect May 18-24, 2006

TOPEX interlaced mission ground-track
Ongoing observational experiment (Jul07-Jun 08)

OBJECTIVES

■ To explore the use and limitations of altimetry data in the coastal area
■ To characterize a coastal front with new technologies

Glider mission simultaneous to Envisat passage along track 773 (perpendicular to the Balearic front, main oceanographic signal in the area)

1st sampling: 6-13 July 2007
2nd sampling: 14-17 September 2007
3rd sampling: 23-27 November 2007
*planned

Glider data (1st sampling)

Balearic front

In Situ Salinity

Dynamic height and $V_g$ – glider ref. level 180 m

45-50 cm/s flowing Northeastwards
Dynamic height at 10 m with a reference level of 180 m obtained from glider data for the July (crosses) and September (circles) missions. Filtered data are in black. Units are cm.

Absolute Dynamic Topography (ADT) along ENVISAT- 773 track obtained by the addition of Sea level anomaly (SLA) plus Mean Dynamic Topography (MDT) from Rio et al. (2007). Crosses correspond to the cycle 59 (8 July 2007) and circles correspond to cycle 61 (16 September 2007). Filtered data are in black. Units are cm.

<table>
<thead>
<tr>
<th></th>
<th>July mission</th>
<th>September mission</th>
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<tbody>
<tr>
<td></td>
<td>Glider</td>
<td>ENVISAT</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Maximum</td>
<td>13.9</td>
<td>14.0</td>
</tr>
<tr>
<td>Minimum</td>
<td>-16.8</td>
<td>-9.2</td>
</tr>
<tr>
<td>Std</td>
<td>7.5</td>
<td>6.7</td>
</tr>
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</table>

Comparison of the across track geostrophic velocities statistics derived from glider and ENVISAT data for July and September missions. The velocities have been estimated from the filtered data. Units are cm/s and positive values mean flow to the Northeast.
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