SIO activities in preparation for SWOT and the next generation observing system

ECCO Meeting 2018

Matt Mazloff, Paul Chamberlain, Teri Chereskin, Bruce Cornuelle, Ganesh Gopalakrishnan, Luke Kachelein, Heriberto Vazquez Peralta, Aneesh Subramanian, Rui Sun, Ariane Verdy, Bia Villas Bôas, Kasia Zaba
Characterizing the California Current

Helmholtz decomposition to separate rotational and divergent components

Assimilation for next generation observing system

- Characterize physical scales and develop tools to map the state
- Hold model accountable to data. As data stream grows must also semi-automate QC: hold data accountable to model

Chereskin et al, submitted, JGR-Oceans,

Acoustic Doppler Current Profiler data: 1993-2004, 39 cruises
Assimilation for next generation observing system

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Chereskin et al, submitted, JGR-Oceans,

Characterizing the California Current

The challenge is to represent both the rotational (balanced, geostrophic) and divergent (ageostrophic) components of the flow.

In the CCS, the energy in these components converge at 70 km
Mapping all parts of the signal

- Surface waves
- Tides
- Internal waves
- Mixing
- Errors
- High-resolution implies high computational cost regional model and multi-grid assimilation

Normalized relative vorticity, $\zeta/f$, at 13m
MITgcm: California Current test bed

MITgcm
- 2 km
- Numerics identical to LLC4320
- Inputs different

Assimilate:
- SWOT (yellow lines)
- Nadir altimetry (Jason in cyan)
- Moorings (red)
- HF radar (magenta)
- NDBC buoys (yellow)
- Glider lines (green)
Developing a Regional Ocean-Atmosphere Coupled Model

- Rui Sun, A. Subramanian, M. Mazloff, B. Cornuelle, A. Miller, I. Hoteit, M. Ralph

Goals

• Developing a coupled atmosphere-ocean-wave model with assimilation capabilities.
• Developing a research tool for studying coupled interactions and extended range predictability.

![Diagram showing coupling between ESMF, MITGCM, WRF, and WaveWatch III]
One-way results: currents affect waves

Currents improve match to altimeter SWH

The eddy variability also affects the Surface wave field
Two-way coupling now started via Earth System Modeling Framework

WRF (atmospheric model) also coupled
Tide model integrated into MITgcm

Assimilation for large-scale field; not for tides

Good match to tide gauge data

<table>
<thead>
<tr>
<th></th>
<th>AmpModel</th>
<th>PhaModel</th>
<th>AmpGauge</th>
<th>PhaGauge</th>
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<td>O1</td>
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<td>Q1</td>
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</table>
• **Multigrid 4D-Var stabilizes the adjoint**

  – 4D-Var optimization relies on the adjoint of the tangent linear model.
  – The adjoint is linear, it doesn’t limit eddy-mean flow interaction – without feedback on mean flow sensitivity can grow without bound
  – Keeping adjoint model stable requires damping growing sensitivities.
  – Most trivial/common way to do this is with increased viscosity in the adjoint (e.g. factor of 10 or 100)
  – This mimics coarse resolution, so why run with the computational expense of the high-resolution forward model?
• **Other multigrid 4D-Var advantages**

  - Allows the forward simulation to use the best parameterizations and modeling schemes (may include tides, surface gravity waves, nonlinear advection and viscosity schemes, biogeochemistry)
  
  - Free to decide what observational information represented in optimization. (E.g. internal wave field can be treated as signal. If treated as noise the forward model can be used to help determine representation error on the fly)
  
  - Regardless of prescribed signal to noise, full cost function facilitates post-analysis validation of all scales. (Maps generated via 4d-var fit one set of scales & provide hypotheses on finer scales, informed and validated from SWOT)
Multi-grid 4D-Var is implemented in various architectures. Notably, it is part of the ECMWF operational methodology. Buehner et al., 2013 state that in February 2013 they were optimizing the 25 km resolution forward model solution using an adjoint run at 100 km resolution.

Multi-grid (or multi-resolution) 4D-Var is seamlessly integrated to ECCO via the adjoint model’s N-level checkpointing algorithm.

Figure 2.1 Schematic of the revised 4D-Var solution algorithm implemented in January 2003 (Cy25r4). Outer loops are performed at high resolution (currently T1279) using the full non-linear model. Inner iterations are performed at lower resolution (first T159, then T255) using the tangent-linear forecast model, linearised around a 12-hour succession of model states (the trajectory) obtained through interpolation from high resolution (S denotes the truncation operator, J the cost function and x the atmospheric state vector).
Reverse order integration (ii)

Adjoint = transpose of TLM

→ evaluated in reverse order
→ model state at every time step required in reverse
→ all state stored or recomputed

Solution: Checkpointing
(e.g. Griewank, 1992,
Restrepo et al., 1998)
balances storing vs. recomputation

\[ u_{k,lev3} \]
\[ \text{adv}_{k,lev3} \]
\[ u_{k,lev3} \]
\[ \text{adv}_{k,lev3} \]
\[ u_{k,lev3} \]
\[ \text{adv}_{k,lev3} \]

heimbach@mit.edu • http://mitgcm.org
http://www.ecco-group.org

JMSF School on Data Assimilation • Japan • August 2003
Multi-grid coupling

A model, $M$, and its adjoint, $M^T$, are used to optimize input adjustments, $F'$, to the input forcing $F$, such that $F_{opt} = F + F'$

Cost function, $J$, is calculated by sampling $M$. It is stored in data and model space and forces $M^T$
A state-of-the-art high-resolution model, $\mathcal{M}$, an upscaled model, $\mathcal{M}$, and its adjoint, $\mathcal{M}^T$, are used to optimize input adjustments, $F'$, to the input forcing $F$, such that $F_{opt} = F + F'$

Cost function, $J$, is calculated by sampling $\mathcal{M}$. It is stored in data space and forces $\mathcal{M}^T$

$\Delta J/\Delta F$ Optimization search

$M$ is periodically restored to downscaled $\mathcal{M}$ state
A state-of-the-art high-resolution model, $\mathcal{M}$, an upscaled model, $\mathcal{M}$, and its adjoint, $\mathcal{M}^T$, are used to optimize input adjustments, $F'$, to the input forcing $F$, such that $F_{opt} = F + F'$.

Cost function, $J$, is calculated by sampling $\mathcal{M}$. It is stored in data space and forces $\mathcal{M}^T$.

$\mathcal{M}$ is periodically restored to downscaled $\mathcal{M}$ state.
34 day example: 1/6 forward, 1/3 back. 52 vertical levels

Two-level checkpointing.

- 1/6 forward run, 30 minute time-step, 557 cores: **97 mins wallclock**
- The 1/3 adjoint run, 1 hour time-step, 229 cores: **25 mins wallclock**
- 1/6 adjoint run, 30 minute time-step, 557 cores: **189 mins wallclock**
- **One iteration of 4D-Var** (122 mins vs 286 mins = 2.3 times faster)
  - With multigrid = ~22 hours per year of 1/6 optimization
  - Without multigrid = ~51 hours per year of 1/6 optimization
  - **Adjoint model run ~4 times faster than forward run!**
Example: 34 day run. 1/6° forward and 1/3° adjoint. Cost is misfit to sea surface temperature (SST).

Normalized gradient with respect to initial conditions of temperature at 2.1 m, 85 m, and 220 m.
Assimilation for next generation observing system

• Characterize physical scales and **develop tools** to map the state
  – High-resolution implies high computational cost → regional domains, multi-grid assimilation
  – Surface waves → couple wave and ocean models
  – Tides → include tide model in ocean model
  – Internal waves → *exploring handling regional model open boundary forcing*
  – Errors → *ensemble approach or use gradient descent information from adjoint*
  – Evolved parameterizations and control vector → *informed from constraints*

• Hold model accountable to data. As data stream grows must **semi-automate QC**: holding the data accountable to model facilitated via state estimation

Surface Water Ocean Topography (SWOT) swath altimeter will measure SSH at 250 m resolution in two 50 km wide swaths on either side of its orbit. This is estimated to generate ~37 GB/day of data.

Image from swot.jpl.nasa.gov.
Why do regional models produce frequency spectra steeper than llc4320 and observations?

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Can a regional model generate enough internal wave energy?

- Mooring has high-frequency energy
- **Global** I1c4320 (2km) replicates mooring energy
- **Regional** ROMS (1km), MITgcm (2km), and NCOM (3.7km) are missing high-frequency energy
• Mooring and global LLC4320 (2km) have high-frequency energy

• Regional ROMS (1km), MITgcm (2km), and NCOM (3.7km) are all missing high-frequency energy

Hypotheses:

• Noise in LLC4320 and/or mooring meaning one or both is wrong.
• Representation of interaction with bottom topography
• How tides forced (i.e. as pressure loading) & their accuracy in LLC4320.
• Tidally generated internal waves do not have time to exchange energy and fill the (Garrett-Munk) spectrum in a regional domain.

If the latter, solutions:

1. Make domain large enough to allow internal waves to transform
2. Prescribe internal wave flux into the domain at the open boundaries
What is impact of local barotropic tidal forcing (imposed as a pressure loading) on the regional setup? 

One year time-series

**Mean**

**Standard Deviation**

**Salinity**

- **M2 Mooring**
  - Model 1: without local tidal forcing.
  - Model 2: with local tidal forcing.
What is impact of local barotropic tidal forcing (imposed as a pressure loading) on the regional setup?

**Time series**

- **Salinity at 60m**
  - M2 Mooring
  - Model 1: without local tidal forcing.
  - Model 2: with local tidal forcing

- **Temperature at 60m**
  - M2 Mooring

**Frequency spectra**

- **Salinity at 60m**
  - M2 Mooring
  - Model 1: without local tidal forcing.
  - Model 2: with local tidal forcing

- **Temperature at 60m**
  - M2 Mooring
Implications of forcing with barotropic tides on boundaries vs barotropic tides on boundary and locally (via pressure loading)

Compare to tide gauge analysis. Data from https://tidesandcurrents.noaa.gov/stations.html?type=Water+Levels
<table>
<thead>
<tr>
<th>Location</th>
<th>% Variance explained</th>
<th>M2 amplitude</th>
<th>K1 amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Tide gauge</td>
<td>Without</td>
</tr>
<tr>
<td>Harvest</td>
<td>71.5%</td>
<td>74.0%</td>
<td>0.49</td>
</tr>
<tr>
<td>Santa Barbara</td>
<td>71.5%</td>
<td>73.4%</td>
<td>0.51</td>
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<tr>
<td>Santa Monica</td>
<td>70.0%</td>
<td>72.2%</td>
<td>0.52</td>
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<tr>
<td>Los Angeles</td>
<td>70.9%</td>
<td>73.1%</td>
<td>0/53</td>
</tr>
</tbody>
</table>

January 2016 shown above for clarity, analysis carried out for full 2016
## Regional model analysis for 12 months

<table>
<thead>
<tr>
<th>Location</th>
<th>% Variance explained</th>
<th>M2 amplitude</th>
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<tr>
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<td>With-out</td>
<td>With local</td>
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</tr>
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<td>73.1%</td>
<td>0.53</td>
</tr>
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</table>

### LLC4320 analyzed for 4 months (June to September 2012)

<table>
<thead>
<tr>
<th>Location</th>
<th>M2 amplitude</th>
<th>K1 amplitude</th>
</tr>
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<tbody>
<tr>
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<td>0.70</td>
<td></td>
</tr>
<tr>
<td>Los Angeles</td>
<td></td>
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</tr>
</tbody>
</table>
Noise in LLC4320?

Vertical velocity ($W$) at 500 m

LLC4320
MITgcm regional

No, but note the difference in $W$ magnitude!
- Mooring and **global** LLC4320 (2km) have high-frequency energy
- **Regional** ROMS (1km), MITgcm (2km), and NCOM (3.7km) are all missing high-frequency energy

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Profiles of RMS W [m/s]

- **LLC4320**
- **Regional**

Color is 40m temperature

**Points:**
- 232.0696°E, 41.9928°S
- 234.8568°E, 40.0168°S
- 232.0696°E, 40.0168°S
- 240.9928°E, 33.7976°S
- 240.9928°E, 33.0072°S
- 240.9928°E, 33.0072°S

**Axes:**
- X-axis: m/s
- Y-axis: E
- Scale: 10^(-3)

**Map:**
- Color represents 40m temperature variation.
• Mooring and **global** LLC4320 (2km) have high-frequency energy

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