Where Do We Go From Here?

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We have a variety of North Atlantic state estimates, from varying data sets, models, durations, methodologies, resolutions, assumptions, and goals.

So what? What is the purpose of all of this?

(1) Curiosity driven research. How does the ocean “work”? (Until recently, this was why we all did oceanography.)

(2) Understanding the possible changes induced in, and induced by, the ocean on the climate and biological systems.

(3) The possibility of true prediction of things we care about in the social sense.

(4) Useful prediction, if possible.
One of the major difficulties in formulating a scientific plan for understanding the climate system is the huge variety of possibilities and interests, such as changes in heat content, salinity, meridional enthalpy transports, carbon uptake and transports, sea surface temperature, .... on time scales of years, decades, centuries,...., dynamics versus kinematics.

*How do you get a focus? A particular problem for designing observing systems.*

A suggestion:
The problem of prediction is an all encompassing one, as it goes to fundamentals of the understanding of the climate system, as well as all the practical issues such as sensitivity to initial conditions, model skill, missing boundary conditions, the design of observing systems, and knowledge of their adequacy.

Consider the regional sea level forecast problem spans essentially all of the problems of the ocean circulation: exchanges of enthalpy with the atmosphere, fresh water inputs, wind-derived circulation changes, abyssal heat and fresh water storage changes, open boundary transport fluctuations,…. and every different time scale from hours to millennia.

All such phenomena and their changes encompass theory and dynamics.

A much more intuitive impact on non-specialists than meridional heat or volume transports.

I will use this as a possible theme for future state estimation and the supporting observation network. Aim is to be quantitative.
Attempts are already being made to predict regional sea level change
The values show the mean change (2091–2100 relative to 1981–2000) projected by ten AR4 climate models under the A1B scenario. Stippling indicates the regions where the ensemble mean divided by the ensemble standard deviation is greater than two. See Supplementary Fig. S1 for the models used in the calculation of the ensemble mean and their projections.

Model projections of rapid sea-level rise on the northeast coast of the United States
Jianjun Yin¹, Michael E. Schlesinger² & Ronald J. Stouffer³

Nature Geoscience 2009

Northeast US could suffer most from sea rise

Add 8 inches for the region, new study says
By Seth Borenstein
Associated Press / March 16, 2009
Directly measured by a satellite. Note how complicated the pattern is. The global mean value is estimated as about 2.8mm/y +/-0.3mm/y According to Peltier (1991) should add another 0.33mm/y for post-glacial rebound.

What controls regional sea level change?

What can change global mean sea level?:

Net temperature change (heat exchange with the atmosphere)
Addition or subtraction of fresh water (exchange with atmosphere, land, ice)
Change in volume of the ocean (post glacial rebound; spreading rate changes)
Melting or formation of sea ice with non-zero salinity

What can change regional mean sea level?

All global contributions plus:

Local temperature shifts from air-sea interaction, advection, and diffusion
Local addition or removal of fresh water
Displacement of ocean circulation features
Tectonic shifts (uplift, …)
Gravity field modification (melting of glacial ice, post-glacial rebound)
Change in ocean load (local atm. pressure)

…. 
Rio & Hernandez, 2004, mean dynamic topography

One day surface elevation from ECCO-GODAE v3.73

General circulation dynamic topography is a 2m signature process subject to lateral shifts.
Lots of issues in every element of this problem:
Global total P about 1m (Peixoto and Oort, 1992) and approximately equal to the net E-R.

Many problems are meteorological in origin.

Note large disagreements
Annual mean area-weighted P-E in Antarctica for various regions and different elevations.

Bromwich et al., 2007, JGR

The “reanalyses” are nearly impossible to use for climate change purposes.
A related scenario in the 1990s-2000s?
- Dramatic increase in the amount and quality of satellite observations assimilated into the reanalyses (or available for assimilation).

(Dee et al., 2009, ECMWF Newsletter (119))

Number of observations assimilated in ERA-Interim

[Dee et al., 2009, ECMWF Newsletter (119)]
Mean annual precipitation (P)
1989-2008
(from D. Bromwich, 2010)
Precipitation by latitude bands
(from D. Bromwich, 2010)
Spurious trends in MERRA precipitation

The figure shows the 2-month running average difference between forecast daily precipitation from MERRA and from ERA-Int, spatially averaged over the 50°S-60°S latitude band.
What to believe in the North Atlantic? In the Arctic?

Needs to be quantified.
Other boundary conditions are equally uncertain. Excess ice melt, runoff,…

**GRACE trend map**

An estimate, but not the “truth”. Issues of temporal aliasing, atmospheric load, spectral leakage, adjustment for post-glacial rebound, and a very short time-span…

E. Schrama
2006.3 to 2009.3

Gt/yr

E. Schrama
what is the ocean doing at the margins?
what will it do in the future?

P. Huybrechts
Consider the background hydrological cycle:

Can one perceive the changes in the N. Atlantic circulation owing to increased fresh water input from the edges?

<table>
<thead>
<tr>
<th>Metric</th>
<th>Greenland</th>
<th>Antarctica</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1mm/d precip over Greenland</td>
<td>0.035 Sv</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>1mm/d precip over Antarctica</td>
<td>0.25 Sv</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>1mm/y to global ocean (order of mag. of sea level rise)</td>
<td>0.015 Sv</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Global mean ocean precip.</td>
<td>12+/-6 Sv</td>
<td>12+/-6</td>
<td>CMAPP website, NOAA, Xie and Arkin, 1997</td>
</tr>
<tr>
<td>Global mean runoff to ocean</td>
<td>37,000 km³/y</td>
<td>1.2</td>
<td>Dai et al, 2009, w/o Greenland/Antarctica</td>
</tr>
<tr>
<td>Groundwater discharge</td>
<td>2.2-2.4 x 10¹⁵ m³/y</td>
<td>0.07</td>
<td>Zektser et al., 2007; see Moore 2010</td>
</tr>
<tr>
<td>Global mean evaporation</td>
<td>-13</td>
<td>To balance runoff+precip</td>
<td></td>
</tr>
<tr>
<td>Greenland climatological runoff</td>
<td>100-200 km³/y</td>
<td>0.003-0.006</td>
<td>Box et al. 2004.</td>
</tr>
<tr>
<td>Antarctica climatological runoff</td>
<td>170 mm/y</td>
<td>0.07</td>
<td>Bromwich et al., 2004, Jacobs et al. 1992, 2613 km³/y (error bar?)</td>
</tr>
<tr>
<td>Net ice mass loss: Greenland</td>
<td>137 to 286 Gt/yr</td>
<td>0.004-0.009</td>
<td>Velicogna, 2009</td>
</tr>
<tr>
<td>Net ice mass loss: Antarctica</td>
<td>104 to 246 Gt/yr</td>
<td>0.003-0.007</td>
<td>“</td>
</tr>
<tr>
<td>1mm/y to global ocean: salinity change</td>
<td>1.3 x 10⁻² /y</td>
<td>negative</td>
<td></td>
</tr>
<tr>
<td>120m sea level rise in 10,000y</td>
<td>1 cm/y globally</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Deglacial salinity change rate</td>
<td>1.3 x 10⁻³ /y</td>
<td>negative</td>
<td>1.1 total 5 change</td>
</tr>
<tr>
<td>Heinrich event 4</td>
<td>2+/-1 m s.l. change over 250+/-150y</td>
<td>0.025-0.3</td>
<td>Roche et al., 2004</td>
</tr>
<tr>
<td>120m drawdown of sea level over 100KY</td>
<td>-0.012</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TOPEX value includes 0.3mm/y from R. Peltier estimate of ocean volume change (PGR). o from Miller & Douglas is pure tide gauge value.

Everything is positive! --- at least. (Global balance is primarily a test of scientific understanding.)
Sea level change sensitivity, western N. Atlantic (US east coast) from (normalized) temperature changes 15 years previously (P. Heimbach from ECCO v3.73)

Normalization is by the expected errors in the measurements.

Clearly, forecasting and understanding of change involve the ocean and atmospheric states over long times
East coast sea level anomaly, t=-15 years, sensitivity to normalized temperature anomaly, 3000m
Sensitivity, east coast sea level, to zonally summed, zonal wind, back to 15 years earlier.
Temperature sensitivity, 26N, N. Atlantic meridional heat flux to disturbances 15 years previous.

Figure 5: Maps of mean times weighted by the amplitude of the normalized response fields, eqn. 5, for two different depth levels. Color scale refers to years (from 0 to 12). A small value in a certain region indicates fast dominant time scales of dynamical link between the region considered and 38N in the Atlantic.
Information flow in the dual model: anti (dual) Kelvin, Rossby waves etc.

Figure 3: A schematic of anti-Kelvin waves (lines) and anti-Rossby waves (contours and dotted arrows) propagating sensitivity from the 2050 line backward in time. Color coding refers to different events discussed in the text. (E1): red, (E2): light blue, (E3): dark blue. (map schematic)
Observations:

Need meteorological forcing back several decades---a demand for useful reanalyses (balanced in energy, water, etc.) with physical budgets

Climatological fresh water inputs including runoff, ice melt, subsurface percolation

*Increments* of ice melt

The ocean state, globally, as far back as is practicable. Predictions of:

*Meteorological forcing*, including winds, E-P, total heat transfer.

The ocean state.
Modelling

Resolution issues---numerical convergence
Surface boundary layer issues (manifold)
Mass conservation (Boussinesq approximation)
Geothermal contribution...

1/9deg
mixed layer depth
1deg
1/54 deg.

Lévy et al., Ocean Mod., 2010

meridional heat transport
At what skill level are predictions useful? What skill level can be achieved with inevitable uncertainty growth backward into the past? What is that skill as a function of prediction lead time?
An understanding of a predicted regional change over e.g., 1 to 10 decades, requires quantitative measurements and budgets (temporal and spatial) for the regional:

Freshwater input/output: precip., evaporation, land ice, melting/forming sea ice, subsurface percolation,
Heat exchange with the atmosphere
Wind-shifts

Adective inputs of volume/mass from the south and from the Arctic (the open boundaries)

Dynamical, quantitative understanding of the volumetric changes and their time-scales and relative contributions.

Quantitative predictability of these different elements.
A Strawman Proposal

Agree on a goal: US east coast sea level trend to be predicted to 15 years with an accuracy equivalent to 0.3mm/y. (Almost all physical processes show up in sea level and/or are affected by sea level.) Altimeter sets of a nominal accuracy goal.

Design an observing system that would be capable of that accuracy.

Develop the models capable of that accuracy.

Formulate a requirement on meteorological reanalyses capable of that accuracy.

Construct a coupled atmosphere-ocean-sea ice-land ice model formally capable of prediction from a known initial state.

Many people will not find this a compelling goal---but it does provide a framework incorporating almost all imaginable ones related to the ocean circulation. A 15-year time scale is humanly accessible. It involves several other communities. Is that a bad thing?
Something for everyone:

Model development
Theory
Observations
Real practical potential

A prize (?):

$10,000 to be given to a forecast---made 12 years in advance---of sea level change along the US east coast (north of Cape Hatteras to Cape Cod ?), reproducing the observed trend to within 0.3mm/y. In the event of more than one successful candidate, tie breaking will be determined by the skill in (1) heat content change north of 30N, (2) sea ice cover in January, (3) September sea ice cover….

(Details, and determination of a winner, to be worked out in practice by an appointed committee.)
Thank you.