Ocean Variability from the Surface to the Abyss

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Key:
= Work Active Since at Brown
= Notable Contribution of F-K Group Member
To understand ocean & climate variability, it is important to distinguish:

- Presence of observable variability
- Understanding of past variability
- Modeling of variability
- Prediction of variability

Focus Today: diurnal to centennial variability
Presence of observable variability

It is easier to observe the ocean consequences of air-sea exchange (ocean heat content (OHC), salinity) rather than exchanges (fluxes) themselves.

However, insufficient for prediction and attribution
## Prediction & Attribution Goal:

**Effects of Anthropogenic Forcing**

<table>
<thead>
<tr>
<th>Forcing agent</th>
<th>Radiative Forcing (W m$^{-2}$)</th>
<th>Confidence Level</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Anthropogenic</strong></td>
<td></td>
<td></td>
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<tr>
<td>Well Mixed Greenhouse Gases</td>
<td><img src="chart.png" alt="Radiative Forcing Graph" /></td>
<td>Very High</td>
</tr>
<tr>
<td>Ozone</td>
<td><img src="chart.png" alt="Radiative Forcing Graph" /></td>
<td>High</td>
</tr>
<tr>
<td>Stratospheric water vapour from CH$_4$</td>
<td><img src="chart.png" alt="Radiative Forcing Graph" /></td>
<td>Medium</td>
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<tr>
<td>Surface Albedo</td>
<td><img src="chart.png" alt="Radiative Forcing Graph" /></td>
<td>High/Low</td>
</tr>
<tr>
<td>Contrails</td>
<td><img src="chart.png" alt="Radiative Forcing Graph" /></td>
<td>Medium/Low</td>
</tr>
<tr>
<td>Aerosol-Radiation Interac.</td>
<td><img src="chart.png" alt="Radiative Forcing Graph" /></td>
<td>High/Medium</td>
</tr>
<tr>
<td>Aerosol-Cloud Interac.</td>
<td><img src="chart.png" alt="Radiative Forcing Graph" /></td>
<td>Low</td>
</tr>
<tr>
<td><strong>Total anthropogenic</strong></td>
<td><img src="chart.png" alt="Radiative Forcing Graph" /></td>
<td></td>
</tr>
<tr>
<td><strong>Natural</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar irradiance</td>
<td><img src="chart.png" alt="Radiative Forcing Graph" /></td>
<td>Medium</td>
</tr>
</tbody>
</table>

*IPCC AR5, 2013*
Question: By Show of Hands Indicate Whether You Have Heard that the IPCC is

- A) Wrong
- B) Independent Police Complaints Commission of England & Wales
- C) Together with Al Gore, they invented the internet
- D) The Intergovernmental Panel on Climate Change, a nonpolitical group that reviews peer-reviewed climate science and summarizes it for policymakers, who won a Nobel Peace Prize shared with Al Gore.
Surface Energy Budget

Category A) T change caused by forced $Q_{TOA}$

Category B) T change caused by unforced $Q_{TOA}$

Category C) T change caused by unforced $Q_{BML}$

$\frac{dT}{dt} = \frac{Q_{net}}{C_m} = -\frac{Q_{TOA} + Q_{BML}}{C_m}$

$Q_{TOA} = RSW + OLR - ISW$

O(2W/m²) change to $Q_{BML}$ as important as GHG

Slight oversimplification—sensitivity + budget

Slide: Brown et al., 2014
What do hydrographic observations show?

Ocean Heat Content not fixed: \( Q_{BML} \) not zero (it even varies)!

28% of anthropogenic forcing equals the warming in the oceans and about 70% goes back to space.

90% of anomalous warming is in the oceans.

0.7 W/m\(^2\) to atmosphere only is about 1.5K/yr

### Trad. Hydrography

(a) 1993–2008 Planetary Energy Imbalance

- Lyman
- Ocean (0.625 ± 0.115)
- Levitus

### From the Argo Era

(b) 2005–2010 Planetary Energy Imbalance

- Ocean (0.51 ± 0.12)
- Argo (0.41)

Hansen et al. (2011)
How do we know OHC?

Traditional Hydrography (http://www.ukosnap.org/)

Autonomous: e.g., Argo and Satellites.
http://www.argo.ucsd.edu/

GO-SHIP repeat sections: Siedler et al. 2013

Argo floats presently active
Another reason to care about ocean warming—and to observe it (by subtraction): Sea Level Rise

\[
\text{(Sea Level)} - \frac{\text{(Ocean Mass)}}{\text{Density/Area}} = \text{Thermosteric Expansion}
\]

IPCC AR5, 2013
Surface, Mixed Layer, Seasons?

Atmosphere:
1.5K/yr
= 3.4m Ocean:
1.5K/yr
= 34m Ocean:
0.15K/yr
=1% of mixed layer seasonality

Beginning December 1949, a weathership or mooring at Ocean Station P (50°N, 145°W, depth 4220 meters)

http://www.oc.nps.edu/
The net $Q_{BML}$ is also about 1% of different flux components and about 1% of net spatial extremes.

Boundary Currents

Eddies

1000 km, months

Full Depth (4km)

Eddy Pot'l Energy:

13EJ vs. 20EJ in Mean Circulation

Eddy Kinetic Power:

About equal to mean circ. 2-3TW

(Wunsch & Ferrari, 2004)

The Mesoscale

100 km

Mesoscale Eddies: How to represent in climate models?

Satellite altimetry view of mesoscale flows

Thanks to Michael Bramble’s Lunch Bunch—A Mesoscale Eddy can be covered with 1-10 Rhode Islands.
Sophisticated analysis to overcome Ship & Argo sampling problems—inhherent uncertainty, $O(0.2 W/m^2)$, on interannual to decadal timescales in global average. $O(10 W/m^2)$ without analysis.

There is observable (autonomous, satellite & ship) ocean heat content variability.

The near surface seasonal cycle, regional variations, and individual flux components are $O(100 \text{ W/m}^2)$

Imbalance of $Q_{\text{TOA}}$ and net mixed layer entrainment $Q_{\text{BML}}$ are $O(1 \text{ W/m}^2)$

In Situ & Satellite agree.

Presence of observable variability
Understanding of past variability

Monday Morning Quarterbacking abounds in variability analyses, e.g.:

You can’t use 1998 as a start year for climate change—it was the biggest ENSO event of the past 100yr...

Phase of the PDO explains the recent warming hiatus, but we don’t know what PDO is...

May explain and test our understanding, but it has little predictive power.
Weather, Atmosphere Fast

Ocean, Climate Slow

3.4m of ocean water has same heat capacity as the WHOLE atmosphere
Modeling of variability
Consider lots of 1D Oceans: one per watermass.

Wind (Ekman) flushing gives upper limit to $\lambda^{-1}$ timescale.
If Connections Occur Between Regions—
Predictability Can Arise, Even in Stochastic Systems.

Tropical Ocean Heat Content

Polar Ocean Heat Content

This is the root cause of most stochastic model predictability beyond persistence.

Global climate models do pretty well at matching heat fluxes and watermasses.

Statistically significant differences in a few timescales & regions from obs. (Ticks=10 W/m²)

Models get better every generation due to improved resolution and parameterizations

What does it take to make these improvements?


Fig. 4. Regional averages of the CCSM4 20C ensemble mean heat flux components differenced with the CORE.
What does a climate model—WITHOUT WARMING—look like in Ocean Heat Content Variability?

Doesn’t even include mesoscale eddies

From the >1000yr steady forcing CCSM3.5 runs of Stevenson et al. 2012

Too Simple: What about directly modeling processes in climate models? Don’t we have big enough computers? or won’t we soon?

Here are the collection of IPCC models...

If we can’t resolve a process, we need to develop a parameterization or subgrid model of its effect.
Flux-Gradient (Anisotropic)

\[ \overline{u_j' \tau'_\pi} = -R_{ji} \nabla_i \overline{\tau_\pi}, \]

AVISO: log10(0.5 (u^2+v^2)) on 19940101

Major Diffusivity

Minor Diffusivity

Vertical Diffusivity


Anisotropy often reduces biases:
- pCFC by up to 24%
- Temp by up to 48%
- Salinity by up to 63%

Mesoscale Eddies have a profound effect on $Q_{\text{BML}}$
Even small changes affect surface warming budget
Complicated Mesoscale Eddy Air-Sea Feedbacks? Resolve!

Effect on net air-sea fluxes observed, parameterization unknown. Bryan et al. 2010, Frenger et al. 2013
What about modeling important processes in climate models? Don’t we have big enough computers? or won’t we soon?

Here are the collection of IPCC models...

If we can’t resolve a process, we need to develop a parameterization or subgrid model of its effect.

10km grid = 2 Providences/grid
By comparing resolved mesoscale eddies to parameterized ones (with same 50km atmosphere), we get another entry in the pile!

$O(0.7 \ W/m^2)$ persistent and $O(0.4 \ K/\text{century})$, i.e., significant warming to upper 1500m of ocean.

MILLIONS OF CPUHRS!

Brown
What about modeling important processes in climate models? Don’t we have big enough computers? or won’t we soon?

Here are the collection of IPCC models...

If we can’t resolve a process, we need to develop a parameterization or subgrid model of its effect.

100m grid = 1 soccer field/grid
The Character of the Submesoscale

(Capet et al., 2008)

- Fronts
- Eddies
- $Ro = O(1)$
- $Ri = O(1)$
- near-surface ($H = 100m$)
- 1-10km, days

Eddy processes often baroclinic instability

Parameterizations = BFK et al (08-11).


Global Ocean Climate is SENSITIVE to these Submesoscale Eddies! At least in parameterized form. Implemented in IPCC AR5 & 6: NCAR, GFDL, Hadley, NEMO,...

20km x 20km x 150m domain

10 Day Simulation

Climate Model Resolution: an issue for centuries to come!

Here are the collection of IPCC models...

If we can’t resolve a process, we need to develop a parameterization or subgrid model of its effect.
20km x 20km x 150m domain
10 Day Simulation

Colors=Temp.
Surfaces on Large w

1km x 1km x 40m sub-domain
about 1 day shown

Near-surface


$Ro \gg 1$

$Ri < 1$: Nonhydro

1-100m (H=L)

10s to 1hr

$w, u = O(10\text{cm/s})$

Stokes drift

Eqtns: Craik–Leibovich


Resolved routinely in 2170
How much does Langmuir mixing affect Globe?

Global Air–sea flux changes by 0.26 W/m² when Langmuir mixing is introduced.

Regions, e.g. Lab Sea: 10–15 W/m²

Dashed lines include wave mixing.

Stokes drift does more than boundary layer mixing!
Making our way to new parameterizations—
Coastal models, oil spills, etc.

There are 851796 drifters in the picture

Movie: Creative Commons

N. Suzuki and BFK. Understanding Stokes Forces in the Wave-Averaged Equations, JGR, in prep, 2015.


Brown
CU, now Scripps
CU, now Tokyo
Are Fronts and Filaments different with Stokes shear force?

\[
\frac{\alpha^2}{R_i} \left[ w_{,t} + v_{j}^L w_{,j} + \frac{M_{Ro}}{R_0 R_i} w w_{,z} \right] = -\pi_{,z} + b - \varepsilon v_{j}^L v_{j,\tau}^s + \frac{\alpha^2}{R e R_i} w_{,\tau}^s
\]


Turbulence Obs & Stats!

We try to check all of the high-resolution models and turbulence parameterizations against data. There is a lot of statistical work that goes along with doing so.


FIG. 5. The log of salinity variance at 5 m with a solid box around the chosen near-homogeneous region in the Kuroshio. The dashed line...
Prediction of variability

Predictability of ENSO events limited to < 1yr

ENSO statistics more predictable?

![Graph showing historical NINO3.4 Sea Surface Temperature Anomaly](image)

![Map showing El Niño Episode Sea Surface Temperatures](image)

![Map showing La Niña Episode Sea Surface Temperatures](image)

![Graph showing Mid-Jan 2014 Plume of Model ENSO Predictions](image)
Almost no change to Direct ENSO variability with GHG… (>200 yr to detect)

Big GHG Change to ENSO impacts!

INDIRECT Proxy Reconstructions won’t work!!!
Understanding of past variability

New: Abyssal Variability is the HARDEST!

- Stochastic damping very slow!
  - huge heat capacity (biggest watermasses on Earth)!
- Timescales may be very long!
  - Watermasses $O(1500\text{yr})$ old by radiocarbon
- Lengthscales may be very short!
  - (weak stratification implies a Rossby radius of $O(2\text{km})$ for modes trapped in AABW only)
- Water “formed” in very small areas!
  - Small-scale atmospheric & oceanic phenomena will be disproportionately important on air-sea effects

Difficult to observe, IMPOSSIBLE TO MODEL = FUN!
Even with Argo, it will be a while until we have long timescale variability. What to do?

Pattern of Warming from Hydrography

Examine CDH-26 sediment core from the Holocene indicated

Purkey & Johnson, 2010
Understanding of past variability

Assessing variability using individual benthic foraminifera

- Benthic foraminiferal $\delta^{18}O$ values record temperature and salinity properties of ambient seawater
  
  \[ T \, (^{\circ}C) = 21.6 - 5.50 \times (\delta^{18}O_{c}-\delta^{18}O_{sw}) \]  
  Bemis et al. 2002

  \[ \delta^{18}O_{sw} = -14.38 + 0.42 \times \text{salinity} \]  
  Conroy et al. 2014

- Individual foraminifera provide 2-3 week snapshots of seawater properties

- We analyze 30-40 individuals within 200 year windows to assess the mean and variance of foraminiferal $\delta^{18}O$ values
  On roughly decadal timescales

\[ \delta^{18}O = \left( \frac{(^{18}O)}{(^{16}O)}_{\text{sample}} - 1 \right) \times 1000 \%_o \]

*Image of individual foraminifer.*
Understanding of past variability

Some individuals >2°C warmer!

Low variability in mean climate

Some individuals colder!
At these three time intervals, the spread of individual values exceeds a size-matched spread of instrumental standards.

The statistical significance of this deviation is given by the p-values of a Kolmogorov-Smirnov test comparing the distributions.

If this is right—abyssal variability may have an **unexpectedly important role**, **intermittently** through the past!
Conclusions

**Presence** of observable variability
- Regional $O(100 \, \text{W/m}^2)$, Global Net $O(1 \, \text{W/m}^2)$
- Difficult due to sampling, obs. density & duration
- Many problems require paleothermometry!

**Understanding** of past variability
- Not always a path to progress w/o models & predictions
- But, discovery of new processes & unexpected variability is a way forward to better predictions!

**Modeling** of variability
- Stochastic models work— but not very predictive.
- Deterministic models: discrepancies in tuning, params, resolution.
- Fun to work on parameterizations & process understanding, though!

**Prediction** of variability
- Possible in some regions, chaos limits the forecast window.
- Accurate global budgets need process-level understanding and modeling.
At these four time intervals, the spread of individual values fits within a size-matched spread of instrumental standards.
Compare to Observational Product