Ocean Variability from the Surface to the Abyss

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DEEP Sciences Colloquium
Brown University 10/1/15

Sponsors: NSF 1245944, 1258907, 1350795, GoMRI, and Institute at Brown for Environment and Society (IBES)

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

Radiative forcing of climate between 1750 and 2011

Forcing agent
- Well Mixed Greenhouse Gases
  - CO₂
  - CH₄
  - N₂O
  - Halocarbons
  - Other WMGHG
- Ozone
  - Stratospheric
  - Tropospheric
- Stratospheric water vapour from CH₄
  - AR4 estimates
- Surface Albedo
  - Land Use
  - Black carbon on snow
- Contrails
  - Contrail induced cirrus
- Aerosol-Radiation Interac.
- Aerosol-Cloud Interac.
  - Medium
  - Low
  - High
  - Medium
- Total anthropogenic
- Natural
  - Solar irradiance
  - Medium

Confidence Level
- Very High
- High
- Medium
- Low

Radiative Forcing (W m⁻²)
- 0
- 1
- 2
- 3
- -1
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 $Q_{BML}$

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

OLR

RSW

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

Space

Atmosphere

Mixed Layer

Deep Ocean

Slide: Brown et al., 2014

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

Slight oversimplification—sensitivity + budget
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/m² to atmosphere only is about 1.5K/yr

Trad. Hydrography

From the Argo Era

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**

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

IPCC AR5, 2013
0.7 W/m²
= Atmosphere: 1.5K/yr
= 3.4m Ocean: 1.5K/yr
= 34m Ocean: 0.15K/yr
= 1% of mixed layer seasonality

Surface, Mixed Layer, Seasons?

Beginning December 1949, a weathership or mooring at Ocean Station P (50°N, 145°W, depth 4220 meters)
The net $Q_{BML}$ is also about 1% of different flux components and about 1% of net spatial extremes.

Boundary Currents

Eddies

100 km, months

Full Depth (4km)

Eddy Potential Energy: 13EJ vs. 20EJ in Mean Circulation

Eddy Kinetic Power: About equal to mean circ. 2-3TW (Wunsch & Ferrari, 2004)

The Mesoscale 100 km (Capet et al., 2008) 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, $O(0.2W/m^2)$, on interannual to decadal timescales in global average.

$O(10W/m^2)$ without analysis.

Presence of observable variability

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.
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 the 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 $h_{tropics}$

Polar Ocean Heat Content $h_{poles}$

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?

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.
Anisotropic Mesoscale Eddy Advection & Diffusive Transport

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

Symmetric = Diff. \hspace{1cm} Antisymmetric = Adv.

Flux-Gradient 
(Anisotropic)

AVISO: \( \log_{10}(0.5 (u^2 + v^2)) \) on 19940101

Major Diffusivity

Minor Diffusivity

Vertical Diffusivity


Along transect

Control: Isotropic

Anisotropic

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 $Q_{BML}$
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, Freenger 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.
By comparing resolved mesoscale eddies to parameterized ones (with same 50km atmosphere), we get another entry in the pile!

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

MILLIONS OF CPUHRS!

Brown

200km x 600km x 700m domain

1000 Day Simulation
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
- $\mathbf{Ro} = O(1)$
- $\mathbf{Ri} = O(1)$
- 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,…

February
Mixed layer depth Bias w/o MLE

Deep Mixed Layer Bias reduced

O(0.1 W/m²) change to global mean net fluxes, Regional: 5 to 50 W/m²

20km x 20km x 150m domain

10 Day Simulation


movie credit: P. Hamlington
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.

3m = 1 office/grid
The Character of the Langmuir Scale

- Near-surface
- $Ro >> 1$
- $Ri < 1$: Nonhydro
- 1-100m (H=L)
- 10s to 1hr
- $w, u = O(10\text{cm/s})$
- Stokes drift
- Eqtns: Craik-Leibovich
- Resolved routinely in 2170

Figure 1 Sketch showing the pattern of mean flow in idealized Langmuir circulation. The windrows may be 2 m to 300 m apart, and the cell form is roughly square (as shown). In practice the flow is turbulent, especially near the water surface, and the windrows (Figure 2) amalgamate and meander in space and time. Bands of bubbles or buoyant algae may form within the downward-going (or downwelling) flow (see Figure 3).

Image: NPR.org, Deep Water Horizon Spill
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.


After 80 Min

Brown
CU, now Scripps
CU, now Tokyo

Are Fronts and Filaments different with Stokes shear force?

\[
\frac{\alpha^2}{Ri} \left[ w_{,t} + u_{,j}^L w_{,j} + \frac{M_{Ro}}{RoRi} w w_{,z} \right] = -\pi_{,z} + b - \epsilon v_{,j}^L v_{,j,zz} + \frac{\alpha^2}{ReRi} w_{,jj}
\]


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?
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!!!

S. Stevenson, BFK, M. Jochum, R. Neale, C. Deser, and G. Meehl.
Will there be a significant change to El Nino in the 21st century?
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
  \[
  \delta^{18}O_{sw} = -14.38 + 0.42 \text{ salinity}
  \]
  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.

\[\delta^{18}O = \left( \frac{\left(\frac{^{18}O}{^{16}O}\right)_{\text{sample}}}{\left(\frac{^{18}O}{^{16}O}\right)_{\text{standard}}} - 1 \right) \times 1000 \%^o\]
Understanding of past variability

Some individuals >2C warmer!

Low variability in mean climate

Some individuals colder!

Figure Credit: Sam Bova
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.

Figure Credit: Sam Bova
Compare to Observational Product