Turbulence and Variability in the Ocean

Baylor Fox-Kemper (Brown DEEP Sciences)
  with Samantha Bova & Tim Herbert (Brown),
  Dibyendu Mandal (UC-Berkley), Arin Nelson & Jeff Weiss (CU-ATOC),
  Royce Zia (Va. Tech.)

GAFD Seminar
University of Exeter 25/4/16
Sponsors: NSF 1245944 and Institute at Brown for Environment and Society (IBES)
To understand ocean & climate variability, it is important to distinguish:

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

Anthropogenic
- Well Mixed Greenhouse Gases
  - CO₂
  - Halocarbons
  - Other WMGHG
  - CH₄
  - N₂O
  - Stratospheric
  - Tropospheric
- Ozone
- Stratospheric water vapour from CH₄
- Surface Albedo
- Land Use
- Black carbon on snow
- Contrails
  - Contrail induced cirrus
- Aerosol-Radiation Interac.
- Aerosol-Cloud Interac.
- Total anthropogenic

Natural
- Solar irradiance

Confidence Level
- Very High
- High
- Medium
- Low

Radiative Forcing (W m⁻²)
-1 0 1 2 3

IPCC AR5, 2013
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 $Q_{BML}$

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

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 (and 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

(b) 2005–2010 Planetary Energy Imbalance

- Ocean (0.51 ± 0.12)

**From the Argo Era**

- 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/

Argo floats presently active

GO-SHIP repeat sections: Siedler et al. 2013
How do we know OHC?

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

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

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

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

IPCC AR5, 2013
0.7 W/m$^2$ = 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.
The Mesoscale

- Boundary Currents
- Eddies
- 100km, 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)

Mesoscale Eddies: How to represent in climate models?
The Mesoscale

- Boundary Currents
- Eddies
- 100km, 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)

Satellite altimetry view of mesoscale flows

AVISO: $\log_{10}(0.5(u^2 + v^2))$ on 19940101
A Mesoscale Eddy can be covered with 1-10 Rhode Islands.
A Mesoscale Eddy can be covered with 1-10 Rhode Islands. Oxfordshires

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 & SSH 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 same heat capacity as the WHOLE atmosphere
Weather, Atmosphere Fast

Ocean, Climate Slow

3.4m of ocean water has same heat capacity as the WHOLE atmosphere
Modeling of variability
Modeling of variability

A stochastic, predictable persistence model: Frankignoul & Hasselmann (77)

\[
\frac{dT}{dt} = f_1' - \lambda T
\]

\[
\text{Mixed Layer}
\]

\[
\text{Restoring}
\]

\[
\text{Random Atmosphere}
\]

Decadal power varies by 2 orders of magnitude

\[
\lambda = \rho^a C_p^q (\rho^w C_p^w)^{-1} C_H (1 + B) \langle |U| \rangle h^{-1}
\]

\[
= (1.7 \text{ month})^{-1}
\]
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.

Stochastic Predator-Prey Model
(Lotka-Volterra)

Two springs connected to each other and to thermal baths at different temperatures

Earth System Model, averaged ocean heat content over tropics (>28S to <28N) or poles (>28N or <28S)

The root cause of most stochastic 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.

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.
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.
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.

In global models, even with sophisticated parameterizations, numerics, and/or eddy-resolving, the overall heating of the abyss is *tunable* by choice among reasonable parameter values.

Prediction of variability

Predictability of ENSO events limited to < 1yr

ENSO statistics more predictable?
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!!!


CU, now NCAR
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
Assessing variability using individual benthic foraminifera

• Benthic foraminiferal $\delta^{18}O$ values record temperature and salinity properties of ambient seawater

$$T \ (°C) = 21.6 - 5.50 \times (\delta^{18}O_c - \delta^{18}O_{sw})$$

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

Understanding of past variability

Understanding of past variability

Some individuals >2°C warmer!

Low variability in mean climate

Some individuals colder!

Understanding of past variability

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!
Some timescales from theory—
What is this variability?

- Advective timescale—“water age”, estimated by Gebbie & Huybers from tracers.

- Baroclinic waves

  https://www.youtube.com/watch?v=oljinlD2yho

- Baroclinic Kelvin & Rossby
Fig. 8. Latitude–depth sections of mean age: (top) the Atlantic averaged between 60°W and 10°E, (middle) the Indian Ocean between 40° and 80°E, and (bottom) the Pacific between the date line and 110°W. The contour interval is 100 years in all panels.
Simpler: Reduced Gravity

If motions are coherent only below a given level \(-h\), and zero above this level, then bottom layer dynamics are just the shallow water equations with \(g'\) as \(g\).

\(g' = g\) (ratio of density difference to total density)

For AABW vs overlying water—potential density ratio is about 0.02%. Layer is roughly 2km thick.

Internal gravity wave speed is \(c^2 = g'(H-h) = (2 \text{ m/s})^2\)

4 months to traverse the Pacific N-S.

But, PV not affected by gravity waves—circulation will not adjust this fast
A plunger in a nonrotating channel
A plunger in a nonrotating channel
A plunger in a rotating channel drives a different wave
A plunger in a rotating channel drives a different wave
A blob of water in a beta-plane rotating channel leaves a rotating high–slow westward propagation
A blob of water in a beta-plane rotating channel leaves a rotating high--slow westward propagation.
Kelvin & Rossby Waves

Kelvin have same speed as gravity waves, but trapped against coastlines. Kelvin waves speed along the coastlines (<1 yr), and generate Rossby waves to adjust the basin interior. Based on the reduced gravity estimate, it will take at least 25 years.

The low stratification of the abyssal water gives only a 20km Rossby radius, so speed is slow and waves are hard to resolve in numerical models.

\[ T = \frac{L_B}{\beta L_D^2} \approx \frac{L_B |f|^2}{\beta g'(H - h)} \approx 25\text{yr} \]
Estimates were for flat bottom oceans, horizontally constant stratification, and non-equatorial rotation.

As there is probably much more variability in the near surface, it is possible that including these effects will make the continuation of upper ocean variability create significant near bottom variability.

However, as the movies only depict heat content (and not PV), more to do to see exactly how this works and quantitatively estimate.
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.
Null Results

Figure Credit: Sam Bova

Brown
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