A more productive, but different, ocean after mitigation

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June 7 2016
Outline

Climate and Modeling

Long-term climate change

Ocean and marine ecosystems

Ocean response to mitigation

Future directions
Earth’s climate is changing rapidly. By understanding interactions between the atmosphere, oceans, land, ice and Earth’s biogeochemical cycles, scientists can better predict how climate will change in the future.
How do we study climate?

An Earth System Model (ESM) is a computer model designed to create a “Virtual Earth” representation of the complex processes of the Earth System.
What affects climate?

MECHANISMS

- energy output of the sun
- volcanic eruptions
- greenhouse gases (e.g. carbon dioxide, methane, water vapor, and ozone)
- aerosols
How do external forcings affect ocean temperature?

- Cooling from **volcanic eruptions**
- Warming from well-mixed **greenhouse gases**
- Net cooling from **volcanic plus solar forcing** offsets a large portion of **anthropogenic warming**
- **Anthropogenic aerosols** offset about half of global ocean warming from **greenhouse gases** in this simulation

(Delworth et al., 2005)
How are model results assessed for reliability and accuracy?

Validating Models

• compare simulations of present-day climate to observations collected from space, land and oceans
• determine how well past climate has been simulated

http://www.moc.noaa.gov/rb/index.html
http://harvardforest.fas.harvard.edu/research/expsitedesc.html
Validating Model Results with Observations

- Cooperative global effort to measure/monitor trace gases (e.g. CO$_2$)
- Used to constrain models and understand processes controlling abundances
- Paucity of sampling sites, spatial and temporal gaps

Source: NOAA/ESRL
Building Confidence in Models

- Model fundamentals built on established physical laws, observations and current understanding
- Models show skill in representing mean climate features and simulating climate variability
- Can reproduce features of past climates and climate change.

Model simulations (yellow) capture the observed global mean near-surface temperature anomaly (black).

Source: IPCC Fourth Assessment
What are the effects of climate change?

*Climate change impacts occur across all earth system components*

- surface temperature has increased
- global temperature change is very likely due to human activity
- sea ice and glaciers are melting
- sea level is rising

*Source: NASA*

*Source: IPCC Fourth Assessment*
What are the effects of climate change?

- hurricane intensity is likely to increase
- increased risk of flooding in low-lying areas

Source: NOAA/GFDL

Projected Changes in Atlantic Hurricane Frequency over 21st Century

<table>
<thead>
<tr>
<th>% Change over 21st Century</th>
<th>Trop. Storm+ Cat. 1 Hurr.</th>
<th>Cat. 2+3 Hurricane</th>
<th>Cat. 4+5 Hurricane</th>
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http://www.nnvl.noaa.gov

http://www.worldviewofglobalwarming.org
What are the effects of climate change?

- likely increase in areas affected by drought
- increasing wildfire risk
What are the effects of climate change?

- ocean acidification

**Healthy reef system**

[Image of healthy reef system](http://en.wikipedia.org)

**Bleached Corals**

[Image of bleached corals](http://www.gbrmpa.gov.au)

GFDL ESM2M RCP8.5 Emissions Model Projection

**Aragonite Saturation State (2010)**

**Aragonite Saturation State (2100)**

[Images of maps showing global climate projections](http://www.gbrmpa.gov.au)
Earth System Model (ESM) components

- Comprehensive ocean and land carbon dynamics
- Interactive/Prognostic CO₂
- Coupling between climate and carbon cycle allows investigation of feedbacks.
Earth System Modeling for Coupled Carbon-Climate

How much CO$_2$ will the land and ocean continue to take up?
What are the biogeochemical feedbacks?
What are the biogeochemical and ecological impacts?
How do we assess long-term climate changes?

- Use Representative Concentration Pathway (RCP) scenario extensions (beyond 2100) and idealized scenarios to assess climate change on century to millenia timescales.

- Climate change commitment – effects of past human activities will be felt into the future.

- Idealized mitigation scenarios:
  - “constant composition” - immediate stabilization of radiative forcing
  - “zero-emission” - immediate cessation of emissions
  - constant emissions
  - artificially restoring CO$_2$ to preindustrial levels
  - reversibility
Constant Composition scenarios

Idealized stabilization of greenhouse gas concentrations in year 2000 - additional warming of 0.6°C by 2100 due to thermal inertia of oceans
Zero Emission scenarios

Immediate cessation of CO₂ emissions:

CO₂ falls off to about 40% of its peak enhancement above pre-industrial levels within a few centuries

Millenia needed for full recovery – long residence time of atmospheric CO₂ and long timescale for deep-ocean processes (e.g. Archer, 2005)

Solomon et al., 2009
Reversibility scenarios

Idealized 1% yr\(^{-1}\) to 4xCO\(_2\) ramp-up/ramp-down scenario:

Hysteresis response - lag in global mean surface temperature and other quantities

Global average sea level rise has a long timescale (centuries) for reversibility

Boucher et al., 2012
Why are oceans and marine ecosystems important?

- Oceans regulate Earth’s climate through uptake and storage of heat and carbon
- Primary producers form the base of the marine food web
- Provide services of high socio-economic value (e.g. fisheries)
- Climate change is projected to affect ocean circulation, nutrient availability and ocean diversity
- Changes in marine community composition and biogeographic redistributions of marine net primary producers under climate change and mitigation strategies can affect net carbon uptake
- Potential marine ecosystem regime shifts could have important consequences for stakeholders (e.g. fisheries)
- Important to assess impact of increasing greenhouse gases, as well as the permanence of their impact
Ocean chlorophyll to infer phytoplankton abundance

Dark blue: warmer waters, low in nutrients, little life

Green/red: Cooler nutrient-rich areas

Coastal regions and river mouths – nutrient-rich

Source: NASA Earth Observatory
How will marine NPP respond to climate change?

Drivers of NPP

- Temperature
- Light
- Nutrients

_Doney, 2006_
CMIP5 models simulate increasing global mean sea surface temperature and decreasing integrated global marine net primary productivity, with large spread.

CMIP3 multi-model ensemble mean: Increased stratification (density difference between 200m and surface) from 2050-2099 relative to 1950-1999.
Lag in sea surface temperature due to thermal inertia of ocean e.g. Boucher et al. (2012).

Does NPP follow temperature?

Decreasing CO$_2$ (t)

Increasing CO$_2$ (t)
**Experimental design – What if?**

**Model:**
GFDL ESM2M fully coupled carbon-climate concentration-driven Earth System Model.
TOPAZ2 ocean biogeochemistry (Dunne et al., 2012, 2013).

**Scenario:**
*Ramp-up/Ramp-down*
RCP8.5 2006-2100 (Riahi et al., 2007), followed by reversal of RCP8.5 from 2101-2195.
Seasonality is preserved, and land use fractions are frozen at 2101 levels for reversal (land use transitions are zero).
30 Tracers

Implicit grazing dynamics
Flexible N:P:Si:Fe:Chl
Aragonite and Calcite

Large phytoplankton
partitioned between
diatoms and
non-diatoms based
on degree of silicate
limitation

Biogeochemistry
DOM cycling
Particle sinking
Atm. Deposition
Gas exchange
River Input
Removal
Sediment Input
Scavenging

Phytoplankton ecology
N\textsubscript{2}-fixer
Small phyto.
Protist
Filter feeder
Detritus

Recycled nutrients
New nutrients

Carbon
Oxygen
Nitrogen
Phosphorus
Iron
Alkalinity
Silicon
Lithogenic

CaCO\textsubscript{3}

ESM2M validation

- Model reproduces carbon stores and fluxes
- NPP patterns similar to observations

Dunne et al., 2013
Lag of sea surface temperature

Hysteresis response of SST similar to e.g. Boucher et al. (2012).

Overall heat retention by the ocean.
Cooling in convective regions.

Percent change from 2146-2195 to 2006-2055.

John et al., GRL, 2015
NPP global response is in contrast to SST

Century scale transient response: NPP exceeds contemporary values after mitigation.

Sub-tropics become more productive over centennial timescale. NPP declines in convective regions.

John et al., GRL, 2015

Percent change from 2146-2195 to 2006-2055.
John et al., GRL, 2015

Maximum MLD and surface NO3 decrease in ramp-up as stratification increases.

Overshoot in ramp-down similar to NPP$_{100}$. 
Sub-tropics associated with co-located regions of residual warming and enhanced surface nitrate.

Largest NPP declines in co-located regions of colder SST and mixed-layer shoaling.

John et al., GRL, 2015
Driving mechanisms for NPP overshoot

Global ocean temperature evolution

Subsurface reversibility:
Percent change relative to 2006-2055 mean.

Continued warming at depth despite surface cooling in the ramp-down weakens stratification in upper 400m.

Global ocean vertical density gradient evolution

Deeper mixed-layers and higher surface nitrate, along with residual surface warming, drives the NPP overshoot.

John et al., GRL, 2015
Surface concentration of large diatoms globally reversible.

Enhanced NPP comes mostly from large non-diatoms.

John et al., GRL, 2015
Community composition spatial reversibility

ΔSurface large diatoms (%)  ΔSurface large non-diatoms (%)

Similar patterns for NPP\textsubscript{100} and surface large non-diatoms: increases in sub-tropics.

*John et al., GRL, 2015*
Driving mechanisms for shift in community composition

Strong depletion of silicate relative to nitrate in top 1000m in latter half of ramp-down and this persists and intensifies under mitigation.

Silicate depletion accompanied by sequestration at depth results in a competitive advantage for large non-diatoms.

John et al., GRL, 2015
Moving forward with GFDL’s ESMs

Application: Multi-member ensembles for detection and attribution, centennial-millennial scales, idealized sensitivity, diverse impacts application.

Comprehensiveness: beyond closing the CO$_2$ cycle to fully comprehensive and self consistent representation of aerosol, Fe, CH$_4$ and N cycles, and ecosystems

Resolution: Resolving regional atmosphere-land interactions and the ocean mesoscale for improved base state and change, and the human and marine applications

Prediction: Integration with seasonal-decadal climate prediction effort, exploring opportunities for experimental biogeochemistry prediction
GFDL’s Prototype High Resolution ESMs

- **ESM2M/ESM2G**
  - based on CM2.1 (2x2.5° atm, 1° ocean)
  - 400 cores, 13-14 model years/day

- **ESM2.5M**
  - based on CM2.5 (C180 atm, 1/4° ocean)
  - Add TOPAZ2, closed C cycle
  - 8800 cores, 7.5 model years/day
  - 25 years of 1990 Control prototype

- **ESM2.6-COBALT**
  - based on CM2.6 (C180 atm, 1/10° ocean)
  - Add COBALT (zooplankton: 33 tracers), closed C cycle
  - 15744 cores, 8 model months/day
  - 50 years of 1990 Control prototype
High resolution ESM2.6-COBALT prototype

California Current Upwelling Signature vastly improved from 1° to 1/10° Resolution
Conclusions

Century scale transient response: NPP exceeds contemporary values after mitigation.

Legacy subsurface warming and weakened vertical density gradients increase mixing and enhance surface nitrate.

Shift in phytoplankton community structure from decreasing silicate availability in the upper ocean.

Global mean response inadequate to assess reversibility, as regional responses can counterbalance/offset to give globally reversible response.

Similar results found for ESM2M-COBALT. Future multi-model intercomparison projects needed to better quantify climate and ecosystem reversibility and assess the legacy effects of anthropogenic climate change.
Acknowledgments:

FP7 Earth system Model Bias Reduction and assessing Abrupt Climate (EMBRACE) WP5 for developing the idea of a reversal scenario.
Thank you!

Questions?