Simulating Southern Ocean Dynamics in Coupled Climate Models

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- NASA
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Ocean Climate Responses & Feedbacks

CHANGING CLIMATE
Higher atmosphere CO₂, altered ocean properties, sea-ice & circulation

OCEAN CO₂ SINK
Ocean acidification

BIODIVERSITY
BIOGEOGRAPHY
PHYSIOLOGY

ECOSYSTEM SERVICES
Fisheries, tourism, shore protection, …

BIOGEOCHEMISTRY
Carbon & nutrient fluxes, CO₂ & other greenhouse gases

ECOSYSTEM SERVICES
Food webs, energy flow

"IPCC-class" Coupled Climate Models

- energy and mass conserving
- internally driven climate variability
- external climate perturbations (e.g., fossil fuel CO₂)
Climate Models to Earth System Models

The Development of Climate models, Past, Present and Future

- Mid-1970s: Atmosphere
  - Ocean & sea-ice model
- Mid-1980s: Atmosphere
- Early 1990s: Atmosphere
  - Land surface
  - Ocean & sea-ice
  - Sulphur cycle model
  - Carbon cycle model
- Late 1990s: Atmosphere
  - Land surface
  - Ocean & sea-ice
  - Sulphate aerosol
  - Non-sulphate aerosol
- Present day: Atmosphere
  - Land surface
  - Ocean & sea-ice
  - Sulphate aerosol
  - Non-sulphate aerosol
  - Carbon cycle
  - Dynamic vegetation
  - Atmospheric chemistry
- Early 2000s?: Atmosphere
  - Land surface
  - Ocean & sea-ice
  - Sulphate aerosol
  - Non-sulphate aerosol
  - Carbon cycle
  - Dynamic vegetation
  - Atmospheric chemistry

IPCC 3rd Assessment
circa 2000
Major uncertainties:
- CO₂ emissions (social, political, economic, geological)
- atmospheric CO₂ (carbon sinks, climate-carbon feedbacks)
- climate sensitivities (clouds, water vapor)

IPCC (2007)

Future Climate Projections
Opportunities

Coupled dynamics & modes - atm.-ocean-sea ice
Past & future projections - extend beyond reanalysis
Carbon-climate feedbacks - major source of uncertainty
Ecological impacts - climate & acidification
Flagship computations - computer resources, multi-model ensembles

Challenges

Coarse resolution - at best eddy-permitting
Internal variability - statistical matching with data
Coupled systems - large regional errors
Simplified biology - lower trophic levels
Coupled Model Uncertainties

Strength of Ocean CO₂ Sink  Sensitivity to Climate Warming

Friedlingstein et al. *J Climate* 2006

20 years of current carbon emissions
- stratification alters mixed layer depth (light) and nutrient supply
- primary productivity lower in subtropics, higher in subpolar gyres & polar regions
"Green-Ocean" Models

Multiple nutrients & phytoplankton functional groups

“RMS Interannual Variability”

“Decadal Trends” (20 years)

21st Century Temperature

T (Celsius)

Boyd et al
Biogeosc. 2008

Boyd et al
Biogeosc. 2008

Attrtribution & Detection
$\Delta$Primary Production

$\Delta$Diatom Index


Marinov et al (in prep)
**Winter Mixed Layer Depth**

**Model**

![Map showing winter mixed layer depth](image1)

**Boyer-Montegut et al. (2004)**

![Map showing winter mixed layer depth](image2)

**Model - Boyer-Montegut et al. (2004)**

![Map showing winter mixed layer depth](image3)

**Zonal Average MLD**

- de Boyer-Montegut 2004
- IPSL
- MPI-M
- NCAR

**Zonal Average MLD$_{\text{max}}$**

- Depth (m)

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**Schneider et al. Biogeosci. 2008**

**Doney et al. J. Mar. Systems 2009**
Rising $CO_2$ also leads to ocean acidification threatening shell-forming plants and animals.
Aragonite Saturation State

Steinacher et al. *Biogeosciences* 2009
The new paradigm for coupled climate models

**CMIP5 (IPCC 5th Assessment)**

- **Decadal Prediction**
  high resolution AOGCMs (~50km) initialized for near-term climate change over next 30 years

- **Earth System Models (ESMs)**
  with coupled carbon cycle and intermediate resolution (~200km) to study longer term feedbacks
New mitigation scenarios: representative concentration pathways (RCPs)

New way of producing/using scenarios devised by WG1, WG2 and WG3 communities (not IPCC)

pre-AR4:
(a) Sequential approach

1 Emissions & socio-economic scenarios (IAMs)

2 Radiative forcing

3 Climate projections (CMs)

4 Impacts, adaptation & vulnerability (IAV)

post-AR4:
(b) Parallel approach

1 Representative concentration pathways (RCPs) and levels of radiative forcing

2a Climate, atmospheric & C-cycle projections (CMs)

2b Emissions & socio-economic scenarios (IAMs)

3 Impacts, adaptation, vulnerability (IAV) & mitigation analysis

- Skill of model physical projections?
  - Base-state and historical trends
  - Mixed layer depth, upwelling, sea-ice

- Magnitudes of biogeochemical feedbacks?
  - Carbon storage & trace gases
  - Climate/carbon mitigation

- Biological sensitivities & resilience to change in temperature, sea-ice, circulation & CO$_2$?
  - Thresholds, multiple-stressors & trophic mismatch
- Enhanced SO observing system
  • Oxygen, nutrient & carbon sensors/platforms
  • Mixed layer depth, stratification & upwelling
  • Biological rates & community composition

- Modelling advances & opportunities
  • Nested high-resolution regional atm-ocean models
  • Biological food-web & impact models (embedded or one-way nested; physics data requirements?)

- Biological time-series & process studies
  • Multi-stressor experiments (ocean acidification, nutrients, trace metals, temperature)
  • Targeted process studies (lab & field)
  • Cross-ecosystem comparisons
Reduced SH Sea-Ice  More Positive Southern Annular Mode

1980-2000  2080-2100

SH JAS 1980-1999 Satellite obs avg = 17.7 (x 10^6 km^2)

Sea Ice Extent Anomalies (x 10^6 km^2)

Year

1850 1900 1950 2000 2050 2100

SH (Nov.-Feb.) Multi-Model Annular Index

hPa

Obs (HodSLP1)
Ozone Forcing
No Ozone Forcing

JAS

1980-2000  2080-2100

JAS

1980-2000  2080-2100
J. Marine Systems Special Issue on
Skill Assessment for Coupled Biological /
Physical Models of Marine Systems
Vol. 76, Issue 1-2, 2009
Greater uncertainty towards higher values due in part to uncertainty in the size and nature of the carbon cycle feedback
• Subtropical gyres: Climate change decreases NO$_3$ supply to the ocean surface, total Chl and Primary Production.

• Ice Biomes: Climate change increases light supply to phytoplankton, increasing total Chl and Primary Production
- Increased stratification over most of the ocean
- Less change in Southern Ocean stratification, because of the counteracting impact of stronger winds
Separate ecological biomes (based on physical principles)

* technique as in Sarmiento et al. 2004