# REPRESENTATION OF EASTERN BOUNDARY CURRENTS IN GFDL'S EARTH SYSTEM MODELS

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## ABSTRACT

The world's major Eastern Boundary Currents (EBC) are critically important areas for global fisheries. Computational limitations have divided past EBC modeling into two types: high-resolution regional approaches that resolve the strong mesoscale structures involved; and coarse global approaches that represent the large-scale context for EBCs but crudely resolve only the largest scales of their local manifestation. These latter global studies have illustrated the complex mechanisms involved in the climate change and acidification response in these regions, with the EBC response dominated not by local adjustments but large-scale reorganization of ocean circulation through remote forcing of water mass supply pathways. While qualitatively illustrating the limitations of regional high-resolution studies in long-term projections, these studies lack the ability to robustly quantify change because of the inability of these models to represent the baseline mesoscale structures of EBCs. In the present work, we compare current generation coarse resolution (1°) and a prototype next generation high-resolution (1/10°) Earth System Models (ESMs) from NOAA's Geophysical Fluid Dynamics Laboratory in representing the four major EBCs. We review the long-known temperature biases that the coarse models suffer in being unable to represent the timing and intensity of upwelling-favorable winds. In promising contrast, we show that the high-resolution prototype is capable of representing not only the overall mesoscale structure in physical and biogeochemical fields, but also the appropriate offshore extent of temperature anomalies and other EBC characteristics. In terms of representation of large-scale circulation, results were mixed, with the high-resolution prototype addressing some, but not all, of the biases in the coarse-resolution ESM. The ability to simulate EBCs in the global context at high resolution in global ESMs represents a fundamental milestone towards both seasonal to interannual ecological forecasting and long-term projection of climate, ecosystem, and acidification baselines and sensitivity.

## INTRODUCTION

Past work on the sensitivity of the California Current system has shown the potential for large changes in ecosystem state under climate variability and change (Rykaczewski and Dunne 2010) that agree qualitatively with long-term observations from CalCOFI (Bograd et al. 2008). Specifically, GFDL's coarse resolution ESMs projected increased nitrate ($NO_3$) in the California Current. While temperature and $NO_3$ are negatively correlated seasonally and interannually, they are positively correlated under climate change. The mechanisms underlying these changes were found to be a combination of poleward migration of the source-water formation region leading to increase in light limitation and preformed nutrient supply combined with an increase in residence time of source waters before upwelling that led to additional accumulation of nutrients before upwelling. This dominance of remote forcing of local California Current changes demonstrated the potentially complex interplay of changes in atmospheric winds and heat fluxes, stratification, ventilation, and water mass pathways modulating the biogeochemical response. Even excluding global climate change driven components of variation, EBCs are exposed to a suite of forcing modes, including: the seasonal cycle driving pressure gradients and winds; remote interannual forcing like El Niño Southern Oscillation, Pacific Decadal Oscillation, and North Pacific Gyre Oscillation; mesoscale eddies (100–150 days, 30–50 km); squirts, fronts, and jets (e.g., topographic forcing); weather (days to weeks); and the diurnal sea breeze (diurnal, few km scale). Perhaps most challenging, the observed pattern of natural upwelling and intensification of coastal chlorophyll, remineralized nutrients, hypoxia, and associated acidification is coherent all along the EBC, but restricted to 10–100 km from the coast (e.g., Feely et al. 2008). This broad combination of challenges has motivated further work in global-scale Earth System Modeling to retain the inclusion of basin-scale climate change mechanisms while addressing limited resolution of coastal dynamics within coarse-resolution global ESMs.

The nature of this challenge is daunting. While ocean observations indicate a strong role for mesoscale (10–100 km scale) variability, Earth System modelers do not have access to computers powerful enough to develop models to resolve these scales in global imple-

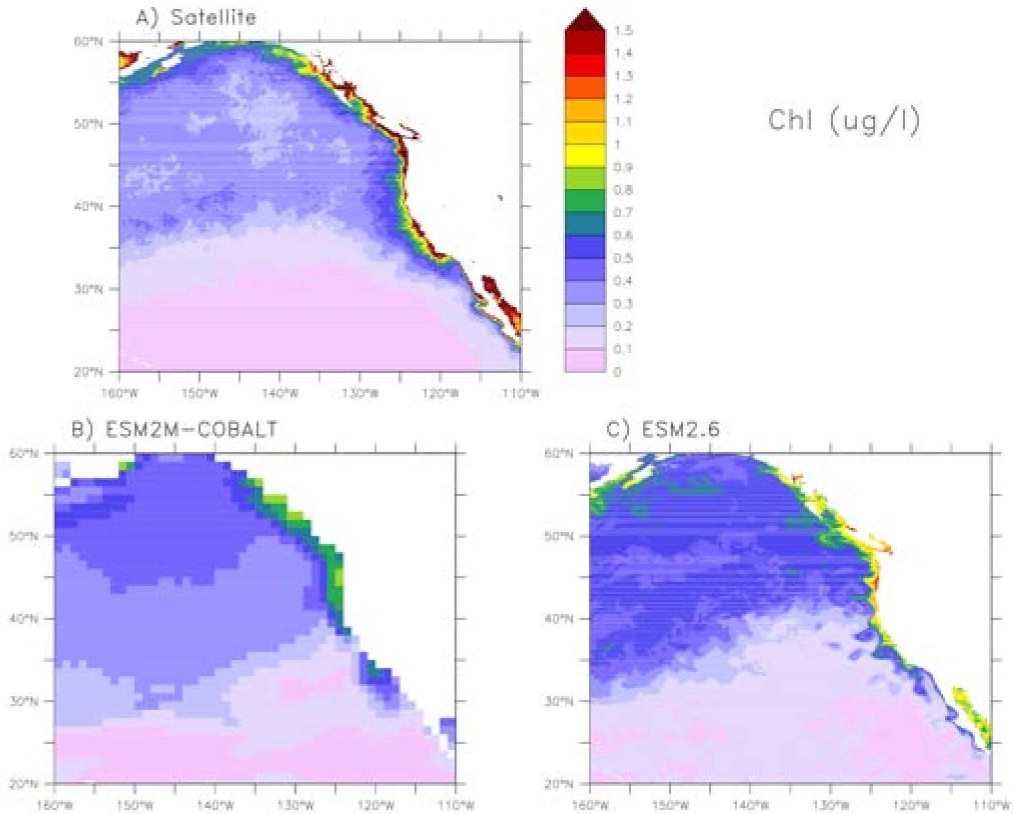


Figure 1. Comparison of surface chlorophyll from SeaWiFS satellite observations (top; http://oceandata.sci.gsfc.nasa.gov/SeaWiFS/Mapped/Monthly/9km/) with coarse, 1˚ resolution COBALT in ESM2M (bottom left; Stock et al. 2014) and 1/10˚ resolution COBALT in ESM2.6 (bottom right; present study).

mentations; the current generation ~1˚ ESMs have considerable regional process-level and fidelity biases. This implies that they commonly misrepresent phenomena such as the position and variability of the major current structures, the scales of either coastal and curl-driven upwelling, topographic and land-sea atmospheric interactions, and mechanistic ecological interactions. At least 1/10˚ resolution is necessary to resolve the Rossby radius of mesoscale eddies in the mid to high latitudes where these phenomena modulate the connection between the ocean surface and interior. Finally, adding biogeochemical tracers is computationally expensive, about 10%–20% per tracer over that of temperature and salinity alone. Overall, while the 1˚ ESM takes about 1.6 hours to run a year on 432 cores, the full 1/10˚ takes about 60 hours to run a year on 15,744 cores—an increase of over a thousand-fold in cost. Such simulations are extremely difficult to configure and run and their results more indicative of prototypes than of exhaustively developed and vetted products.

## METHODS

To address the challenge of our computational inability to run long simulations of comprehensive biogeochemical and ecological models at high global resolution, we considered a suite of models assessing sensitivity across three dimensions of potential efficiency: biogeochemical comprehensiveness, spatial resolution, and simulation time. We compared a hierarchy of biogeochemical comprehensiveness including: CMIP5 GFDL Earth System Models which used Tracers of Ocean Phytoplankton with Allometric Zooplankton version 2 (TOPAZv2); the next generation Carbon Ocean Biogeochemistry and Lower Trophics (COBALT); the simplified Biogeochemistry with Light, Nutrients and Gas (BLING; Galbraith et al. 2012); and even further reduced mini-BLING with only dissolved inorganic carbon, phosphate, and oxygen. In the spatial resolution dimension, we compare mini-BLING and COBALT at 1˚ (ESM2M; Dunne et al. 2013) and 1/10˚ (Delworth et al. 2013; Griffies et al. 2015) ocean resolution for baseline simulation characteristics and fidelity. In the simulation time dimension, we compared ESM2M TOPAZ long spin-up with short spin-up to assess the role of equilibration, and compared historical/future simulation (240 years) with the shorter, idealized 1%CO2/yr to doubling perturbation (80 years) to assess the role of perturbation timescale to biogeochemical response. The analysis described herein focuses on the baseline simulation characteristics of the short simulation combining the comprehensive COBALT ecosystem model with the highest spatial resolution climate simulation (~1/10 degree ocean, 50 km atmosphere). We refer to this model as ESM2.6.

GFDL's current ESM2M and ESM2G are publicly available as part of CMIP5. They use Tracers of Ocean Phytoplankton with Allometric Zooplankton version 2 (TOPAZv2) to simulate a coupled suite of multi-elemental mechanisms controlling the ocean carbon cycle. This, in turn, is done through their interacting cycles that incorporate allometric, optimal allocation, and ballast theory through global process-level calibration and distributional biogeochemical validation. Taking TOPAZ as it's starting point, GFDL's next generation biogeochemistry enhances representation of ecosystem structure towards improvement of resolution of energy flows through the planktonic food web and more robust applications, meeting NOAA's stewardship mandate for Living Marine Resources. This model, Carbon Ocean Biogeochemistry and Lower Trophics (COBALT; Stock and Dunne 2010; Stock et al. 2013), increases the number of zooplankton types from 1 to 3 and adds explicit bacteria with a considerable augmentation of theoretical and observational justification for structural and parameter decision making.

## RESULTS

The sensitivity to resolution at higher comprehensiveness is illustrated for the California Current EBC in Figure 1. Comparison of 1˚ and 1/10˚ resolutions in the most comprehensive COBALT model demonstrates vast improvement in the ability to represent the ecological response to mesoscale dynamics. Most striking is the improved ability to represent high chlorophyll associated with mesoscale upwelling and transport along the northern portion of the California Current upwelling region. In addition, there are improvements in the representation of the transition between mesotrophy in the offshore subpolar gyre and oligotrophy in the offshore subtropical gyre (blue to purple in fig. 1). Furthermore, the high-resolution model captures modes of mesoscale variance within the subpolar gyre that the coarse model is incapable of generating.

The relative ability of these models to represent the patterns of depressed temperature and elevated chlorophyll associated with EBC upwelling is shown more quantitatively in Figure 2. While the 1˚ resolution model (red) struggles to capture the signature of upwelling at all latitudes, ESM2.6 captures both the quantitative depression of temperature at the coast and the spatial scale of return to open ocean conditions offshore (top panel of fig. 2). However, those offshore temperatures tend to be too warm in both models to a similar extent. In terms of chlorophyll, ESM2.6 exhibits both similarly vast improvement in the qualitative structure nearshore and marked improvement offshore, but the highest values of chlorophyll in ESM2.6 (about 1.2 µg/l; <0.1 after the log transform in fig. 2) remain an order of magnitude lower than satellite observations, which exceed 10 µg/l (>1 after the log transform in fig. 2).

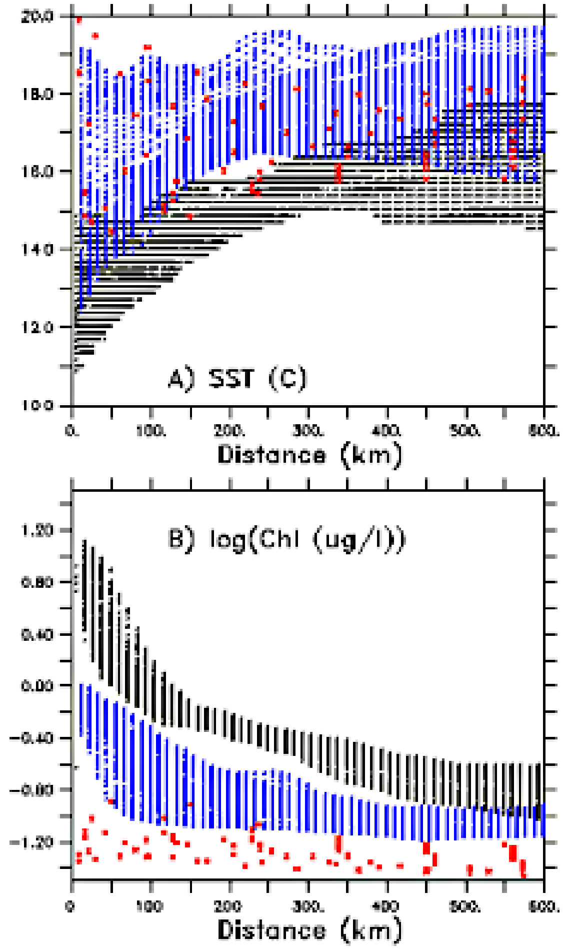


Figure 2. Comparison of Satellite Observations (Black), with coarse, 1˚ resolution COBALT in ESM2M (red; Stock et al. 2014) and 1/10˚ resolution COBALT in ESM2.6 (red; present study) for sea surfaces temperature (C; top; http://www.nodc.noaa.gov/SatelliteData/pathfinder4km/) and log(chlorophyll µg/l) (bottom; http://oceandata.sci.gsfc.nasa.gov/SeaWiFS/Mapped/Monthly/9km/). The number of points in each case reflects the pixel resolution in each case—similar for ESM2.6 and the satellite observations, but considerably lower in the 1˚ resolution model.

Overall, we consider these extremely exciting results and are highly confident that future high-resolution models will be vastly more applicable to living marine resource applications when computational capacities allow full implementation. While these models are revolutionary in representing various aspects of mesoscale dynamics as they may impact ecosystems on the global scale, many challenges remain. One of these challenges is that the high-resolution model retains much of the large-scale biases seen in the coarse-resolution model. A second challenge is that while higher resolution improved representation of areas with peak chlorophyll values about 1.2 μg/l, satellite and field observations commonly exceed 10 μg/l chlorophyll in blooms. Whether this lack of ecological dynamism captured in ESM2.6 is related to a lack of physical dynamics of fronts and other submesoscale phenomena, to lack of pelagic ecological biodiversity—particularly with respect to coastal diatoms, or related to a lack of representation of coastal and benthic interactions—is a focus of current and future work.

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