DOE Final Progress Report

Title:	Iron Fertilization of the Southern Ocean: Regional Simulation and Analysis of C-Sequestration in the Ross Sea
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Prog Mgr	Jeffrey S. Amthor, Phone: 301-903-2507 Division: SC-23.3
PI:	Kevin Arrigo
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Introduction

A modified version of the dynamic 3-dimensional mesoscale Coupled Ice, Atmosphere, and Ocean model (CIAO) of the Ross Sea ecosystem has been used to simulate the impact of environmental perturbations upon primary production and biogenic CO2 uptake. The Ross Sea supports two taxonomically, and spatially distinct phytoplankton populations; the haptophyte Phaeocystis antarctica and diatoms. Nutrient utilization ratios predict that P. antarctica and diatoms will be driven to nitrate and phosphate limitation, respectively. Model and field data have confirmed that the Ross Sea is iron limited with only two-thirds of the macronutrients consumed by the phytoplankton by the end of the growing season.

In this study, the CIAO model was improved to simulate a third macronutrient (phosphate), dissolved organic carbon, air-sea gas exchange, and the carbonate system. This enabled us to effectively model pCO_2 and subsequently oceanic CO_2 uptake via gas exchange, allowing investigations into the affect of alleviating iron limitation on both pCO2 and nutrient drawdown.

New Additions

First, cycling of Fe is treated very simply in the current version of CIAO, with a single bio-available Fe pool that is augmented from melting sea ice and mixing of Fe-rich deep waters to the surface. Therefore, we will implement a more complex Fe cycle in CIAO by adding state variables for ligand bound and unbound Fe(II) and Fe(III), as well as the processes of photoreduction, scavenging, and redox reactions (described more thoroughly below).

Second, the effectiveness of a Fe-fertilization strategy to sequester carbon depends upon the degree and depth of remineralization within the water column. We will test a number of models of particle flux and remineralization in the Ross Sea and implement these within the framework of CIAO. Models will be tested/developed using high temporal resolution estimates of surface primary production, weekly to monthly resolution sediment trap data from surface (<200 m), intermediate (500 m), and deep waters (1000 m), and vertical profiles of POC, TDIC, DOC, and O_2 collected over a number of annual cycles.

Finally, large-scale biogeochemical GCMs suggest that nitrification (oxidation of ammonium to nitrate) and denitrification in waters where sinking organic carbon from Fe-stimulated phytoplankton blooms is decomposed can be a significant source of N_2O to the atmosphere. In some cases, the radiative heating resulting from the liberation of this potent greenhouse gas can more than offset the impact of a decrease in atmospheric CO_2 resulting from Fe-fertilization. More importantly, model results suggest that the impact of Fe-fertilization on N_2O emissions is greater when the fertilization is carried over small temporal and spatial scales [Jin and Gruber 2003]. Unfortunately, the resolution of these models precluded evaluation of this effect for fertilized patches smaller than 1×10^6 km^2, much larger than any in situ fertilization experiment carried out to date. We propose to use a higher resolution regional model (625 km^2) to evaluate

N_2O production and its potential impact at the smaller patch sizes likely to be employed in the field.

Hypotheses to be tested

Three major hypotheses will be tested during the course of the proposed study. Hypothesis 1 deals with the degree of Fe-cycle complexity required to simulate the dynamics of added Fe in surface waters; Hypothesis 2 addresses the most effective Fe fertilization strategy given differences in particle flux and export for blooms dominated by different phytoplankton taxa (e.g. diatoms and P. antarctica); Hypothesis 3 is concerned with assessing the degree of feedback between CO_2 sequestration and N_2O liberation as a result of Fe additions.

Summary of most recent results

Results from the model control run agree favorably with satellite microwave imagery of sea ice in the Ross Sea. Model sensitivity studies suggest that polynya dynamics are insensitive to the amount of snowfall, the presence of the Ross Ice Shelf cavity, tides, and solar radiation penetrating through the ice. The model results also corroborate earlier findings that both the advection of sea ice and heat entrainment from warm Modified Circumpolar Deep Water play a role in Ross Sea polynya development. More importantly, the model further demonstrates that advection of sea ice due to winds plays the primary role in summer polynya formation. Additionally, we suggest that 1) heat entrainment reduces the rate of sea ice formation rather than melts existing sea ice, and 2) advection of sea ice due to synoptic wind events associated with variations in atmospheric pressure are the processes primarily responsible for the formation and expansion of the Ross Sea summer polynya.

We are continuing to run our coupled model of the southwestern Ross Sea to learn more about C sequestration in the Southern Ocean. Our most recent model results are currently under review by the journal *Nature*. The paper deals with the fact that C-sequestration on the Antarctic continental shelves has been grossly neglected in previous studies of the global C cycle. Of the 7-9 Pg C yr^{-1} released as CO_2 into the atmosphere by humans, 25-35% is taken up by the ocean through physical and biological processes. Large sinks for anthropogenic CO_2 include the North Atlantic and the Southern Ocean where sinking of surface waters sequesters CO_2 for hundreds to thousands of years. Large-scale estimates of the magnitude of the CO_2 sink in the Antarctic zone of the Southern Ocean vary widely, from 0.05 to 0.56 Pg C yr^{-1}, but do not adequately resolve the CO_2 flux associated with Antarctic continental shelves. In our most recent paper, we show for the first time that Antarctic shelf waters are a strong sink for anthropogenic CO_2 due to high biological productivity, intense winds, high ventilation rates, and extensive winter sea ice cover. Using a mechanistic three-dimensional biogeochemical model of the Ross Sea, we demonstrate that a large fraction of the CO_2 fixed seasonally by phytoplankton is sequestered within deep waters that form on the continental shelf. Net primary production (NPP) in these waters is ~0.055 Pg C yr^{-1}. Some of this carbon sinks to depth, driving an influx of anthropogenic CO_2 of 20-70 g C m^{-2} yr^{-1} (equivalent to ~24% of annual NPP). Adjacent to the coast, air-sea CO_2 fluxes are higher than the continental shelf average, often exceeding 50% of annual NPP due to increased ventilation rates driven by stronger winds. The total atmospheric CO_2 sink on the Ross Sea continental shelf of 0.013 Pg C yr^{-1} is equivalent to 27% of the most recent estimate of the CO_2 sink for the entire Southern Ocean. Taking other Antarctic shelves into account, this value could rise to 45-138%. Given these results, it is essential that these highly productive waters be included in future budgets of anthropogenic CO_2.

Published papers resulting from this proposal

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