Mixed Layer Controls on Ocean Carbon Cycling and Ocean Acidification

*Christopher L Sabine[1], Andrea Fassbender[1,2,3], Adrienne Sutton[1,4], Meghan F. Cronin[1]

1.NOAA Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Seattle WA 98115 USA, 2.University Corporation for Atmospheric Research, Boulder, CO 80307 USA, 3.School of Oceanography, University of Washington, Seattle WA 98115 USA, 4.Joint Institute for the Study of the Ocean and Atmosphere, University of Washington, Seattle WA 98115 USA

The development of buoy-based autonomous carbon sensors has improved our ability to examine ocean carbon cycle dynamics and ocean acidification on time scales ranging from days to years. Processes contributing to mixed layer carbon inventory changes can be quantitatively assessed to understand the relative importance of physics, chemistry, and biology while helping us to better understand the magnitude of long-term change in the context of natural variability. Here we compare two North Pacific time series sites: The Kuroshio Extension Observatory (KEO) in the western subtropical North Pacific and Ocean Station Papa in the eastern subpolar North Pacific. Preliminary results at KEO indicate that 4.5 ±2.2 mol C m^{-2} yr^{-1} is exported as organic carbon and 0.4 ±1.1 mol C m^{-2} yr^{-1} is exported as calcium carbonate, with much of the export occurring during the spring bloom. At Papa, the organic and inorganic carbon exports are 2 ±1 and 0.3 ±0.3 mol C m^{-2} yr^{-1}, respectively. Unlike KEO, export at Papa is spread out over the spring and summer months, then switches to net heterotrophy during the winter. Net organic carbon export at KEO is twice that of Papa, but the particulate inorganic carbon to particulate organic carbon ratio at Papa is about twice that of KEO. Observations suggest that both sites experience present day surface pH and Ω_{arag} conditions outside the bounds of pre-industrial variability throughout the year.

Keywords: carbon cycle, North Pacific, ocean acidification

The ocean acidification trend in the western equatorial Pacific for the past three decades

*Masao Ishii[1], Daisuke Sasano[1], Naohiro Kosugi[1], Katsuya Toyama[1], Hideyuki Nakano[1], Hisayuki Yoshikawa Inoue[2], Keith B Rodgers[3]

1.Meteorological Research Institute, Japan Meteorological Agency, 2.Hokkaido University, 3.Princeton University

The western zone of the tropical Pacific Ocean includes the “Coral Triangle”, which comprises the most important coral habitats on Earth with maximum marine biodiversity. One of the emerging issues that broadly threatens the coral reef ecosystems over the tropical and subtropical oceans is ocean acidification. Acidification is the consequence of not only the approximately 25% anthropogenic CO_2 emissions being absorbed by the ocean, but also with land use changes. A direct manifestation is the lowering of the pH of the ocean (increasing acidity) and the saturation level of the calcium carbonate minerals aragonite and calcite, which are important components of skeletal materials for many marine organisms including corals. Here we demonstrate the occurrence of ocean acidification in the warm western equatorial zone of the Pacific with the data of CO_2 system measurements over the past ~30 years since mid-1980s. In surface water within 125ºE-160ºW, 5ºS-5ºN, the partial pressure of CO_2 was increasing at a mean rate of +1.15 ±0.08 μatm yr^{-1} while that in the atmosphere was +1.74 ±0.01 μatm yr^{-1}. Total alkalinity, being salinity-normalized at S=35, has not shown any significant trend towards increasing or decreasing levels since early 1990 (NTA = 2296.6 ±3.8 μmol kg^{-1}). They are indicative of the increase in salinity-normalized dissolved inorganic carbon (NDIC) at +0.67 ±0.08 μmol kg^{-1} yr^{-1}, lowering of pH at -0.0011±0.0001 yr^{-1} and a reduction of saturation index of aragonite (Ωarag) and calicite (Ωarag) at -0.0097±0.0007 yr^{-1} and -0.0064±0.0005 yr^{-1}, respectively. The trend towards increased preformed_NDIC (+0.63 ±0.11 to +0.73 ±0.12 μmol kg^{-1} yr^{-1}) has also been observed on density classes of 23.0 –25.5σ_θ in the Equatorial Undercurrent that delivers waters to the equatorial divergence, and subsequently through transport in the South Equatorial Current to the surface of the warm western zone. Results of the measurements and numerical simulations with an ocean biogeochemistry / general circulation model suggest that equatorward transport of anthropogenic CO_2 by the shallow meridional overturning circulation from both hemispheres is an important process for the acidification in the equatorial Pacific. It is subsequently transported back into the subtropics and is considered to be contributing to the CO_2 increase and ocean acidification in the surface layers of the subtropical ocean.

Keywords: ocean acidification, equatorial Pacific

Colloidal pumping as a removal process of dissolved iron: a model study

*Kazuhiro Misumi[1], Adrian B Burd[2], Matthew C Long[3], J. Keith Moore[4], Lindsay Keith[3], Daisuke Tsumune[1], Takaki Tsubono[1]

1.Environmental Science Research Laboratory, Central Research Institute of Electric Power Industry, 2.University of Georgia at Athens, 3.National Center for Atmospheric Research, 4.University of California at Irvine

Iron cycle is incorporated in many ocean models as its importance to marine organisms. The models, however, tends to overestimate dissolved iron (dFe) concentrations in large dust deposition areas. Such overestimation can be attributed to inappropriate formulation of iron removal where the rates are calculated as a first order function to the simulated dFe. Although some models assume higher order functions to estimate the removal rates, there is no scientific basis to explain the representations. It is known that adsorption of dissolved thorium (dTh) to colloids and subsequent coagulation (so-called “colloidal pumping”) is important to remove dTh. As colloidal iron is observed in various locations, “colloidal pumping” can play an important role on iron scavenging. This study aims to build a new iron scavenging parameterization based on “colloidal pumping”. A mechanistic model to calculate a coupled adsorption/coagulation process is described in Burd et al. (2000) and is applied to dTh scavenging. We firstly conducted an experiment using their model to highlight an importance of “colloidal pumping”. In this experiment, we suppose an open-ocean box having a typical ^{238}U concentration that produces ^{234}Th by radioactive decay. Colloidal particles (< 1 μm) are continuously added to the box, and the model is run to be a steady state. Increase in colloidal particles results in colloidal coagulation and thus formation of particles. Simulated outgoing ^{234}Th fluxes are mainly seen in diameters larger than 1 μm where the gravitational settling is significant. We then conducted an experiment without adsorption of dTh to colloids, namely turn off “colloidal pumping”. As dTh is removed only by adsorption directly to large aggregates, removal efficiency is much decreased and the simulated dTh concentration becomes several times higher. The result suggests that ignoring “colloidal pumping” results in overestimation of dissolved metals in ocean models.

Keywords: Colloidal pumping, Iron, Nutrients, Scavenging

Development of a marine ecosystem model including nitrite

*Chisato Yoshikawa[1], Yoshikazu Sasai[1], S. Lan Smith[1], Akiko Makabe[1], Takuro Nunoura[1], Masahide Wakita[1], Makio Honda[1]

1.Japan Agency for Marine-Earth Science and Technology

Nitrite is an intermediate product during nitrification and denitrification. Few marine ecosystem models including nitrite have been developed. However, many phytoplankton species have been observed to assimilate and release significant amounts of nitrite, although those processes are not well understood. The lack of these processes may cause uncertainty about predictions of primary production. As nitrite is a precursor of nitrous oxide (N_2O), which is a significant anthropogenic greenhouse gas and a stratospheric ozone destroyer, a marine ecosystem model including nitrite is also necessary for development of a marine N_2O model as a base model. In this study, a 1D marine ecosystem model including nitrite was developed, in order to understand the nitrite production and consumption processes quantitatively and to develop the relevant equations. We applied this model to the JAMSTEC time-series subarctic and subtropical sites (K2 and S1) in the western north Pacific. The nitrite concentrations observed at the highly productive K2 site during 20 cruises from 2004 to 2014 were relatively high (0.0-1.0 μM), and with maxima observed around σ_θ=26.4 kg/m^3 throughout the year. The nitrite concentrations observed at the less productive S1 site during 19 cruises from 2010 to 2014 were relatively low (0.0-0.5 μM) with maxima observed around σ_θ=25.0 kg/m^3 throughout the year. Nitrification rates determined by ^{15}N-labeling during the cruises in June 2013 and in July 2014 were 0-34 nmolN/L/day in at K2, and 0-11 nmolN/L/day at S1. Maximum rates were observed around σ_θ=26.4 kg/m^3 at K2 and σ_θ=25.1 at S1, consistent with the density at which nitrite was maximal. These results suggest that active production and remineralization cause nitrite accumulate at K2 more than at S1. Our model was validated with observed nitrate, ammonium, nitrite, and chlorophyll *a* concentrations and nitrification rates at K2 and S1. The model successfully simulated the higher nutrient and chlorophyll *a* concentrations and nitrification rates at K2 compared with S1, and also represented the subsurface maxima of nitrite and ammonium concentrations and nitrification rate. Case studies were conducted to test different formulations for the equations in this model. In the case without photoinhibition of nitrification, the simulated densities of nitrite, ammonium, and nitrification maxima are much shallower than observed at both stations. Surface nitrification rates could be measured at K2 because nitrate is not depleted at the surface, and the rates were not detected at depths sallower than 40 m. However, simulated surface nitrification rates were 6-13 nmolN/L/day in the case without photoinhibition of nitrification. These results suggest that our previous model, which did not include photoinhibition of nitrification, may underestimate the nitrite and ammonium concentrations in the euphotic layer and the regeneration rate. In this presentation, we will also show the differences in densities of nitrification and nitrite maxima and regeneration rate as obtained using the different equations for nitrification as applied in various existing marine ecosystem models.

Keywords: Marine ecosystem model, Marine Nitrogen Cycle, Nitrite

Biogeochemical classification of the global ocean based on phytoplankton growth limitation

*Taketo Hashioka[1], Takafumi Hirata[2], Maki Noguchi[1], Sanae Chiba[1]

1.Japan Agency for Marine-Science and Technology, 2.Hokkaido University

A biological province provides an integrated view of regional characteristics of marine ecosystem and surrounding environment. Various definitions of biological province have been proposed based on regional differences in seasonal variation of satellite derived chlorophyll-a concentration and physical environments represented by temperature and salinity. In this decade, several new biogeochemical data that characterize regional difference in marine ecosystem became available. One is an estimation of phytoplankton community structure from satellite observation. Another is an estimation of limitation factors of phytoplankton growth from modeling studies. Particularly, nutrient limitations characterize regional difference in biogeochemical mechanism, while temperature and light dependencies mainly characterize a latitudinal difference in phytoplankton growth. In our study, we propose a new biogeochemical classification as a combination between the global distributions of the dominant phytoplankton group and their nutrient limitation. Namely, our provinces provide information what type of phytoplankton is dominant/coexist in each region and what type of nutrient limitation is controlling the phytoplankton growth. To obtain a climatological view of nutrient limitation, we used not a specific model result, but a diagnostic estimation based on a classical relationship of nutrient limitation (Michaelis-Menten formula) with observed macronutrients from World Ocean Atlas 2013 and a multi-model median of iron/ammonium concentration from model intercomparison projects, Coupled Model Intercomparison Project (CMIP5) and MARine Ecosystem Model Intercomparison Project (MAREMIP). Based on our classification, it revealed that the background mechanism, i.e., limitation factor of phytoplankton growth, is regionally different even if the same type of phytoplankton dominates. On the other hand, even in the geographically separated regions that recognized as the different provinces in the previous studies based on chlorophyll variability, the similarity in biogeochemical mechanism among provinces has been found. This result suggests that the regions with different mechanism potentially responds to climate change differently, even if the current ecological property seems the same between provinces.

Keywords: Marine Ecosystem, Biogeochemical provinces, Ecosystem Modeling

Impact of physiological flexibility on the dynamics of phytoplankton biomass, production, and nutrient distribution in a 1-D model of the near-surface ocean

*S. Lan Smith[1], Yoshikazu Sasai[1], Bingzhang Chen[1]

1.Marine Ecosystem Dynamics Research Group, Research Centre for Global Change, Japan Agency for Marine-Earth Science and Technology

We compare results from the recently developed FlexPFT (Flexible Phytoplankton Functional Type) model, which includes the flexible physiological response (i.e., photo-acclimtation) of phytoplankton, to those of a typical inflexible control PFT (CtrlPFT) model, as applied in most NPZD-type models. Both models have been embedded within the General Ocean Turbulence Model (GOTM), which is here applied as a 1-D (vertical) model of mixing and transport within the upper few hundred meters of the ocean. Simulations were conducted of two contrasting time-series observation sites in the North Pacific: subarctic stn. K2 (47 degrees N, 160 degrees E) and subtropical stn. S1 (30 degrees N, 145 degrees E), both of which are maintained by JAMSTEC: http://ebcrpa.jamstec.go.jp/k2s1/en/. The FlexPFT model is better able to reproduce consistently the observed vertical distributions of chlorophyll, primary production, and particulate organic nitrogen, compared to the CtrlPFT. This is because the FlexPFT accounts for changes in the chl:N:C ratio of biomass with changing environmental conditions. Therefore vertical profiles and seasonal response obtained from the FlexPFT differ substantially from those obtained from the CtrlPFT. Although the importance of photo-acclimation has long been recognized in subtropical regions, our results suggest that this process may also be quite important in subarctic regions as well. We discuss some implications of this result for understanding biogeochemical cycles and plankton ecosystems.

Keywords: plankton, physiology, ecosystem, model, photo-acclimation

Trophic amplification of ocean productivity trends under climate change

*Charles A Stock[1], John P Dunne[1], Jasmin G John[1]

1.Geophysical Fluid Dynamics Laboratory

Pronounced projected 21st century trends in regional oceanic net primary production (NPP) raise the prospect of significant redistributions of marine resources. Recent results further suggest that NPP changes may be amplified at higher trophic levels. Here, we use the Geophysical Fluid Dynamics Laboratory’s Earth System Model coupled with the COBALT (Carbon, Ocean Biogeochemistry and Lower Trophics) plankton ecosystem model (ESM2M-COBALT) to assess the extent of trophic amplification and the mechanisms underlying it. We focus on projected changes in mesozooplankton production –a key prey item for forage fish and the larval stages of larger fish. Globally, mesozooplankton production was projected to decline by 7.9%, but changes in some regions approached 50% and were twice the size of projected NPP changes. Changes in three planktonic food web properties –zooplankton growth efficiency (ZGE), the trophic level of mesozooplankton (MESOTL), and the fraction of NPP consumed by zooplankton (zooplankton–phytoplankton coupling, ZPC), explain the projected amplification. We will also describe preliminary results relating projected changes mesozooplankton production to potential changes in fish catch.

Keywords: Climate Change, Primary Production, Mesozooplankton

Expanding our Knowledge on Copepod Community Structure in Subarctic and Subtropical Communities as Revealed by the Species Functional Traits

*Carmen García-Comas[1], Sanae Chiba[1], Hiroya Sugisaki[2], Taketo Hashioka[1], S. Lan Smith[1,3]

1.JAMSTEC, 2.Fisheries Research Agency, 3.CREST, JST

In order to manage the effects of climate change on marine resources, a more thorough understanding of community structuring is desired. Here, we analyze copepod species data from the ODATE collection (3142 samples, 40 years, 10 º x 10º area of the Oyashio-Kuroshio Transition System, east of Japan). The area hosts species characteristic of subarctic and subtropical communities. 163 copepod species were classified into five categorical functional traits (i.e., size, food, reproduction, thermal-affinity and coastal-offshore habitat), following online databases and local taxonomic keys. We observe an opposite hump-shaped relationship of species evenness (lower at mid-point) and functional diversity (Rao's Q) (higher at mid-point) with species richness. Subtropical Kuroshio communities tend to be richer with higher species evenness, and yet subarctic and transition waters tend to host communities of higher functional diversity. The distribution of trait values within each functional trait was further examined in relation to the species rank according to their abundance. In subtropical communities, the distribution of trait values in the species rank is homogenous, mirroring the average frequency of those trait values in the species pools. In contrast, in subarctic communities the distribution of trait values differs along the species rank, with dominant species (rank 1) having favorable trait values more often than expected by chance (i.e., frequency of the trait values in rank 1 higher than the average frequency of those trait values in the species pools). Our results suggest that subtropical communities may be niche-saturated towards the most adapted trait values, so that merely having those most adapted trait value confers no strong competitive advantage to a species.

Keywords: species diversity, functional diversity, functional trait, copepod, plankton

A new perspective on the foraging ecology of apex predators in the California Current: results from a fully coupled ecosystem model.

*Jerome Fiechter[1], Luis Huckstadt[1], Kenneth Rose[2], Daniel Costa[1], Enrique Curchitser[3], Katherine Hedstrom[4], Christopher Edwards[1]

1.Univ. California Santa Cruz, 2.Louisiana State Univ., 3.Rutgers Univ., 4.Univ. Alaska Fairbanks

Results from a fully coupled ecosystem model for the California Current Large Marine Ecosystem are used to describe the impact of environmental variability on the foraging ecology of its most abundant apex predator, California sea lions. The ecosystem model consists of a biogeochemical submodel embedded in a regional ocean circulation submodel, and both coupled with a multi-species individual-based submodel for forage fish (sardine and anchovy) and California sea lions. Sardine and anchovy are specifically included in the model as they represent important prey sources for California sea lions and exhibit significant interannual and decadal variability in population abundances. Output from a 20-year run (1989-2008) of the model demonstrates how different physical and biological processes control habitat utilization and foraging success of California sea lions on interannual time scales, with the dominant modes of variability linked to sardine abundance and coastal upwelling intensity. The results also illustrate how variability in environmental conditions, forage fish distribution, and prey assemblage affect sea lions feeding success. While specifically focusing on the foraging ecology of sea lions, the modeling framework has the ability to provide new and unique perspectives on trophic interactions in the California Current, or other regions where similar end-to-end ecosystem models may be implemented.

Keywords: Ecosystem model, Foraging ecology, California Current, Marine predators

Simulated influence of the 1976-77 regime shift on anchovy and sardine in the California Current System

*Haruka Nishikawa[1], Enrique N Curchitser[2], Jerome Fiechter[3], Kenneth A Rose[4], Kate Hedstrom[5]

1.JAMSTEC/Rutgers University/JSPS Postdoctoral fellow, 2.Rutgers University, 3.University of California, Santa Cruz, 4.Louisiana State University, 5.University of Alaska Fairbanks

The well-known 1976-77 regime shift in the Pacific Ocean affected many species in the California Current System (McGowan et al., 2003). Chavez et al. (2003) labeled the periods before and after the 1976-77 regime shift as a cool “anchovy regime” followed by a warm “sardine regime.” However, the responses and mechanisms for what happened in that period for the Northern anchovy (*Engraulis mordax*) and the Pacific sardine (*Sardinops caeruleus*) in the California Current remains elusive.
In this study, we used a fully-coupled end-to-end model (Fiechter et al., 2015; Rose et al., 2015) to simulate the variation in population dynamics of anchovy and sardine for past 50 years. This model is a multi-species, spatially explicit (3D), time-evolving, and consists of four coupled submodels (hydrodynamics, Eulerian nutrient-phytoplankton-zooplankton-detritus (NPZD), an individual-based full life cycle anchovy and sardine model; agent-based fishery). The end-to-end and spatial detail features of the model allows us to not only simulate population dynamics but also to analyze the bottom up effects of environmental variation on the temporal and spatial dynamics of the populations.
Analysis of a 50-year historical simulation (1959-2008) showed that anchovy recruitment (survival to age-1) was lower just after 1977, while sardine recruitment was relatively unaffected by the regime shift. These different responses to the 1976-77 regime shift have been hypothesized to be a contributor to the species replacement from anchovy to sardine observed in the 1980s. The recruitment success of both species was influenced by the growth and survival of individuals in the larval stage. The modeled zooplankton density shift from high to low in 1976-77 was most drastic in winter in the coastal area. Anchovy larvae feed extensively in the winter in the coastal area, while sardine larvae were mainly distributed in the offshore area in the spring. The differential seasonal and spatial responses of zooplankton in the simulation caused anchovy recruitment to be more sensitive than sardine to the 1976-77 regime shift. The zooplankton shift itself was a result of the nutrient concentration changes in surface layer. Nutrient concentrations decreased from 1977 due to the weakening of both the coastal upwelling and mixed layer shoaling, which reduced the vertical nutrient flux from the bottom layer to the surface layer.
Our end-to-end modeling approach provided a consistent analysis that linked the climate regime shift to anchovy and sardine population responses. In addition, our results suggest a possible mechanism for the responses related to seasonal and spatial aspects of the nutrient dynamics affecting the food for larvae that lead to a negative effect on anchovy recruitment and relatively little response of sardine. These results support the idea that anchovy and sardine populations are controlled by the different environmental factors related to their differences in habitat niches (Rykaczewsk and Checkley, 2008).

Keywords: California current system, End-to-end model, Regime shift

Reproducing migration history of Japanese sardine using otolith $\delta^{18}O$ and a data assmilation model

*Tatsuya Sakamoto[1], Kosei Komatsu[2,1], Kotaro Shirai[1], Yasuhiro Kamimura[3], Chikako Watanabe[3], Atsushi Kawabata[4], Michio Yoneda[5], Toyoho Ishimura[6], Tomihiko Higuchi[1], Takashi Setou[3], Manabu Shimizu[3]

1.Atmosphere and ocean research institute , 2.Graduate School of Frontier Sciences, The University of Tokyo, 3.National Research Institute of Fisheries Science, Fisheries Research Agency, 4.Fisheries Agency, 5.National Research Institute of Fisheries and Environment of Inland Sea, Fisheries Research Agency, 6.National Institute of Technology, Ibaraki College

Using the combination of otolith oxygen stable isotope ratio ($\delta^{18}O$) and data assimilation model, a new method to reproduce migration histories of Japanese sardine (*Sardinops melanostictus*) was developed. Firstly, dependence of otolith $\delta^{18}O$ on temperature was examined for the first time for Japanese sardine. Juveniles were reared in three different water temperature (14.6, 18.7, 22.0 °C) for a month. Sagittal otoliths were collected and areas formed in latest 28 days were extracted by micromill for $\delta^{18}O$ analysis. $\delta^{18}O$ of rearing water was also measured and a linear relationship between otolith $\delta^{18}O$ and temperature was determined as follows: $\delta_{otolith} = \delta_{water} -0.186 (T) + 2.770$, $r^2 = 0.91$ (1).
Secondly, the distribution of seawater $\delta^{18}O$ in the western North Pacific and relationship between salinity was investigated. During 2012-2015, surface water samples were taken from 90 different locations for $\delta^{18}O$ analyses. Surface $\delta^{18}O$ showed a clear poleward gradient and linear regression analysis revealed that $\delta^{18}O$ and salinity were strongly correlated: $\delta_{water} = 0.601(S) -20.564$, $r^2 = 0.93$ (2), which enabled us to estimate seawater $\delta^{18}O$ from salinity. These results were essential to convert the otolith $\delta^{18}O$ profile into migration history. Micro-volume $\delta^{18}O$ analysis and our original microsampling technique enabled us to extract otolith $\delta^{18}O$ profile in a temporal resolution of 10-15days through whole life of juveniles approximately 200 days post hatch. For dates corresponding to each value of the profile, surface temperature and salinity in the range of 30-55 °N, 130-180 °E were extracted from FRA-ROMS, a data assimilation ocean model which reproduce ocean environment realistically. Temperature and salinity in each grid were converted into otolith $\delta^{18}O$ value using Eq. (1) and (2). Grids in which the calculated otolith $\delta^{18}O$ value was equivalent to actually analyzed value were considered to be the location of the individual on the date. Movements of the juveniles reproduced by this method clearly showed the northward migration from the Kuroshio-Oyashio transition zone to the Oyashio region and the estimated location on the date approached to the actual sampling point, which indicated the high accuracy of the method.

Keywords: sardine, otolith oxygen stable isotope, data assimilation model

