NOAA/OAR Ocean Acidification Sustained Investment Workplan Supplement:

High-resolution ocean-biogeochemistry modeling for the East and Gulf coasts of the U.S. in support of the coastal monitoring and research objectives of the NOAA OA Program

A Proposal from
NOAA/Atlantic Oceanographic and Meteorological Laboratory, and
University of Miami/Cooperative Institute for Marine and Atmospheric Studies,

To the
NOAA Ocean Acidification Program: Enhancement of Existing OA Observational and Experimental Technologies

By
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Project Title: High-resolution ocean-biogeochemistry modeling for the East and Gulf coasts of the U.S. in support of the coastal monitoring and research objectives of the NOAA OA Program

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Project Summary:

Analysis of the data collected during the first (2007) and the second (2012) Gulf of Mexico and East Coast Carbon (GOMECC) cruises showed measurable temporal pH and aragonite saturation state (Ω_{ar}) changes along the eight major transects. However, it is challenging to determine how much of this temporal change between the two cruises was due to ocean acidification and how much is due to variability on seasonal to interannual scales. Indeed, the expected 2% average decrease in Ω_{ar} due to increasing atmospheric CO_2 levels over the 5-year period was largely overshadowed by local and regional variability from changes in ocean circulation, remineralization/respiration and riverine inputs. Therefore, in order to provide useful products for the ocean acidification (OA) research community and resource managers, it is important to filter out seasonal cycle and other variability from the multi-annual trend. Here, we propose to use a high-resolution regional ocean-biogeochemistry model simulation for the period of 1979 - present day (real-time run) to fill the temporal gap between the 1st and 2nd GOMECC cruise data. In addition we will fine-tune and validate the model by using extensive surface water pCO_2 observations from the ships of opportunity in the coastal region (SOOP-OA) and from remotely sensed data. Then, we will use the real-time model run to estimate the 5-year trends (2012 – 2007) of OA and the carbon and biogeochemical variables along the East and Gulf coasts of the U.S. We will also examine the future OA variability in the East and Gulf coasts of the U.S. by downscaling the future climate projections under different emission scenarios developed for the IPCC-AR5. Based on the results obtained from the proposed model simulations, we will provide an observational strategy suitable for elucidating multi-annual trend of carbon and biogeochemical variables along the East and Gulf coasts of the U.S.

1. Scientific/Technical/Management

1.1 Background

Ocean acidification (OA), resulting from dissolution of atmospheric anthropogenic CO_2 in oceanic waters (Orr et al., 2005), is an emerging global threat to marine ecosystems (Doney, 2010, Fabry et al., 2008). The atmospheric CO_2 increase causes long-term increases in sea surface CO_2 concentration, resulting in the decrease of carbonate ions (CO_3^{2-}) and the reduction of pH (Feely et al. 2008, Thomas et al. 2007). In a recent ocean model intercomparison study, Bopp et al. (2013) estimated that the average global ocean surface pH would decrease approximately 0.35 units over this century under the high emission scenario, RCP 8.5. Such a decrease is predicted to alter patterns of biogenic carbonate formation and may also significantly affect other ocean biogeochemical cycles (Doney 2010, Orr et al. 2005, Feely et al. 2008).

In support of the coastal ocean monitoring and research objectives of the NOAA OA Program, as dictated by the Federal Ocean Acidification Research and Monitoring (FOARAM) Act, the Gulf of Mexico and East Coast Carbon (GOMECC) cruises were designed to obtain a snapshot of key carbon, physical, and biogeochemical parameters along the East and Gulf coasts of the U.S. This is the first effort to undertake comprehensive measurements of all primary inorganic carbon system parameters in the East and Gulf coasts of the U.S. Wang et al. (2013) used the first GOMECC-1 cruise (2007) dataset to show that the waters of the Northeastern U.S. shelves are more susceptible to acidification pressures than the southern counterparts. The most intensely buffered and supersaturated surface waters (aragonite saturation state, Ω_{ar} >5.0) were in the northern Gulf of Mexico (nGOM) river-plume waters; the least intensely buffered and least supersaturated waters (Ω_{ar} < 1.3) were at depth in the Gulf of Maine. Many shell-forming organisms are sensitive to the magnitude and change of aragonite saturation state. Wanninkhof et al. (2015) compared the data collected from the first (2007) and the second (2012) cruises and investigated the change in surface and subsurface patterns of inorganic carbon parameters along the East and Gulf coasts of the U.S. The general features in GOMECC-2 are similar to those observed during the GOMECC-1 cruise. The results showed that the supersaturated surface waters in nGOM became less supersaturated during 2012 summer (Figure 1). Along the East coast, there was a large decrease in surface Ω_{ar}. In the Northeast U.S., a decrease in inflow of the Labrador Sea slope water containing low Ω_{ar} caused a large increase in Ω_{ar}. The changes in Ω_{ar} were largely explained in terms of changes in major circulation features and corresponding changes in T, S and inorganic carbon parameters rather than invasion of anthropogenic CO_2. Cai et al. (2011) assessed the combined impact of eutrophication and OA on acidity using the data collected in the nGOM during May and August of 2007 and showed that eutrophication in those waters was associated with the enhanced OA of subsurface waters.

Although preliminary analysis of the data collected during the two GOMECC cruises showed measurable temporal pH and Ω_{ar} changes along the eight major transects (Figure 1), it is not possible to determine if these temporal changes between the two cruises are due to trend or an artifact of the sparsely collected data. Indeed, the expected 2% average decrease in Ω_{ar} due to increasing atmospheric CO_2 levels over the 5-year period was largely overshadowed by local and regional variability from changes in ocean circulation, remineralization/respiration and riverine inputs. In order to provide useful datasets for the OA research community and resource managers, it is important to filter out the seasonal cycle and high frequency variability from the multi-annual trend. Regional models of ocean carbon chemistry can generate synthetic understanding of the past trends and can be also used for future OA projections. It is important to point out that, as demonstrated by Liu et al. (2012; 2015), coarse-resolution global models, such as Coupled Model Intercomparison Project phase-5 (CMIP5) climate models, are incapable of adequately simulating important regional ocean dynamic features in the GOM. Therefore, here we propose to use high-resolution regional ocean-biogeochemical models to properly simulate the historical and future variability of OA in the East and Gulf coasts of the U.S. We will fine tune and validate the models by using the extensive coverage of SOOP-OA and the resulting regional carbon flux maps that will be created under a separate project by R. van Hooidonk.

1.2 Objectives

This project aims to develop, validate and use a high-resolution regional ocean-biogeochemistry model (1) to fill the temporal gap between the 5-yearly GOMECC cruise data; (2) to downscale the CMIP5 model projection of the carbon and biogeochemical parameters along the East and Gulf coasts of the U.S. for the 21st century, and (3) to optimize the observational strategy of the future GOMECC cruises.

1.3 Significance

The GOMECC cruises were only performed during the 2007 and 2012 summer season. Therefore, it is important to fill in temporal gaps between GOMECC cruises, with the potential for this approach to be applied to other coasts in the future. Hindcast and projection of future OA at a fine-scale resolution is also identified as a critical gap and key objective for the OAP. The 5-year differences (2012 – 2007) of the carbon and biogeochemical variables along the East and Gulf coasts of the U.S. will be first estimated by using the real-time model run. By filling the spatial and temporal gaps and comparing trends seen at monitoring buoys and forecasts, more useful OA information along the East and Gulf coasts of the U.S. will be available to the managers for an efficient use of resources and observation strategies.

1.4 Technical Approach and Methodology

To achieve the three major modeling objectives of this project, we propose to use two high-resolution regional ocean biogeochemistry models. These models will be used to simulate carbon, physical and biogeochemical processes along the East and Gulf coasts of the U.S. for the recent decades (1979 - present day) and for the entire 21st century. First, we will perform the global ocean-biogeochemistry ocean experimental run (1979-present). Then, the results of global model simulations will be used to provide the boundary conditions for the high-resolution regional models over the western North Atlantic Ocean (WNA, Figure 2).

1.4.1 Global ocean biogeochemistry model (MOM-TOPAZ)

The newly released Modular Ocean Model version 5 (MOM5) will be coupled to the updated TOPAZ biogeochemical model (Tracers of Phytoplankton with Allometric Zooplankton, thereafter MOM-TOPAZ, Griffies et al., 2004, Gnanadesikan et al., 2006, Dunne et al., 2013). The global MOM-TOPAZ covers the global ocean with a grid size of 360×200 on a tripolar grid with a longitudinal resolution of about 1.0° and a variable latitudinal resolution of approximately 0.3° near the equator. There are 50 vertical layers. To spin up the global model, the temperature and salinity fields will be initialized based on hydrographic climatological fields obtained from the World Ocean Atlas 2013 (WOA13, http://www.nodc.noaa.gov/OC5/woa13/), and the model will be integrated for 500 years using the ERA-Interim surface flux fields at 1.0°×1.0° resolution (http://apps.ecmwf.int/datasets/data/interim-full-daily/), which include 6-hourly surface winds, downward shortwave and longwave radiation, surface air temperature, surface specific humidity, and precipitation. The monthly river runoff is based on Dai and Trenberth (2002) and Dai et al. (2009). After the total of 500 years of spin-up run, the MOM-TOPAZ will be integrated from 1979 to the present day using the real-time ERA-Interim surface flux fields.

The biogeochemical component (TOPAZ) is a Nutrient-Phytoplankton-Zooplankton-Detrius (NPZD) model, which includes 30 tracers to describe the cycles of carbon, nitrogen, phosphorus, silicon, iron, oxygen, alkalinity and lithogenic material as well as pelagic calcite and aragonite and surface sediment calcite dynamics (Dunne et al., 2013). The modeled ecosystem is represented by three explicit phytoplankton groups (“small,” “large,” and diazotrophic), which are prognostic variables. The small group dominates under nutrient limitation; this size class resists sinking. Large phytoplankton represents diatoms and other phytoplankton that bloom and sink quickly. Finally, diazotrophs fix nitrogen gas directly from the atmosphere. Phytoplankton growth rates are modeled as a function of variable chlorophyll to carbon ratios and co-limited by nutrients and light. Phytoplankton loss and production of sinking detritus utilize the size-based relationship of Dunne et al. (2005) with mineral-driven penetration of sinking detritus (Klaas and Archer 2002; Dunne et al. 2007). TOPAZ diagnoses plankton mineral formation of calcite, and aragonite. TOPAZ includes seasonal time-scale dissolved organic material and heterotrophic biomass with fixed N:P and multiannual dissolved organic material with variable N:P. Gas exchange of O_2 and CO_2 follows Najjar and Orr (1998). Nitrification is inhibited by light after Ward et al. (1982). TOPAZ includes second-order iron scavenging with ligand kinetics, lithogenic particle scavenging, water column denitrification under suboxia, and sediment denitrification after Middelburg et al. (1996). In the absence of both NO_3 and O_2, a respiration deficit is accumulated as negative O_2. TOPAZ includes external inputs of atmospheric nitrogen deposition (Horowitz et al. 2003); lithogenic dust and soluble iron (Fan et al. 2006); river nitrogen (Seitzinger et al. 2005); and river inputs of dissolved inorganic carbon, alkalinity, and lithogenic material set to balance Holocene burial of calcite and lithogenic material (Dunne et al. 2007). Biogeochemical tracers will be initialized from WOA13 observations for NO_3, NH_4, PO_4, SiO_4, and O_2 and the GLobal Ocean Data Analysis Project (GLODAP; Key et al. 2004) for alkalinity and dissolved inorganic carbon (DIC). A more detailed description of the biogeochemical model structure can be found in Dunne et al. (2010, 2013). A schematic diagram that summarizes the global MOM-TOPAZ model simulation is shown in Figure 3.

1.4.2 Regional Ocean Biogeochemical Model (MOM-TOPAZ and ROMS)

To study ocean acidification along the East and Gulf coasts of the U.S., the high-resolution MOM-TOPAZ will be employed. The regional MOM-TOPAZ will have a fully eddy-resolving horizontal resolution of 1/12° over the western North Atlantic Ocean, the GOM and the Caribbean Sea (100ºW-60ºW, 10ºN-45ºN). The initial conditions are derived from the global model. For atmospheric forcing, the high-resolution (0.125°×0.125°) ERA-Interim surface flux fields will be used to force the regional model. A one-way nesting approach will be adopted here to connect the “parent model” (global MOM-TOPAZ) with the “child model” (WNA MOM-TOPAZ) via the eastern open boundary at 60°W (see Figure 2). The nested model will be forced by sea level fluctuations, all the prognostic tracers at the eastern open boundary and freshwater inflows at river heads. More specifically, along the eastern open boundary, Flather condition (Flather 1976) will be used for surface elevation and barotropic velocity. The Flather condition can be thought of as applying an adjustment to the externally prescribed normal velocity based on the difference between modeled and externally prescribed surface elevations. The Orlanski radiation conditions (Orlanski, 1976) for tracers (including T, S, and biogeochemical tracers, NO_3, NH_4, PO_4, O_2, etc.) and baroclinic velocity will be used in conjunction with relaxation (with time scale of 6hr inflow and 12hr outflow) to the regional solutions following Herzfeld et al. (2011; 2012). The sea surface elevation, current velocity and tracers will be also nudged in a sponge zone with a width of 20 grid point along the eastern open boundary to the boundary values obtained from the global MOM-TOPAZ.

The model domain is a region strongly influenced by fresh water and nutrients delivered from the major rivers, i.e. Mississippi and Atchafalaya River system. Thus, freshwater, nitrogen, and alkalinity input from major rivers along the East and Gulf coasts of the U.S. will be included in the regional model simulation. For rivers located inside the U.S., daily riverine fresh water discharge and nutrient concentrations, including NO_3, NH_4 and alkalinity values, will be retrieved from the US Geological Survey (USGS) river gauges (e.g., Aulenbach et al., 2007). For the Chesapeake Bay, at the riverine boundaries of 8 major tributaries, daily discharge will be prescribed using USGS and Chesapeake Bay Program (CBP) monitoring data. For the riverine alkalinity, if it is not available from USGS, the GOMECC and nGOM cruises data will also be used to provide the riverine alkalinity values along the East and Gulf coasts of the U.S. (Wanninkhof et al., 2014, Cai et al., 2010). For example, the Mississippi and Atchafalaya River System has the highest total alkalinity (TA, 2400 μmol kg^{-1}), whereas tropical margins influenced by the Amazon and Orinoco rivers have the lowest TA (~300 μmol kg^{-1}), the South Atlantic Bight (~600 μmol kg^{-1}), Mid-Atlantic Bight (~700 μmol kg^{-1}), and Labrador Sea (~1100 μmol kg^{-1}) are in the middle (Cai et al., 2010). Where the riverine data are not available, i.e. Mexican and Cuban rivers, we will instead utilize the long-term estimation or climatological means developed by Milliman and Farnsworth (2011), Fluentes-Yaco et al. (2001), and Nixon (1996). The model will be initialized with the T/S, sea surface elevation, current velocity, carbon and biogeochemical fields from the global MOM-TOPAZ. The model will run from 1979 to present day. A schematic diagram that summarizes the regional MOM-TOPAZ is shown in Figure 4. The model output will include the OA related variables, i.e. pCO_2, Ω_{ar}, hydrogen ion concentration (H+) , DIC and TA.

The MOM-TOPAZ has already been used and proved successful for the coastal biogeochemical processes (Herzfeld et al 2011, 2012; Schmidt et al. 2012). Lee and Liu, PIs of this proposal have extensive experience in tuning a high-resolution MOM configured for the similar regional domain (Liu et al. 2015). A snapshot of salinity and ocean current during July/2007 using the high-resolution MOM is shown in Figure 5.

To ensure that the model simulation provides similar spatial and temporal variability as the observational cruise data, we also plan to use the high-resolution Regional Ocean Modeling System (ROMS, Haidvogel et al., 2008) to study the OA and biogeochemical processes in the East and Gulf coasts of the U.S. ROMS is a free-surface, terrain-following, primitive equations ocean model widely used by the scientific community for a diverse range of regional applications (e.g., Haidvogel et al., 2008). The physical ocean model will be coupled to the NPZD model developed by Fennel et al. (2006). This NPZD model includes two species of dissolved inorganic nitrogen (NO_3 and NH_4,), one functional phytoplankton group, chlorophyll as a separate state variable to allow for photoacclimation, one functional zooplankton group, and two pools of detritus representing large fast-sinking particles and small suspended particles (Fennel et al., 2006). Application of the nitrogen cycle model to the nGOM has been described and validated in Fennel et al. (2011) and dissolved oxygen has been added to the model as an additional state variable as described in Fennel et al. (2013). Fennel et al (2006, 2011) and Xue et al. (2013) have examined the circulation and biogeochemical variability in the GOM using ROMS. For our ROMS hindcast simulation for the East and Gulf coasts of the U.S., the model domain, the resolution, surface forcing, initial and boundary conditions are the same as the regional MOM-TOPAZ, and the eastern OBCs will be obtained from the global MOM-TOPAZ (see Figure 4).

For future projections, the model domain and model parameters are same as the regional ocean-biogeochemistry model, while surface forcing, initial and boundary conditions are obtained from the CMIP5 model simulations under two future emission scenarios, closely following the modeling strategy used in Liu et al. (2012, 2015). The CMIP5 model data will be downloaded from the CMIP5 webpage (http://cmip-pcmdi.llnl.gov/cmip5) for the two future emission scenarios (RCP4.5 and RCP8.5). The RCP4.5 and RCP8.5 scenarios represent the medium-low and high emission scenarios, respectively (Taylor et al., 2012). We will use either the regional MOM-TOPAZ or ROMS depending on their ability to reproduce the carbon and biogeochemical variables from the GOMECC cruises.

1.5 Proposed Tasks

1.5.1 Task-1) Model validation and improvement

The high-resolution hindcast regional simulations (1979-present) will be compared with available observations including the past two GOMECC cruise data and the 3rd GOMECC cruise data, when they become available, to determine if the model could reasonably simulate spatial and temporal variations of carbon, physical, and biogeochemical parameters along the East and Gulf coasts of the U.S. More specifically, the regional model output from MOM-TOPAZ and ROMS will be compared with available observations primarily from GOMECC-1 and GOMECC-2 in terms of physical, biogeochemical and carbon variables, including T, S, Chl, pH, pCO_2, DIC and TA. The aragonite saturation states (Ω_{ar}) will be used as a prime OA indicator for model-data comparison. The spatial and temporal variability of those fields, including the intraseasonal and seasonal variability, will be examined. This variability will be compared with the surface SOOP-OA data and data from the Surface Ocean Carbon Atlas (SOCAT) database (www.socat.info; see Figure 6 for the pCO_2 pattern obtained from the SOOP-OA cruises during 1979-present) with focus on pCO_2 that is the prime indicator of OA. The surface water pH, TA and DIC discrete data taken from the SOOP-OA cruises at the frequency of about twice per year with 30-80 samples per cruise since 2012 will be directly compared with the model output at the corresponding time and location. Regional scale comparisons will be made with the empirical maps for the region with monthly resolution using the SOOP-OA data and remotely sensing data following the Caribbean Ocean Acidification data suite as detailed in Gledhill et al. (2008, 2009) The statistical methods, including Taylor diagrams (Xue et al., 2013), will also be used to examine how well modeled and observed patterns of the OA variables match each other in terms of their correlation, their root mean-square difference (RMSD), and their normalized standard deviations. If necessary, a set of sensitivity experiments will be performed to improve the model performance.

1.5.2 Task-2) Determine multi-annual trend in the GOMECC cruise data

After validating, the regional hindcast models will be used to fill the temporal gap between the 1st and 2nd GOMECC cruise data. The 5-year trend (2012 – 2007) of the carbon and biogeochemical variables along the East and Gulf coasts of the U.S. will be first estimated by using the real-time model run. Then, we will determine to what extent the simulated 5-year trend is affected by the sampling frequency, which will range from 5-yearly to bi-monthly. As suggested by Wanninkhof (2015), the OA variability is strongly influenced by large-scale oceanographic changes and the coastal processes. The water mass properties and current variability, which affect the carbon variability in the study area, will also be examined. By performing statistical analysis of the model output, we will attempt to provide the model-based confidence level of the 5-year differences derived from the 1st and 2nd GOMECC cruise data, and also from the 3rd GOMECC cruise data when they become available.

1.5.3 Task-3) Future projection of OA along the East and Gulf coasts of the U.S.

We will downscale the CMIP5 models using either the high-resolution MOM-TOPAZ or ROMS, depending on their performances, to properly simulate the future OA along the East and Gulf coasts of the U.S. The downscaling simulations will be performed for the period of 2006 – 2100 under two climate change scenarios: RCP4.5 (medium-low emission) and RCP8.5 (high emission). Based on the model analyses from the task-2 and -3 described above, an observational strategy of the future GOMECC cruises suitable for elucidating multi-annual trend of carbon and biogeochemical variables for surface and subsurface along the East and Gulf coasts of the U.S. will be provided.

1.5.4 Future Tasks

After completing the proposed three tasks, we plan to use the super-high resolution (2km) shelf model to further study the OA and biogeochemical processes in the East and Gulf coasts of the U.S. The super-high resolution will provide insights on OA at local scales. While this task cannot be performed with the resources requested, our efforts in the proposed work plan are geared towards this goal. Aside from the computational challenges of nesting the 2km resolution model into the high-resolution domain, continental and benthic boundary conditions need to be established, along with the physical forcing at the land-ocean interface to properly represent the environment.

1.6 Project Management

PIs Lee and Wanninkhof will be in charge of the project management. Wanninkhof works with the NOAA OA program. Along with Barbero, he is in charge of the GOMECC and SOOP-OA cruises and they have extensive experience about the OA variability along the East and Gulf coasts of the U.S. (Wanninkhof et al., 2014; 2015). Lee and Liu will lead the ocean-biogeochemical modeling component of the proposal, define the experiments and run the hindcast and forecast model simulations. Lee has extensive experience in ocean modeling at both regional and global scales, focusing on the areas of Atlantic climate change and variability. Liu has extensive experience in the regional ocean modeling (Liu et al., 2012; 2013; 2015), and has already performed downscaled high-resolution MOM model simulations, focusing on the Gulf of Mexico and Caribbean Sea (Liu et al., 2012; 2015). Wanninkhof and Barbero will be involved with the carbon and biogeochemical parameters for validating the hindcast and forecast simulations. van Hooidonk will help to tune the ocean-biogeochemical model and validate the model output using the ocean acidification product suite for the realm, which he is developing. He will also use the novel downscaling methodology that he has developed (van Hooidonk et al. 2015). All PIs will collaborate on the analysis and model/data comparisons, and synthesizing and disseminating the results via scientific papers, report or presentations.

1.7 Schedule – Timeline – Metrics

The proposed study will be performed over a 3-year period. The first year of the project will be primarily devoted to set up and tune the ocean-biogeochemical model. The global model will first be executed to provide the boundary conditions for the regional hindcast models. The regional hindcast model simulations (i.e., regional MOM-TOPAZ and ROMS) will be performed, tuned and compared with available observations including the GOMECC cruises. If necessary, a set of sensitivity experiments will be performed to improve the model performance. In year 2, we will mainly examine the spatial and temporal variations of carbon, physical, and biogeochemical parameters along the East and Gulf coasts of the U.S. and determine multi-annual trends in the GOMECC cruise data. In year 3, we will use the regional high-resolution model to project the future OA variability in the East and Gulf coasts of the U.S. More specifically, we will proceed as follows, in terms of the tasks detailed in Section 1.5:

	Task-1 Model Setup & Run	Take-2 Model Validation	Task-3 Future Projection
FY15	×		
FY16	×	×	×
FY17			×

1.8 Relevance and outcome of work

This project will directly address the FOARAM Research Priority Theme 3): “Modeling to Predict Changes in the Ocean Carbon Cycle and Impacts on Marine Ecosystems and Organisms.” It will also be applicable to FOARAM Research Priority Theme 1) “Research to Understand Responses to Ocean Acidification”. The benefits of the proposed work relate directly to improve the understanding of the regional biogeochemical processes of OA over the East and Gulf coasts of the U.S. and its impact on marine ecosystems, which will further enhance the existing OA observational and experimental technologies and optimize the observational strategy of the future GOMECC cruises.

1.9 Deliverables

Deliverables from this project will include:

1) High-resolution ocean-biogeochemical hindcast for the East and Gulf coasts of the U.S. for 1979-present day, including carbon biogeochemical outputs such as pH, pCO_2, DIC, TA and Ω_{ar} at multiple depths
2) Future projections of OA variability for the East and Gulf coasts of the U.S. for 2006-2010
3) Estimates and analysis of the spatial and temporal OA variability along East and Gulf coasts of the U.S.
4) Publication of results in scientific journals, and in FOARAM reports
5) Formal presentation of results to OA scientists and resource managers

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Figures

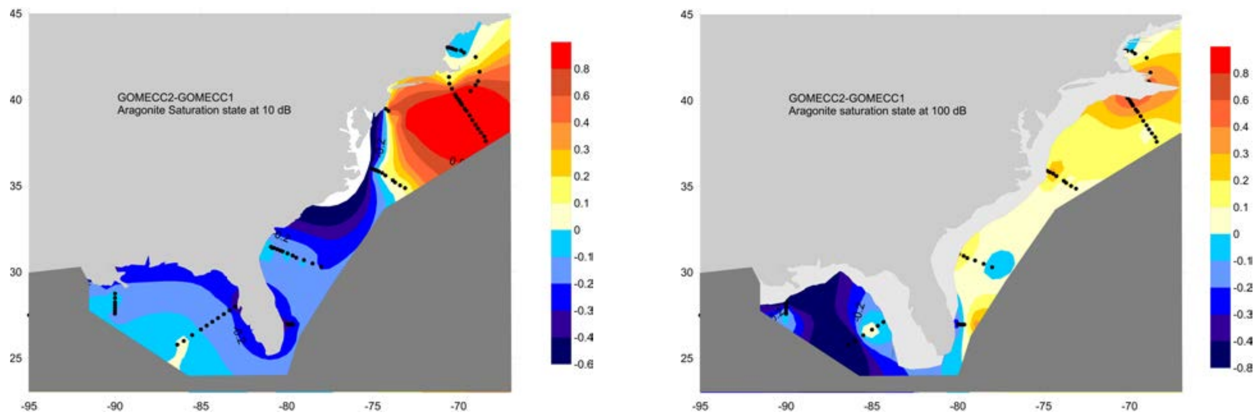

Figure 1. Differences in Ωar along isosurfaces of (left panel) 10 dbar and (right panel) 100 dbar between GOMECC-2 and GOMECC-1. Data from the cross-shelf transects are extrapolated, bin-averaged in 0.5° grids and then subtracted. GOMECC-2 stations are shown. From Wanninkhof et al (2015).

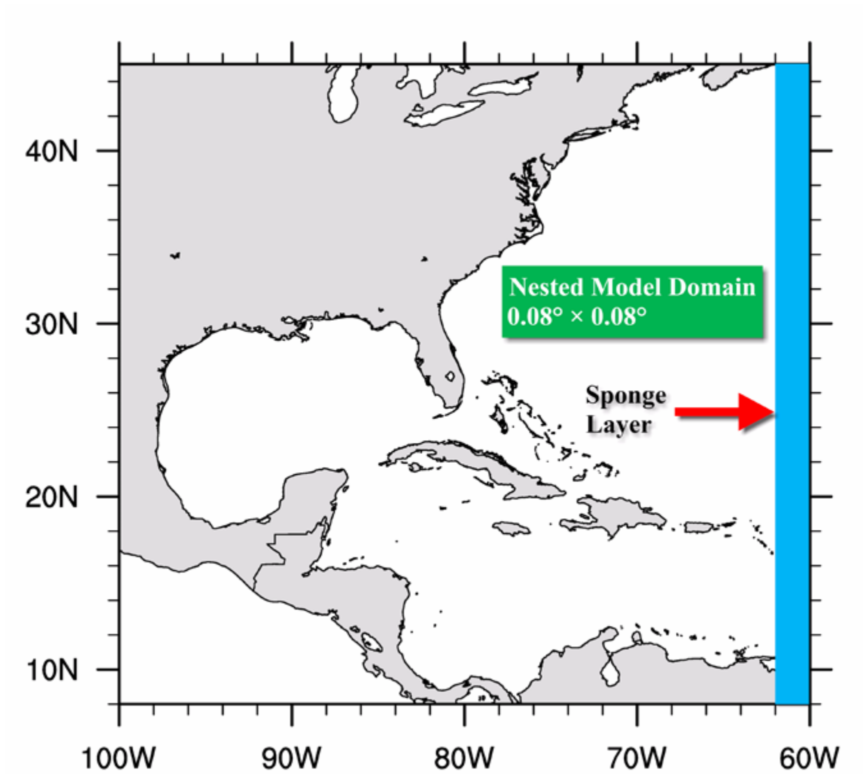

Figure 2. Regional high-resolution model domain. Light blue region show the sponge zone along the east open boundary (60°W). In this zone, the sea surface elevation, current velocity and tracers will be also nudged to the boundary values obtained from the global MOM-TOPAZ.

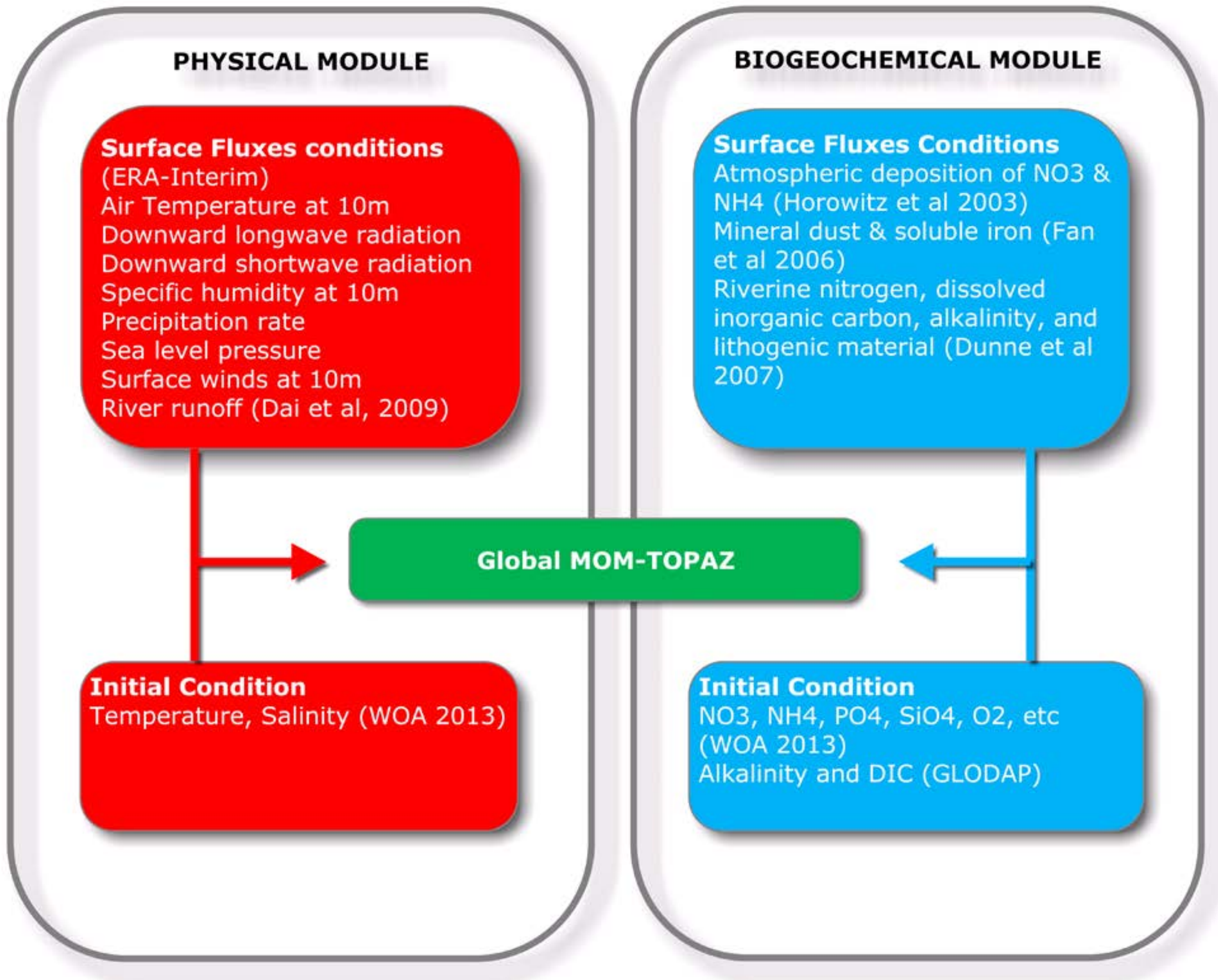

Figure 3. A schematic diagram for the global MOM-TOPAZ simulation.

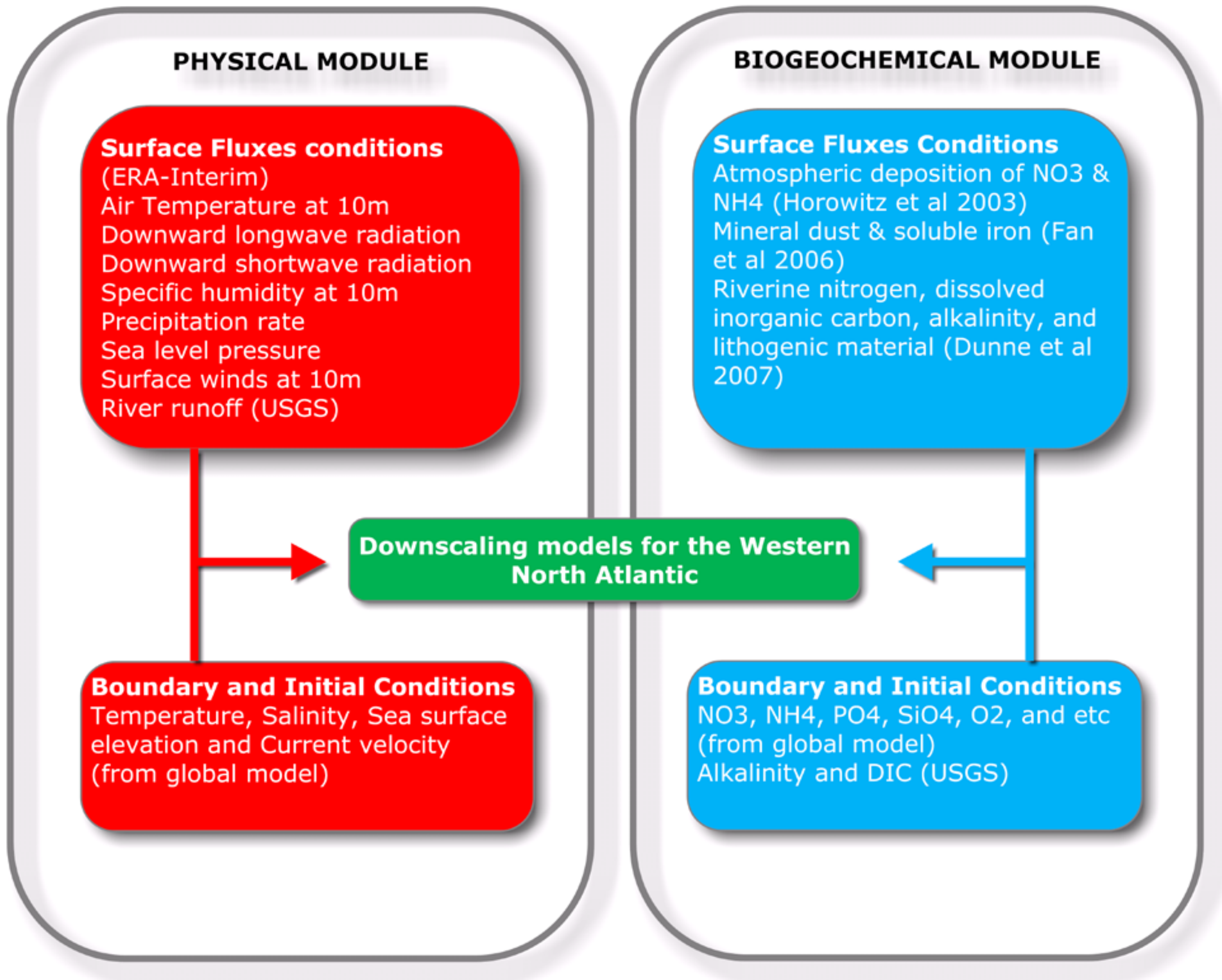

Figure 4. A schematic diagram for the regional MOM-TOPAZ and ROMS over the western North Atlantic Ocean.

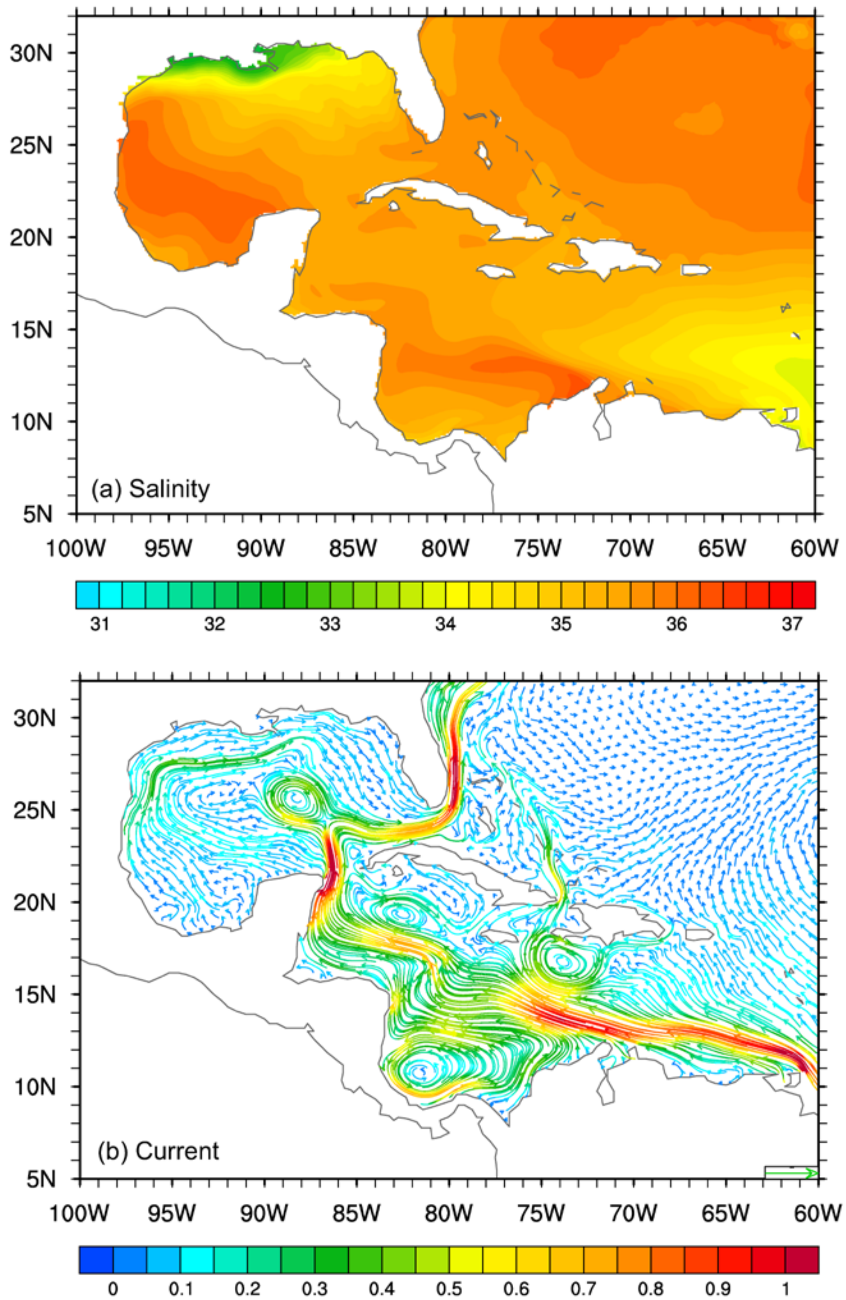

Figure 5. A snapshot of (upper panel) salinity and (lower panel) ocean current during July/2007 obtained from the high-resolution MOM simulation. Reproduced from Liu et al. (2015).

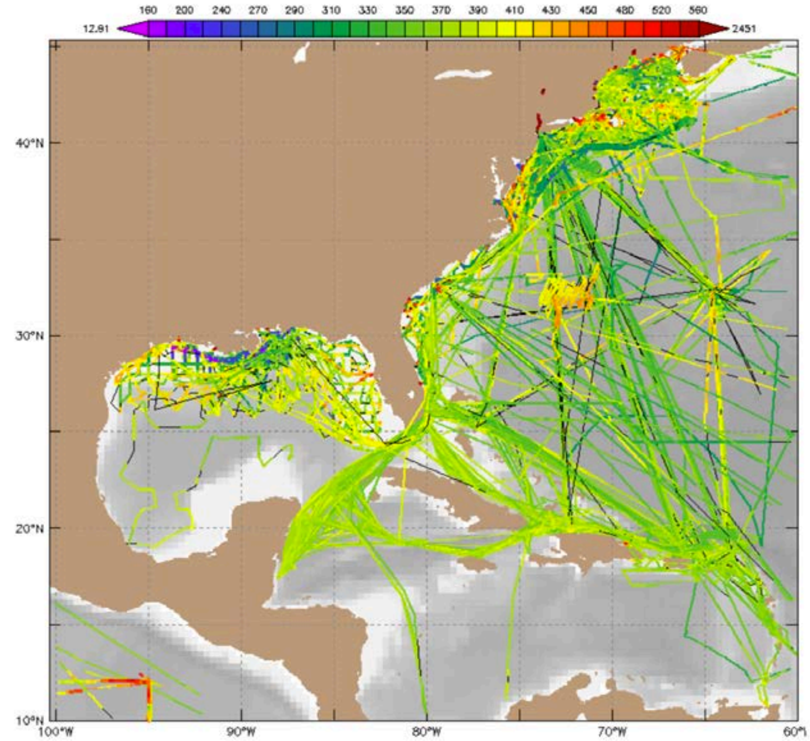

Figure 6. The pCO_2 pattern obtained from the SOOP-OA cruises during 1979-2014.

Budget Justification and Narrative

Yanyun Liu will mainly setup, run and validate the ocean-biogeochemical model simulations under the guidance of Sang-Ki Lee and Rik Wanninkhof during the project period. Rik Wanninkhof, Leticia Barbero and Ruben van Hooidonk will work with Liu and Lee to validate the carbon and biogeochemical parameters in the hindcast and forecast simulations during FY16 and FY17. All PIs will collaborate on the analysis and model/data comparisons, and synthesizing and disseminating the results via scientific papers, report or presentations. Therefore, salary requests from NOAA/OAP include funds for Yanyun Liu (FY15: 5mon; FY16: 9mon; FY17: 8mon), S.-K. Lee (FY15: 1.5mon; FY16: 1.5mon; FY17: 1.5mon), Leticia Barbero (FY16: 1mon; FY17: 1mon), and Ruben van Hooidonk (FY16: 1mon; FY17: 1mon). Rik Wanninkhof will carry out this project at no salary cost requested from NOAA/OAP.

Two trips for attending scientific meetings for dissemination of scientific results or for collaborating with John Dunne (NOAA/GFDL) are budgeted for FY16 and FY17. Publication page charges are also budgeted for FY16 and FY17.

All of the proposed model simulations will be performed using NOAA high performance computing system (HPCS) - JET and GAEA (S.-K. Lee and Y. Liu already have accounts and are authorized to use the required CPUs and scratch disk resources), but a storage disk array unit of 30TB, which will be used to download the model outputs from JET and GAEA and store them in AOML data servers, is budgeted in the first year.

Budget Tables

Budget tables for FY15, FY16 and FY17 are attached in the next pages.

Data Management Plan

Completing the first two tasks will provide the model-based confidence limit of the 5-year trend of the key carbon and biogeochemical variables along the East and Gulf coasts of the U.S. derived from the past and future GOMECC cruise data. The task-3 will result in two scenarios (RCP4.5 and RCP8.5) of dynamically downscaled projection of the key carbon and biogeochemical variables along the East and Gulf coasts of the U.S. for the 21st century. An observational strategy of the future GOMECC cruises suitable for elucidating the multi-annual trend will be also delivered. All model data products will be made available in a user friendly and documented format to the Ocean Acidification data management system at NOAA/NODC within 6-months of completion of the effort.

					FY15 ($)	FY15 ($)
11-1X FULL TIME PERMANENT	**Labor Type**	**Institution**	**Months**	**unding Sourc**	**Matching**	**OAP Request**
	d, Contr, Oth	**(Lab, CI, etc.)**			**($)**	**($)**
Wanninkhof	FED	AOML	1	AOML	$13,225	
Lee	CIMAS	UMiami	1.5	OAP		12039
Liu	CIMAS	UMiami	5	OAP		22544
Barbero	CIMAS	UMiami	0	OAP		0
Van Hooidonk	CIMAS	UMiami	0	OAP		0
Subtotal		**11-1X FULL TIME PERMANENT Cost Total:**			$13,225	34583
12-XX PERSONNEL BENEFITS	**Description**	**Institution**	**Months**		**Matching**	**OAP Request**
Wanninkhof	FED (33%)	AOML	1	AOML	$4,364	
Lee	CIMAS(39.5 %	UMiami	1.5	OAP		4755
Liu	CIMAS(39.5 %	UMiami	5	OAP		8905
Barbero	CIMAS(39.5 %	UMiami	0	OAP		0
Van Hooidonk	CIMAS(39.5 %	UMiami	0	OAP		0
Subtotal		**12-XX PERSONNEL BENEFITS Cost Total:**			$4,364	13660
21-XX TRAVEL	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
Subtotal		**21-XX TRAVEL Cost Total:**				0
22-XX TRANS OF THINGS	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
Subtotal		**22-XX TRANS OF THINGS Cost Total:**			$0	0
23-XX Utilities/Rent	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
Subtotal		**23-XX Utilities/Rent Cost Total:**			$0	0
24-XX Printing	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
Subtotal		**24-XX Printing Cost Total:**			$0	0
25-XX CONTRACTUAL SERVICES/TRAINING	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
Subtotal		**25-XX CONTRACTUAL SERVICES/TRAINING Cost Total:**				0
26-XX SUPPLIES & MATERIALS	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
Subtotal		**26-XX SUPPLIES & MATERIALS Cost Total:**				0
31-XX EQUIPMENT	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
Storage Disk						5000
Subtotal		**31-XX EQUIPMENT Cost Total:**				5000
XX-XX OTHER	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
Subtotal		**XX-XX OTHER Cost Total:**				0
77-XX Overhead	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
FED salaries	53%	AOML/OAR/NOAA			$9,322.30	0
CIMAS salaries	26%	CIMAS/Umiami				12543
Subtotal		**77-XX Overhead Cost Total:**			$9,322	12543
				Project Total:	$26,912	65786

					FY16 ($)	FY16 ($)
11-1X FULL TIME PERMANENT	**Labor Type**	**Institution**	**Months**	**unding Sourc**	**Matching**	**OAP Request**
	d, Contr, Oth	**(Lab, CI, etc.)**			**($)**	**($)**
Wanninkhof	FED	AOML	1	AOML	$13,357	
Lee	CIMAS	UMiami	1.5	OAP		12400
Liu	CIMAS	UMiami	9	OAP		41797
Barbero	CIMAS	UMiami	1	OAP		5115
Van Hooidonk	CIMAS	UMiami	1	OAP		4907
Subtotal		**11-1X FULL TIME PERMANENT Cost Total:**			$13,357	64218
12-XX PERSONNEL BENEFITS	**Description**	**Institution**	**Months**		**Matching**	**OAP Request**
Wanninkhof	FED (33%)	AOML	1	AOML	$4,408	
Lee	IMAS(40.5 %	UMiami	1.5	OAP		5022
Liu	IMAS(40.5 %	UMiami	9	OAP		16928
Barbero	IMAS(40.5 %	UMiami	1	OAP		2072
Van Hooidonk	IMAS(40.5 %	UMiami	1	OAP		1987
Subtotal		**12-XX PERSONNEL BENEFITS Cost Total:**			$4,408	26008
21-XX TRAVEL	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
						2000
						0
						0
Subtotal		**21-XX TRAVEL Cost Total:**				2000
22-XX TRANS OF THINGS	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
Subtotal		**22-XX TRANS OF THINGS Cost Total:**			$0	0
23-XX Utilities/Rent	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
Subtotal		**23-XX Utilities/Rent Cost Total:**			$0	0
24-XX Printing	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
						2000
						0
Subtotal		**24-XX Printing Cost Total:**			$0	2000
25-XX CONTRACTUAL SERVICES/TRAINING	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
Subtotal		**25-XX CONTRACTUAL SERVICES/TRAINING Cost Total:**				0
26-XX SUPPLIES & MATERIALS	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
						0
Subtotal		**26-XX SUPPLIES & MATERIALS Cost Total:**				0
31-XX EQUIPMENT	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
						0
Subtotal		**31-XX EQUIPMENT Cost Total:**				0
XX-XX OTHER	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
Subtotal		**XX-XX OTHER Cost Total:**				0
77-XX Overhead	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
FED salaries	53%	AOML/OAR/NOAA			$9,416	0
CIMAS salaries	26%	CIMAS/Umiami				23459
Subtotal		**77-XX Overhead Cost Total:**			$9,416	23459
				Project Total:	$27,181	117685

11-1X FULL TIME PERMANENT	Labor Type d, Contr, Oth	Institution (Lab, CI, etc.)	Months	unding Sourc	Matching FY17 ($)	OAP Request FY17 ($)
Wanninkhof	FED	AOML	1	AOML	$13,491	
Lee	CIMAS	UMiami	1.5	OAP		12772
Liu	CIMAS	UMiami	8	OAP		38267
Barbero	CIMAS	UMiami	1	OAP		5268
Van Hooidonk	CIMAS	UMiami	1	OAP		5054
Subtotal		11-1X FULL TIME PERMANENT Cost Total:			$13,491	61361
12-XX PERSONNEL BENEFITS	**Description**	**Institution**	**Months**		**Matching**	**OAP Request**
Wanninkhof	FED (33%)	AOML	1	AOML	$4,452	
Lee	CIMAS(41.5 %	UMiami	1.5	OAP		5300
Liu	CIMAS(41.5 %	UMiami	8	OAP		15881
Barbero	CIMAS(41.5 %	UMiami	1	OAP		2186
Van Hooidonk	CIMAS(41.5 %	UMiami	1	OAP		2097
Subtotal		12-XX PERSONNEL BENEFITS Cost Total:			$4,452	25465
21-XX TRAVEL	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
						2000
Subtotal		21-XX TRAVEL Cost Total:				2000
22-XX TRANS OF THINGS	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
						0
						0
Subtotal		22-XX TRANS OF THINGS Cost Total:			$0	0
23-XX Utilities/Rent	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
Subtotal		23-XX Utilities/Rent Cost Total:			$0	0
24-XX Printing	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
						2000
						0
Subtotal		24-XX Printing Cost Total:			$0	2000
25-XX CONTRACTUAL SERVICES/TRAINING	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
Subtotal		25-XX CONTRACTUAL SERVICES/TRAINING Cost Total:				0
26-XX SUPPLIES & MATERIALS	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
						0
						0
						0
						0
Subtotal		26-XX SUPPLIES & MATERIALS Cost Total:				0
31-XX EQUIPMENT	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
						0
Subtotal		31-XX EQUIPMENT Cost Total:				0
XX-XX OTHER	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
Subtotal		XX-XX OTHER Cost Total:				0
77-XX Overhead	**Description**	**Institution**	**Comment**		**Matching**	**OAP Request**
FED salaries	53.0%	AOML/OAR/NOAA			$9,509.68	0
CIMAS salaries	26%	CIMAS/Umiami				22575
Subtotal		77-XX Overhead Cost Total:			$9,510	22575
				Project Total:	$27,452	113401

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Education

PhD, Old Dominion University, Norfolk, Va (Oceanography)	1995
MSc, Old Dominion University, Norfolk, Va (Oceanography)	1993
BSc, Inha University, Incheon, South Korea (Oceanography)	1991

Professional Service

Scientist, CIMAS, University of Miami	2011 - Present
Associate Scientist, CIMAS, University of Miami	2007 - 2010
Assistant Scientist, CIMAS, University of Miami	2005 - 2007
Postdoctoral Associate, CIMAS, University of Miami	2002 - 2004
Associate Scientist: Maritime Research Institute, Samsung Heavy Industries	1996 - 2001
Graduate Research Assistant, Old Dominion University	1991 - 1995

Refereed publications (2013, 2014 and 2015)
Liu, H., C. Wang, S.-K Lee and D. B. Enfield, 2015: Inhomogeneous influence of the Atlantic warm pool on United States precipitation. Atmos. Sci. Lett., 16, 63-69, doi:10.1002/asl2.521.

Liu, Y., S.-K. Lee, D. B. Enfield, B. A. Muhling, J. T. Lamkin, F. Muller-Karger and M. A. Roffer, 2015: Potential impact of climate change on the Intra-Americas Seas: Part-1. A dynamic downscaling of the CMIP5 model projections. J. Marine Syst., 148, 56-69, doi:10.1016/j.jmarsys.2015.01.007.

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Ji, X., J. D. Neelin, S.-K. Lee and C. R. Mechoso, 2014: Interhemispheric teleconnections from tropical heat sources in intermediate and simple models. J. Climate, 27, 684-697, doi: http://dx.doi.org/10.1175/JCLI-D-13-00017.1.

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<u>Current projects</u>

(1) NOAA/CPO MAPP Program: Toward developing a seasonal outlook for the occurrence of major U. S. tornado outbreaks, PIs: S.-K. Lee, R. Atlas, C. Wang, D. B. Enfield, and S. Weaver, $430.0K, August 1, 2012 to July 31, 2015.

(2) NOAA/CPO MAPP Program: Variability and predictability of the Atlantic warm pool and its impacts on extreme events in North America, PIs: C. Wang, S.-K. Lee and D. B. Enfield, $442.2K, August 1, 2012 to July 31, 2015.

(3) NASA: Management and conservation of Atlantic Bluefin Tuna (Thunnus Thynnus) and other highly migratory fish in the Gulf of Mexico under IPCC climate change scenarios: A study using regional climate and habitat models, PIs: M. A. Roffer, J. T. Lamkin, F. E. Muller-Karger, S.-K. Lee, B. A. Muhling, and G. J. Goni, $722K, 1 Sep 2011 – 31 Aug 2015.

(4) NOAA: Sustained and targeted ocean observations for improving Atlantic tropical cyclone intensity and hurricane seasonal forecasts, PIs: G. Goni, S.-K. Lee, W. McCall, J. Morell, H.-S. Kim, C. Wang, D. Enfield, E. Ulhorn, abnd J. Cione, $700K, 1 Feb 2014 – 31 Jan 2016.

<u>Collaborators over past 48 months</u>

C. Wang, D. Enfield, M. Baringer, H. Liu and Y. Liu (AOML and CIMAS)
B. Kirtman, A. Clement, and B. Mapes (Univ. of Miami)
R. Mechoso, D. Neelin and X. Ji (UCLA)
P. DiNezio (Univ. of Hawaii)
F. Muller-Kargers (University of South Florida)
M. Roffer (ROFFS)
A. Wittenberg, B. Muhling and L. Zhang (GFDL)
J. Lamkin (NOAA-NMFS Miami)

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Current

Postdoctoral Associate, CIMAS, University of Miami and NOAA/AOML 2010 - present

Education

PhD, North Carolina State University, Raleigh, NC (Marine Science)	2010
MSc, Ocean University of China, P.R. China (Marine Meteorology)	2005
Dual BSc, Ocean University of China, (Meteorology & Computer Science)	2002

Professional experiences

Postdoctoral Associate, CIMAS, University of Miami and NOAA/AOML	2010 - present
Graduate Research Assistant, North Carolina State University	2005 - 2010
Graduate Research Assistant, Ocean University of China	2002 - 2005

Publications

Liu, Y., S.-K. Lee, C. Wang, D. B. Enfield, B. A. Muhling and J. T. Lamkin, 2015. Co-variability of North Atlantic sea surface temperature and ocean gyre circulation, submitted.

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Field of interests

Regional ocean modeling, Ocean-atmosphere interaction, Climate variability and climate changes, Ocean circulation dynamics, Biogeochemical ocean modeling

Professional skills

Computer languages and software: FORTRAN, MATLAB, GRADS, NCL.
Ocean-Atmosphere model: Cane-Zebiak model, HYCOM, MICOM, MOM, ROMS.

Collaborators over past 48 months

S.-K. Lee, D. B. Enfield (NOAA-AOML/PHOD)
J. T. Lamkin, (NOAA-NMFS/SEFSC)
B. A. Muhling (NOAA-GFDL)
M. A. Roffer, M. Upton, G. Gawlikowski (ROFFS)
F. Muller-Karger (University of South Florida)
R. Wanninkhof, R. van Hooidonk (NOAA-AOML/OCED)
J. M. Morrison (University of North Carolina, Wilmington)
D. Kamykowski, L. Xie, F. H. M. Semazzi (North Carolina State University)

Supplementary Materials

1) Supporting letter from John Dunne (NOAA/GFDL)
2) The original LOI of this proposal
3) Reviewers' comments on the LOI
4) Reply to the reviewers' comments

UNITED STATES DEPARTMENT OF COMMERCE
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March 24, 2015

TO: Dr. Rik Wanninkhof
NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami FL

Dr Sang-Ki Lee and Dr. Yanyun Liu
University of Miami, Cooperative Institute for Marine and Atmos. Studies, Miami, FL

SUBJECT: Support of "High-resolution ocean-biogeochemistry modeling for the East and Gulf coast of the U.S. in support of the coastal monitoring and research objectives of the NOAA OA Program"

Dear Drs. Wanninkhof, Lee and Liu,

The purpose of this letter is to express my enthusiastic support for your proposal "High-resolution ocean-biogeochemistry modeling for the East and Gulf coast of the U.S. in support of the coastal monitoring and research objectives of the NOAA OA Program", which would utilize both the output from GFDL Earth System Model (ESM) simulations run as part of the 5th Coupled Model Intercomparison Project (CMIP5) in support of the Intergovernmental Panel on Climate Change's 5th Assessment as boundary conditions as well as the publicly available biogeochemical code for Tracers of Phytoplankton with Allometric Zooplankton Version 2 (TOPAZv2). If funded, I will be available to consult on the implementation of the TOPAZ code in the Modular Ocean Model version 4.1 that you have already demonstrated success in downscaling, and on interpretation of model output as it leads to new insights on biogeochemical downscaling. Building on the success of the physical downscaling effort, I hope to gain from your group's scientific insights on the strengths, limitations, and sensitivities of model representation of biogeochemistry, ecosystem and acidification in TOPAZ as it is applied to the topic of downscaled Earth System Projection of such sensitive environmental regions such as the Eastern Gulf of Mexico and Southeast Atlantic seaboard of the US which are critical and vulnerable foci of NOAA's environmental stewardship mandate. I have every hope and expectation that the results of this work should help us understand biogeochemical and ecosystem changes and acidification under climate change as well as the underlying physiological, ecological, and biogeochemical mechanisms to inform both the viability of NOAAs past and future strategies to monitor living marine resources under the influence of climate variability and change and associated GFDL modeling efforts.

Looking forward to our future collaborations,

John Dunne
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NATIONAL OCEANIC AND ATMOPSHERIC ADMINISTRATION OCEAN ACIDIFICATION PROGRAM
LETTER OF INTENT FOR BUILD-OUT INVESTMENTS

1. Sustained Investment Topic: Enhancement of Existing OA Observational and Experimental Technologies
2. Project Title: High-resolution ocean-biogeochemistry modeling for the east and gulf coast of the U.S. in support of the coastal monitoring and research objectives of the NOAA OA Program
3. PIs: Rik Wanninkof (Lead PI, AOML; Rik.Wanninkof@noaa.gov), Sang-Ki Lee (CIMAS and AOML), Yanyun Liu, Leticia Barber, Ruben van Hooidonk (CIMAS and AOML)
Collaborators: B. Muhling (CIMAS and SEFSC), J. Lamkin (SEFSC) and J. Dunne (GFDL)

4. Statement of the Problem: The Gulf of Mexico and East Coast Carbon (GOMMECC) cruise was designed to obtain a snapshot of key carbon, physical, and biogeochemical parameters along the east coast and gulf coast of the U.S. in support of the coastal monitoring and research objectives of the NOAA Ocean Acidification Program. Preliminary analysis of the data collected during the first (2007) and the second (2012) cruises shows an interesting and measurable temporal pH change along the eight major transects. However, it is quite challenging to determine if this temporal change between the two cruises is due to a robust trend or an artifact of the sparsely collected data. In order to provide useful dataset for ocean acidification research community and resource managers, it is important to filter out seasonal cycle and to separate short-term interannual variability from the multi-annual trend. This project aims to use a high-resolution regional ocean-biogeochemistry model (1) to fill the temporal gap between the two GHOMMECC cruise data; (2) to optimize the observational strategy of the future GOMMECC cruses; and (3) downscale the CMIP5 model projection of the carbon and biogeochemical parameters along the east and gulf coast of the U.S. for the 21st century.

5. Brief Summary of Scope of Work:
Methodology: To achieve the three major goals of the project, we propose to use a high-resolution regional ocean biogeochemistry model. This model will be used to simulate carbon, physical and biogeochemical processes along the east and gulf coast of the U.S. for the recent decades (1979 – present day) and for the 21st century. The newly released Modular Ocean Model version 5 (MOM5) will be coupled to the updated TOPAZ biogeochemical model (Tracers of Phytoplankton with Allometric Zooplankton; Dunne et al., 2005). The updated TOPAZ model includes all major nutrient elements (i.e., N, P, Si and Fe) and 25 tracers to describe the cycles of carbon, nitrogen, phosphorus, silicate, iron, oxygen, alkalinity, aragonite, and lithogenic material (Dunne et al., 2010), and uses three explicit phytoplankton groups (small, large, and diazotrophic) (Polovina et al., 2011; Dunne et al., 2012). The model domain will cover the Atlantic Ocean between 20ºS and 75ºN. The high-resolution MOM5-TOPAZ model will have a fully eddy-resolving horizontal resolution of 5 ~ 10 km over the western Atlantic Ocean, the Gulf of Mexico and the Caribbean Sea (100ºW-60ºW, 10ºN-45ºN) decreasing linearly to 12.5 ~ 25 km resolution in the rest of the Atlantic model domain. The initial and boundary conditions for the high-resolution model will be obtained from either available observations and atmospheric reanalysis products or the 18 ensemble-averaged CMIP5 climate model simulations, closely following the modeling strategy used in Liu et al. (2012, 2014).

Task-1) Model validation and improvement**:** The high-resolution regional MOM5-TOPAZ model will be forced with observed surface flux fields for the period of 1979 - present day. This model run will be compared with available observations including the first (2007) and second (2012) GOMMECC cruise data to determine if the high-resolution model could reasonably simulate spatial and temporal variations of carbon, physical, and biogeochemical parameters along the east and gulf coast of the U.S. If necessary, a set of model sensitivity experiments will be performed to improve the high-resolution model. The PIs of this proposal have extensive experience in tuning a high-resolution MOM4-TOPAZ configured for the same regional ocean domain as demonstrated in Liu et al. (2012; 2014).

Task-2) Determine multi-annual trend between the 1st and 2nd GOMMECC cruise data: The optimized real-time high-resolution MOM5-TOPAZ model simulation for the period of 1979 - present day (from the task-1) will be used to fill the temporal gap between the two GOMMECC cruise data. The 5-year trend (2012 – 2007) of the carbon and biogeochemical variables along the east and gulf coast of U.S. will be first estimated by using the real-time model simulation. Then, we will determine to what extent the 5-year trend is affected by the sampling frequency, which ranges from 5-yearly to bi-monthly. By performing statistical analysis of the model output, we will estimate the amplitude of seasonal cycle and interannual variability, and the confidence limit of the 5-year trend derived from the GOMMECC cruise data. Based on the model analysis, an observational strategy of the future GOMMECC cruises suitable for elucidating multi-annual trend of carbon and biogeochemical variables along the east and gulf coast of the U.S. will be suggested.

Task-3) Future projection of ocean acidification along the east and gulf coast of U.S.: As demonstrated by Liu et al. (2012; 2014), coarse-resolution models, such as CMIP5 climate models, are not capable of simulating important physical ocean features in the Gulf of Mexico. Therefore, it is necessary to downscale the CMIP5 models using a high-resolution regional ocean biogeochemistry model to properly simulate the future ocean acidification in the east and gulf coast of the U.S. The downscaling simulations will be performed for the period of 2006 – 2100 to estimate the potential changes of carbon and biogeochemical variables along the east and gulf coast of the U.S. under two climate change scenarios: RCP4.5 (medium-low emission) and RCP8.5 (high emission). The uncertainty in the projected ocean acidification will be also estimated by using the CMIP5 model spread.

Estimated Project Cost: 100K/year for three years (October/2015 – September/2018)

6. Expected Outcomes: Completing the first two tasks will estimate the amplitude of seasonal cycle and interannual variability of the key carbon and biogeochemical variables along the east and gulf coast of the U.S., and the confidence limit of the 5-year trend derived from the 1st and 2nd GOMMECC cruise data. An observational strategy of the future GOMMECC cruses suitable for elucidating multi-annual trend of carbon and biogeochemical variables along the east and gulf coast of the U.S. will be also delivered. The task-3 will result in two scenarios (RCP4.5 and RCP8.5) of dynamically downscaled projection of the key carbon and biogeochemical variables along the east and gulf coast of the U.S.

Title: High--resolution ocean--biogeochemistry modeling for the east and gulf coast of the U.S. in support of the coastal monitoring and research objectives of the NOAA OA Program

PIs: Sang Ki Lee, Yanyun Liu, Leticia Barbero, Ruben van Hooidonk and Rik Wanninkof

Importance/Relevance:

I think that the need to establish that observed temporal changes are based in a distinct trend vs. an artifact of sampling is essential and it should be done now. I do not believe that the proposed work will lead to the advancement of ocean acidification research due to some inherent problems in the technical feasibility of the proposed work (see technical merit section). Of the LOIs that I read, this one had dense jargon which it made it difficult to understand the objectives. I do agree that these physical data MUST be coupled with data on plankton

There is not much data available about the pH trends in the East Coast and Gulf region, it is important to fill in temporal gaps between GOMECC cruises, with the potential to this approach begin applied to other coasts. Both filling the historical gaps , compare to trends seen at monitoring buoys and forecast, seeing that this is a region in the US where very little is known about OA trends. If modeling can inform future track cruises makes for an efficient use of resources

High-resolution regional models of ocean carbon chemistry generate synthetic understanding of past trends and are the best tool for generating projections of future conditions**.** Outputs from this model could be useful for managers and for management strategy evaluations. This work could catalyze other modeling work related to OA in the region**.** Will this model be able to capture near coast areas where biological productivity is high and are important for modeling biological response to OA?

The ability to assimilate the existing (and future datasets) to both hind-cast and project ocean acidification at fine-scale resolution is a critical gap and key objective for the OAP. The applications of this model for experimental work, observing system optimization along the east-coast, and for policy decision tools could be significant were it to prove successful. The cost is quite reasonable and the benefit yield is disproportionately high were it to be successful.

Scientific/Technical Merit:

The proposed study aims to use the MOM5-TOPAZ model to simulate variety of OA or OA related processes along the gulf and east coasts of the US for recent decades and into the future. The model appears to rely on a number of a parameters (e.g. nutrients and phytoplankton size classes) that do appear to have been collected on previous cruises and may not be collected on some (or all) of the cruises outlined in the Workplan. What datasets for these parameters do the PIs plan to use when it is not avaiable from the cruise? How do the PIs plan to ensure that the datasets provide similar spatial and temporal resolution as the cruise data or even the model itself?

The explanation of this LOI relied heavily on the use of models which were not well explained. I think there is great merit in coupling physical and biological data and thus support the objectives. However, the objectives were poorly explained and relied on a tremendous amount of understanding of previous research.

Team seems proficient in the skills needed for proposed project. I am curious as to what region is covered by these models (out to shelf's edge? Will the model resolution allow for freshwater inputs to be elucidated?

I really like how this team plans to get three uses out this modeling exercise – understanding trends, optimizing future monitoring, and projections of future conditions. This project is interdisciplinary as it links ocean observations with ocean modeling. Models like the one proposed are the foundation for projecting future biological impacts of OA, be it with explicit ecosystem models or qualitative exercises that identify OA refugia and hot spots. The budget seems inflated, but I'm not super familiar with cruise costs.

It's rather ambitious with considerable risk that task 1 will reveal significant variance between the model and observations. It's not clear if the TOPAZ model accounts for the coastal biogeochemical processes

Title: High-resolution ocean-biogeochemistry modeling for the East and Gulf coasts of the U.S. in support of the coastal monitoring and research objectives of the NOAA OA Program

We would like to thank the reviewer for the thoughtful comments and suggestions. We have incorporated these comments in the proposal. Here, we briefly explain how we address each of the comments. The reviewer's comments are in italic font, and our replies are in normal font.

Importance/Relevance:
I think that the need to establish that observed temporal changes are based in a distinct trend vs. an artifact of sampling is essential and it should be done now. I do not believe that the proposed work will lead to the advancement of ocean acidification research due to some inherent problems in the technical feasibility of the proposed work (see technical merit section). Of the LOIs that I read, this one had dense jargon which it made it difficult to understand the objectives. I do agree that these physical data MUST be coupled with data on plankton

Reply: We further clarified our objectives in the first section of the proposal (section 1.1 and 1.2). In the proposal, we tried our best to clearly explain these jargons (section 1.4).

There is not much data available about the pH trends in the East Coast and Gulf region, it is important to fill in temporal gaps between GOMECC cruises, with the potential to this approach begin applied to other coasts. Both filling the historical gaps, compare to trends seen at monitoring buoys and forecast, seeing that this is a region in the US where very little is known about OA trends. If modeling can inform future track cruises makes for an efficient use of resources

Reply: We do agree with the reviewer's comments. The importance of our proposed work is further emphasized in section 1.3. The 5-year differences (2012 – 2007) of the carbon and biogeochemical variables along the East and Gulf coasts of the U.S. will be first estimated by using the real-time model run. By filling the spatial and temporal gaps and comparing trends seen at monitoring buoys and forecasts, useful OA information along the East and Gulf coasts of the U.S. will be available to the managers for an efficient use of resources.

High-resolution regional models of ocean carbon chemistry generate synthetic understanding of past trends and are the best tool for generating projections of future conditions. Outputs from this model could be useful for managers and for management strategy evaluations. This work could catalyze other modeling work related to OA in the region.

Reply: We agree with the reviewer's comments. The outputs of this model will provide useful information to the OA research community and resource managers.

Will this model be able to capture near coast areas where biological productivity is high and are important for modeling biological response to OA?

Reply: We understand the reviewer's concern. However, the MOM-TOPAZ has already been used and proved successful for the coastal biogeochemical processes (e.g., Herzfeld et al 2011, 2012; Schmidt et al. 2012). We also would like to point out that the PIs of this proposal have extensive experience in tuning a high-resolution MOM configured for the similar regional domain (Liu et al. 2015).

The ability to assimilate the existing (and future datasets) to both hindcast and project ocean acidification at fine-scale resolution is a critical gap and key objective for the OAP. The applications of this model for experimental work, observing system optimization along the east-coast, and for policy decision tools could be significant were it to prove successful. The cost is quite reasonable and the benefit yield is disproportionately high were it to be successful.

Reply: Thank you. That is also our main goal.

Scientific/Technical Merit:
The proposed study aims to use the MOM5-TOPAZ model to simulate variety of OA or OA related processes along the gulf and east coasts of the US for recent decades and into the future. The model appears to rely on a number of a parameters (e.g. nutrients and phytoplankton size classes) that do appear to have been collected on previous cruises and may not be collected on some (or all) of the cruises outlined in the Workplan. What datasets for these parameters do the PIs plan to use when it is not avaiable from the cruise? How do the PIs plan to ensure that the datasets provide similar spatial and temporal resolution as the cruise data or even the model itself?The explanation of this LOI relied heavily on the use of models which were not well explained. I think there is great merit in coupling physical and biological data and thus support the objectives. However, the objectives were poorly explained and relied on a tremendous amount of understanding of previous research.

Reply: Thank you. All the model inputs for the high-resolution regional model simulation, including atmospheric forcing, initial and boundary, are explained in section 1.4 and summarized in Fig. 4. The modeled ecosystem is represented by three phytoplankton groups ("small," "large," and diazotrophic), which are prognostic variables. We plan to use daily riverine freshwater discharge, nutrients, and alkalinity obtained from US Geological Survey (USGS) if those data is not available from the GOMECC cruises. Where the riverine data are not available (i.e. Mexican and Cuban rivers) we will use the long-term estimation or climatological means from Dunne et al. (2007). These input variables will be interpolated to the model grid. The details of the regional hindcast model can be found in section 1.4.2. We will also compare the cruise data, the other available dataset (SOOP-OA) and the model output during the available periods and validate our regional hindcast model. In the proposal, we also add more details about the MOM-TOPAZ model based on the reviewer's comments (Section 1.4). We also clarified our objectives in the section of proposed tasks (section 1.5).

Team seems proficient in the skills needed for proposed project. I am curious as to what region is covered by these models (out to shelf's edge? Will the model resolution allow for freshwater inputs to be elucidated?

Reply: The high-resolution MOM-TOPAZ will have a fully eddy-resolving horizontal resolution of 1/12° over the western North Atlantic Ocean (100ºW-60ºW, 10ºN-45ºN). The 1/12° model resolution can resolve the freshwater, nitrogen, and alkalinity input from major rivers. After completing the proposed three tasks, we plan to use the super-high resolution (2km) shelf model to further study the OA and biogeochemical processes in the East and Gulf coasts of the U.S. The super-high resolution shelf model will provide insights on OA at local scales. While this task cannot be performed with the resources requested, our efforts in the proposed work plan are geared towards this goal.

I really like how this team plans to get three uses out this modeling exercise – understanding trends, optimizing future monitoring, and projections of future conditions. This project is interdisciplinary as it links ocean observations with ocean modeling. Models like the one proposed are the foundation for projecting future biological impacts of OA, be it with explicit ecosystem models or qualitative exercises that identify OA refugia and hot spots. The budget seems inflated, but I'm not super familiar with cruise costs.

Reply: The plans and proposal tasks are clearly described in section 1.5. The project is interdisciplinary as the reviewer stated. We will validate our regional hindcast model using the GOMECC and SOOP cruises, simulate and investigate the OA related processes along the East and Gulf coasts of the U.S. for recent decades and the 21st century by using the high-resolution regional ocean-biogeochemistry model simulation. The budget (~100k/yr) is mainly for the salaries for defining, running, validating and analyzing the hindcast and forecast model simulations. No cruise costs are involved here. The two GOMECC cruises have been completed under separated projects.

It's rather ambitious with considerable risk that task 1 will reveal significant variance between the model and observations. It's not clear if the TOPAZ model accounts for the coastal biogeochemical processes

Reply: We understand the reviewer's concern. However, the MOM-TOPAZ has already been used and proved successful for the coastal biogeochemical processes (e.g., Herzfeld et al 2011, 2012; Schmidt et al. 2012). We also would like to point out that the PIs of this proposal have extensive experience in tuning a high-resolution MOM configured for the similar regional domain (Liu et al. 2015). To ensure the model simulation provide similar spatial and temporal variability as the observational cruise data, we also plan to test and use the high-resolution Regional Ocean Modeling System (ROMS, Haidvogel et al., 2008) to study the OA and biogeochemical process in the East and Gulf coasts of the U.S. ROMS is widely used by the scientific community for a diverse range of regional applications (e.g., Haidvogel et al., 2008). Fennel et al (2006, 2011) and Xue et al. (2013) have examined the circulation and biogeochemical variability in the GOM using ROMS. In summary, both MOM-TOPAZ and ROMS will be used to simulate the OA related processes along the East and Gulf coasts of the U.S.