Activity 1: Application and Analysis of a Coupled Hydrodynamic-Biogeochemical Model (ROMS-RCA) in Shallow-Water Habitats of the Chesapeake Bay

1. Name, Address and Contact Information for Applicant

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2. Background

i). Project Title
Activity 1: Application and Analysis of a Coupled Hydrodynamic-Biogeochemical Model (ROMS-RCA) in Shallow-Water Habitats of the Chesapeake Bay

ii). Brief Description of UMCES
The University of Maryland Center for Environmental Science (UMCES) is a scientific research center within the University System of Maryland, with a mission of environmental discovery, research, scientific integration and application, and education, is carried out at four laboratories located across the state. While the Center's research and science application activities emphasize the Chesapeake Bay and its watershed, its reach extends worldwide.

iii). Documentation of Non-Profit Status
The University of Maryland Center for Environmental Science is a state institution of higher education and a wholly owned agency or instrumentality of the State of Maryland.

iv). Brief Biographies of Applicant Leads Including Resumes
Dr. Jeremy Testa is the lead-PI on this project. Dr. Testa is an estuarine systems ecologist with expertise in coastal ecology and biogeochemistry. Dr. Testa has utilized numerical models of varied complexity to explore questions related to phytoplankton, oxygen, and nutrient dynamics in Chesapeake Bay and other coastal ecosystems. Dr. Testa hold a B.S. in Environmental and Forest Biology from The State University of New College Of Environmental Science and Forestry (2003) and an M.S (2006) and Ph.D. (2013) in Oceanography and Systems Ecology from the University of Maryland, under the supervision of Dr. Michael Kemp. Dr. Testa is currently an Assistant Professor at the UMCES Chesapeake Biological Laboratory in Solomons Maryland, and has held prior positions as a Visiting Scientist at the University of Copenhagen (Denmark) and as a Faculty Research Assistant at the UMCES Horn Point Laboratory in Cambridge Maryland. Dr. Testa has been a participant in Chesapeake Bay Program Tidal Monitoring and Analysis Workgroup Participant (2013), a member of the Atlantic Estuarine Research Society (AERS) Executive Board since 2010, and a co-developer of science education modules as part of the NSF-funded Centers for Ocean Sciences Education Excellence (COSEE; 2008). Dr. Testa co-authored a white paper report to the Maryland Department of Natural Resources in 2009 (#1 below) that described an ecosystem-scale ecological assessment of the Corsica River estuary, an important Chesapeake shallow-water system. Several relevant products for Dr. Testa are:

1. Boynton, W.R., J.M. Testa, and W.M. Kemp. 2009. An Ecological Assessment of the Corsica River Estuary and Watershed: Scientific Advice for Future Water Quality Management. Final Report to Maryland Department of Natural Resources. Ref. No. [UMCES]CBL 09-117.
2. Testa, J.M. and W.M. Kemp, 2011. Oxygen - Dynamics and Biogeochemical Consequences. In: Wolansky, E. and McLusky, D.S. (eds.), *Treatise on Estuarine and Coastal Science*, Vol 5, pp. 163-199. Waltham: Academic Press.
3. Testa, J.M. and W.M. Kemp. 2008. Regional, seasonal, and inter-annual variability of biogeochemical processes and physical transport in a partially stratified estuary: a box-modeling analysis. *Marine Ecology Progress Series* 356: 63-79.

4. Testa, J.M. and W.M. Kemp. 2012. Hypoxia-induced shifts in nitrogen and phosphorus cycling in Chesapeake Bay. *Limnology and Oceanography* 57: 835-850.
5. Testa, J.M., W.M. Kemp, W.R. Boynton, and J.D. Hagy III. 2008. Long-term changes in water quality and productivity in the Patuxent River estuary: 1985 to 2003. *Estuaries and Coasts* 31: 1021-1037.
6. Kemp, W.M., J.M. Testa, D.J. Conley, D. Gilbert, and J.D. Hagy. 2009. Temporal responses of coastal hypoxia to nutrient loading and physical controls. *Biogeosciences* 6: 2985-3008.
7. Stæhr, P.A., J.M. Testa, W.M. Kemp, J.J. Cole, K. Sand-Jensen, S.V. Smith. 2012. The metabolism of aquatic ecosystems: History, methods, and applications. *Aquatic Sciences* 74: 15-29.

Dr. Damian Brady is a co-PI on this project. Dr. Brady has expertise in coastal ecology and numerical modeling of sediment and water-column processes in coastal systems. Additionally, Dr. Brady works to link numerical models of water quality with exposure and biological impacts in shallow water estuarine ecosystems. Dr. Brady received a B.S. from Roger Williams University in 2000 and a Ph.D. in Marine Biology/Biochemistry from the University of Delaware in 2008 working with Dr. Timothy E. Targett. Subsequently, Dr. Brady was a post-doctoral associate with Dr. Dominic Di Toro from 2008-2010 working on a numerical model of Delaware's Coastal bays, a shallow water estuarine system adjacent to the Chesapeake Bay. Dr. Brady takes a management-based approach to modeling and is currently a member of the Comprehensive Management Plan team for Delaware's Coastal Bays and editor of the State of the Bay report for Delaware's Coastal Bays. Recently (April 17-18, 2013), Dr. Brady was a member of NOAA's Northern Gulf of Mexico Hypoxia Modeling Technical Review Team at the Stennis Space Center in Mississippi. Several relevant products generated by Dr. Brady are:
1. Zhang, Q., Brady, D.C., & Ball, W.P. (2013) Long-term seasonal trends of nitrogen, phosphorus, and suspended sediment load from the non-tidal Susquhanna River Basin to Chesapeake Bay. *Science of the Total Environment*, 452-453: 208-221
2. Tyler, R.M., Brady, D.C., Targett, T.E. (2009) Temporal and spatial dynamics of diel-cycling dissolved oxygen in estuarine tributaries. *Estuaries and Coasts.* 32(1): 123-145.
3. Brady, D.C. & Targett, T.E. (2013) Movement of juvenile weakfish (*Cynoscion regalis*) and spot (*Leiostomus xanthurus*) in relation to diel-cycling hypoxia in an estuarine tributary: Assessment using acoustic telemetry. *Marine Ecology Progress Series,* 491: 199-219
4. Brady, D.C., Targett, T.E. (2010) Characterizing the escape response of air-saturation and hypoxia-acclimated juvenile summer flounder (*Paralichthys dentatus*) to diel-cycling hypoxia. *Journal of Fish Biology,* **77**(1): 137-152.
5. Breitburg, D.L., Craig, J.K., Fulford, R.S., Rose, K.A., Boynton, W.R., Brady, D.C., Ciotti, B.J., Diaz, R.J., Friedland, K.D., Hagy, J.D. III, Hart, D.R., Hines, A.H., Houde, E.D., Kolesar, S.E., Nixon, S.W., Rice, J.A., Secor, D.H., Targett, T.E. (2009) Nutrient enrichment and fisheries exploitation: interactive effects on estuarine living resources and their management. *Hydrobiologia,* 629(1): 31-47.
6. Brady, D.C., Tuzzolino, D.M., Targett, T.E. (2009) Behavioral responses of juvenile weakfish, *Cynoscion regalis*, to diel-cycling hypoxia: swimming speed, angular correlation, expected displacement and effects of hypoxia acclimation. *Canadian Journal of Fisheries and Aquatic Sciences.* 66(3): 415-424.
7. Fennel, K., Brady, D.C., Di Toro, D.M., Fulweiler, R., Gardner, W.S., Giblin, A., McCarthy, M.J., Rao, A., Seitzinger, S., Thouvenot-Korppoo, Tobias, C. (2009) Modeling denitrification in aquatic sediments. Biogeochemistry. 93(1-2): 159-178.

Dr. Ming Li is a co-PI on this project. Dr. Li has expertise in coastal physical dynamics with experience using numerical models to examine sediment transport, storm surges, dissolved oxygen dynamics, and physical processes. Dr. Li received his Bachelors of Engineering in fluid mechanics from Hohai University (1983) and his Ph.D. in Geophysical Fluid Dynamics from the University of Oxford (1991) under the supervision of T. Brooke Benjamin. Dr. Li has been a Professor at the University of Maryland Center for Environmental Science, Horn Point Laboratory since 2001, while he previously was a Research Scientist at the Institute of Ocean Sciences, Canada (1996-2001) and a Research Associate at the University of Victoria, Canada (1991-1996) under the supervision of Chris Garrett and David M. Farmer. Dr. Li has been a member of the National Science Foundation proposal evaluation panel (2003, 2007), the National Atmospheric and Oceanic Administration proposal review panel (2010) and has convened sessions on the "Impact of climate variability and change on estuaries and coastal ocean", at the American Geophysical Union Fall Meeting in San Francisco (2008) and the "Impact of eutrophication and climate change on marginal seas" at the ASLO Ocean Science Meeting (2010). Dr. Li has advised or co-advised 18 graduate students and several post-doctoral fellows and teaches courses on the physics of marine and estuarine environments, climate variability and its impact on estuaries and ecosystem, transport processes and plankton distributions at the University of Maryland. Several relevant products generated by Dr. Li are:

1. Cheng, P, M. Li and Y. Li. 2013. Generation of an estuarine sediment plume by a tropical storm. *Journal of Geophysical Research*, 118, 1–13, doi:10.1029/2012JC008225.
2. Lee, Y.J., W.R. Boyton, M. Li and Y. Li. 2013. Role of later winter-spring wind influencing summer hypoxia in Chesapeake Bay. *Estuaries and Coasts*, doi: 10.1007/s12237-013-9592-5.
3. Li, M., L. Zhong and L. W. Harding. 2009. Sensitivity of plankton biomass and productivity to variations in physical forcing and biological parameters in Chesapeake Bay. *Journal of Marine Research*, 67,667-700.
4. Hilton, T. W., R. G. Najjar, L. Zhong and M. Li. 2008. Is there a signal of sea-level rise in Chesapeake Bay salinity? *Journal of Geophysical Research*, 113: C09002, doi:10.1029/2007JC004247.
5. Li, M., L. Zhong, W. C. Boicourt, S. Zhang and D.-L. Zhang. 2007. Hurricane-induced destratification and restratification in a partially-mixed estuary. *Journal of Marine Research*, 65, 169-192.
6. Li, M. and Z. Rong. 2012. Effects of tides on freshwater and volume transports in Changjiang River plume. *Journal of Geophysical Research*, 117, C06027, doi:10.1029/2011JC007716.
7. Jia, P. and M. Li. 2012. Circulation dynamics and salt budget in a lagoonal estuary. *Journal of Geophysical Research,* 117, C01003, doi:10.1029/2011JC007124.
8. Jia, P. and M. Li. 2012. Dynamics of wind-driven circulation in a shallow lagoon with strong horizontal density gradient. *Journal of Geophysical Research*, 117, C05013, doi:10.1029/2011JC007475.
9. Li, Y. and M. Li. 2012. Wind-driven lateral circulation in a stratified estuary and its effects on the along-channel flow. *Journal of Geophysical Research*, 117, C09005, doi:10.1029/2011JC007829.
10. Li, Y. and M. Li. 2011. Effects of winds on stratification and circulation in a partially mixed estuary. *Journal of Geophysical Research*, 116, C1202, doi:10.1029/2010JC006893.

Key Collaborative Products from Testa, Brady, and Li

1. Testa, J.M., D.C. Brady, D.M. Di Toro, W.R. Boynton, and W.M. Kemp. 2013. Sediment flux modeling: Nitrogen, phosphorus and silica cycles. *Estuarine, Coastal and Shelf Science* 131: 245-263
2. Testa, J.M., Y. Li, Y.-J. Lee, M. Li, D.C. Brady, D.M. Di Toro, and W.M. Kemp. 2013. Quantifying the effects of nutrient loading and carbon production on dissolved O_2 in Chesapeake Bay using a coupled hydrodynamic-biogeochemical model. *Journal of Marine Systems*. In Review.
3. Brady, D.C., J. Testa, D. Di Toro, W. Boynton, M. Kemp. 2012. Sediment flux modeling: Calibration and application for coastal systems. *Estuarine and Coastal Shelf Science* 24: 1-18.
4. CBEO Project Team: Ball, W.P., Brady, D.C., Brooks, M.T., Burns, R, Cuker, B.E., Di Toro, D.M., Gross, T.F., Kemp, W.M., Murray, L., Murphy, R.R., Perlman, E., Piasecki, M., Testa, J.M., Zaslavsky, I. (2008) Prototype system for multi-disciplinary shared cyberinfrastructure: Chesapeake Bay Environmental Observatory (CBEO). *Journal of Hydrologic Engineering, ASCE*. 13(10): 960-970.

v). Funding Requested: $74,957; UMCES Cost-Share (cash) $4,131; Total Project Costs $79,088.

vi). DUNS Number

The DUNS Number for UMCES is 021463831.

3. Workplan

i). Meeting the Objectives and Requirements

Shallow-water habitats are key components of many coastal ecosystems. These habitats often reside at the land-water interface and mediate the transfer of land-derived materials to deeper, subtidal regions. Benthic-pelagic coupling is strong in shallow systems (Kemp, et al. 1992), which can result in enhanced nutrient recycling and associated high productivity. Because light penetrates to the sediment surface in many shallow systems, submerged aquatic vegetation and benthic algal communities often inhabit these environments. These benthic communities alter nutrient and carbon cycling, but also provide food and habitat for many important organisms (Fig. 1). Because shallow-water areas constitute the majority of Chesapeake Bay (76% of area < 10 m), nutrient and sediment dynamics in these habitats can have important consequences for Bay ecology. Despite their ubiquity and potential importance, such shallow-water systems have generally been understudied in the Chesapeake Bay region, while current modeling efforts have experienced difficulties in reproducing shallow-water hydrodynamic and biogeochemical processes (Friedrichs, et al. 2012).

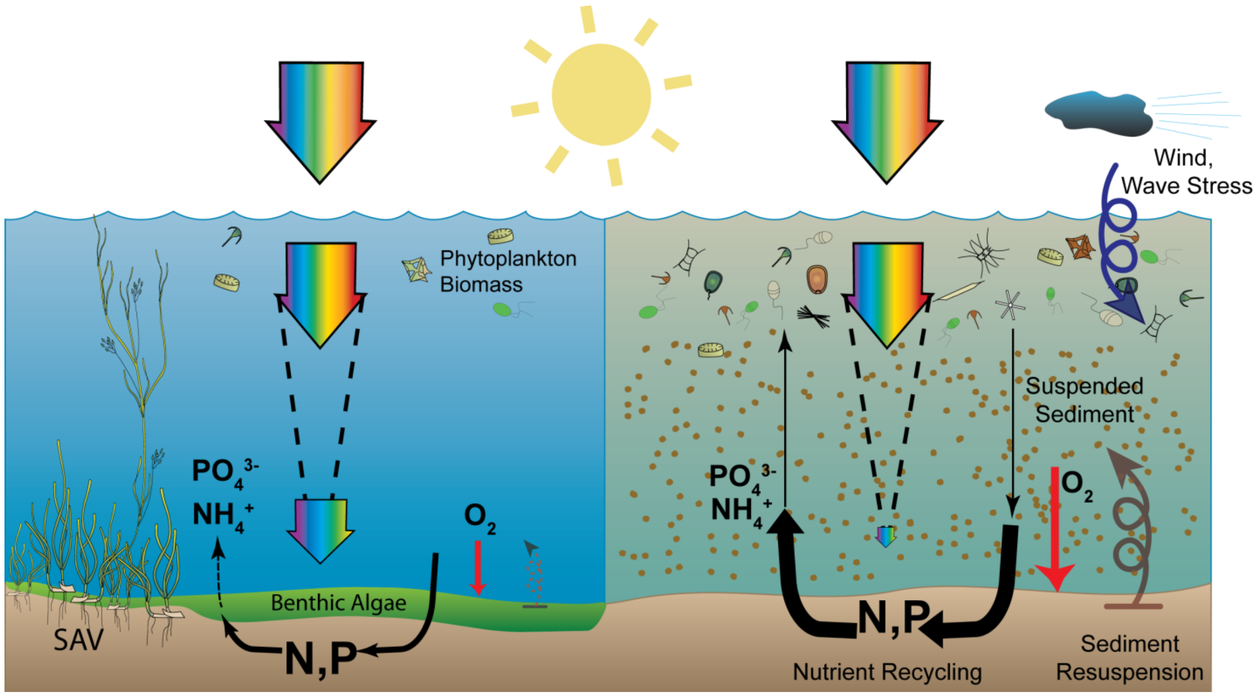

Figure 1: Key biogeochemical processes in shallow water habitats in Chesapeake Bay. The availability of light drives nutrient and carbon dynamics in shallow coastal ecosystems, as once light reaches the sediment, benthic algal communities can (1) absorb nutrients and retain them in sediments, (2) stabilize sediments and limit resuspension, and thus (3) lead to elevated water clarity. In the absence of light at the sediment surface, limited benthic algal growth leads to high sediment nutrient recycling and potentially less stable sediments.

Modeling shallow-water ecosystem dynamics and their response to alterations in physical forcing and nutrient loading presents an interesting challenge. Chlorophyll-*a* and dissolved O_2 can vary substantially over the course of a day in shallow-water systems (D'Avanzo and Kremer 1994, Tyler, et al. 2009), due to the compressed water-column and strong interaction with metabolically-active sediments. As a result, NPDZ-type biogeochemical models have not been commonly applied in such systems. Shallow-water systems may also have different nutrient load response curves than their deeper, water-column-dominated counterparts (D'Avanzo, et al. 1996, Nixon, et al. 2001). In the shallow water habitats of Chesapeake Bay, for example, there appears to be non-linear relationships between total nitrogen loading and chlorophyll-*a* (Fig. 2). Specifically, algal biomass may respond more slowly to nutrient loading at low and high loading rates. Such non-linearities may result from feedbacks associated with the availability of light at the sediment surface. When sediments are illuminated, benthic algae trap nutrients in the sediment and inhibit algal growth in the water-column, but when sediments do not receive light, sediment-nutrient release is enhanced and algal growth in the water-column is stimulated (Fig. 3). These feedbacks interact with resuspension processes, where wind-induced resuspension can increase water-column turbidity, thus reducing benthic algal production. In contrast to traditional water quality modeling approaches, shallow-water models must capture these dynamics over relatively short time/space scales.

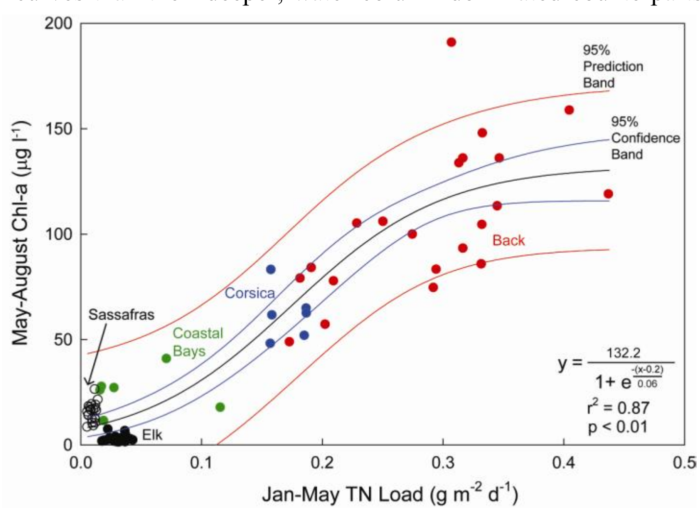

Figure 2: Relationship of winter-spring TN loading to summer chlorophyll-a in several shallow, well-mixed estuaries in the Chesapeake Bay region (Testa and Boynton, unpublished)

Hydrodynamic simulations in shallow-waters also have different challenges than in deeper-waters. As many shallow-water systems are small (in terms of area) and have complex shorelines, hydrodynamic models must have sufficiently fine resolution to resolve small-scale flows and spatial inhomogenieties (Jia and Li 2012a, b). Shallow-water models may also be more sensitive to frictional parameterizations, as wind stress and bottom friction impose strong controls on the flows. Finally, exchanges between shallow water bodies and the deep main stem of the estuary need to be considered. Clearly, these considerations must be accounted for in any shallow-water model applied in the Chesapeake Bay.

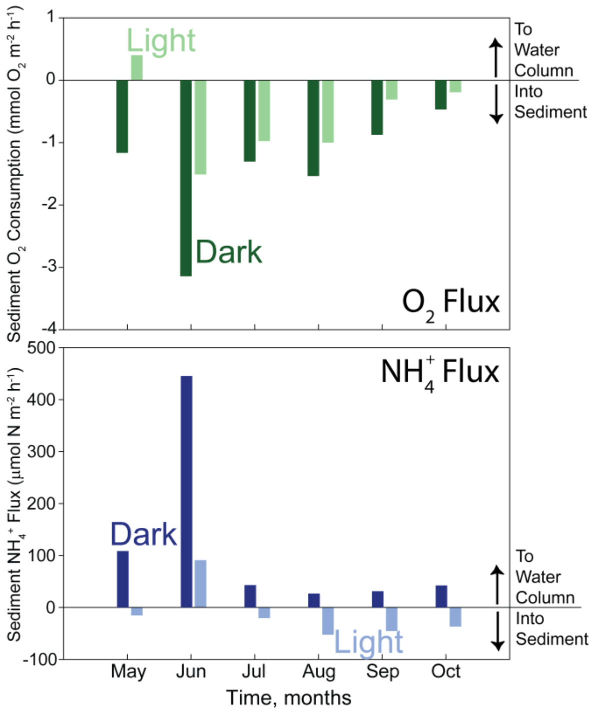

Figure 3: Measured sediment-water O_2 (top) and NH_4^+ (bottom) fluxes in the Corsica River estuary under conditions of no light and illumination (left panel). Clearly, the availability of light leads to reduced sediment O_2 demand and sediment NH_4^+ release. Data from Jeff Cornwell and Mike Owens.

We propose to apply and enhance an existing, coupled hydrodynamic-biogeochemical model (ROMS-RCA) to shallow-water habitats in Chesapeake Bay to simulate the dynamics of physical transport, benthic and pelagic algae, dissolved O_2, nutrients, and organic carbon. The modeling framework involves an offline coupling of the Regional Ocean Modeling System (ROMS; Li, et al. 2005) to a water-column and sediment biogeochemical model called RCA (Row-Column AESOP). ROMS has been validated against a wide range of observational data and has demonstrated considerable capability in reproducing estuarine dynamics at tidal, synoptic, and seasonal time-scales in Chesapeake Bay (Li, et al. 2005) and in shallow-estuaries like Albemarle-Pamlico Sound (Jia and Li 2012a) and Delaware's Coastal Bays (Kemp and others 2012). ROMS-RCA has been successfully applied in both Chesapeake Bay (Testa, et al. 2013b) and in the extremely shallow (≤ 2 m) Delaware Coastal Bays to simulate algal, O_2, and nutrient dynamics over seasonal and daily time-scales. RCA itself has been applied in many diverse coastal systems, including Massachusetts Bay, Jamaica Bay, and Long Island Sound. A crucial component of RCA for simulating shallow-ecosystems is its fully-coupled sediment biogeochemical model (Brady, et al. 2013, Testa, et al. 2013a), which includes two layers that represent the near-surface aerobic layer and underlying anaerobic environments. The sediment model simulates the cycling of carbon, O_2, nitrogen, phosphorus, silica, and sulfur. RCA allows for up to three phytoplankton groups, as well as state variables representing particulate and dissolved organic carbon, nitrogen

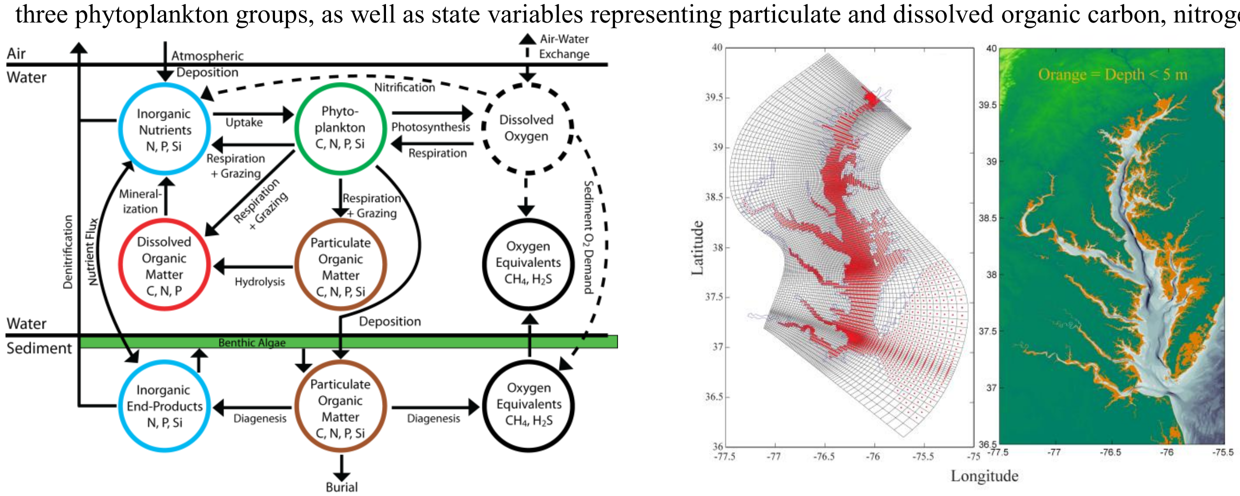

Figure 4: (left) Diagram of the RCA, including sediment and water-column processes, including the addition of a benthic algal layer at the sediment surface. In the middle is the ROMS-RCA model domain in Chesapeake Bay to the right is a map of Bay bathymetry with orange areas indicating the areas of habitat less than 5 meters in depth.

and phosphorus, dissolved inorganic nitrogen, phosphorus, and silica, biogenic particulate silica, and O_2 (Fig. 4). RCA also includes a state variable that represents O_2 equivalents associated with sulfide and methane released from sediments. Included in the ROMS-RCA package is a routine to compute multiple skill metrics and generate Taylor diagrams for model-observation comparisons – this package would be enhanced by Activity 2 of this agreement.

ROMS-RCA simulations in Chesapeake Bay have reproduced both the concentrations of key water-column constituents (chl-a, O_2, nutrients, water clarity) and associated rates of primary production, respiration, and sediment-water nutrient and O_2 fluxes (Fig. 5; Testa, et al. 2013b). Capturing both the *concentrations* and *transformation rates* of key variables is particularly important in shallow-water systems, where the primary variability occurs on the order of hours. ROMS-RCA offers several advantages that allow it to simulate such short-term dynamics in Chesapeake Bay, including the aforementioned sediment biogeochemical model and separate cycles of nitrogen, silica, and phosphorus, all of which may be limiting for phytoplankton growth at some place and time in Chesapeake Bay (Fisher, et al. 1992). ROMS-RCA has also reproduced *inter-annual variability* in O_2, chlorophyll-*a*, nutrients, and water clarity in many deeper regions (Fig. 5). Perhaps more importantly, ROMS-RCA has reproduced many fundamental functional relationships between nutrient loading, chlorophyll-*a*, and hypoxic volume in nutrient load alteration scenarios, as have been documented with observations (Testa, et al. 2013b),. Thus, the processes and interactions included in the ROMS-RCA package will likely capture inter-annual variability and ecosystem responses to nutrient load reductions in the shallow-water ecosystems included in this proposed agreement.

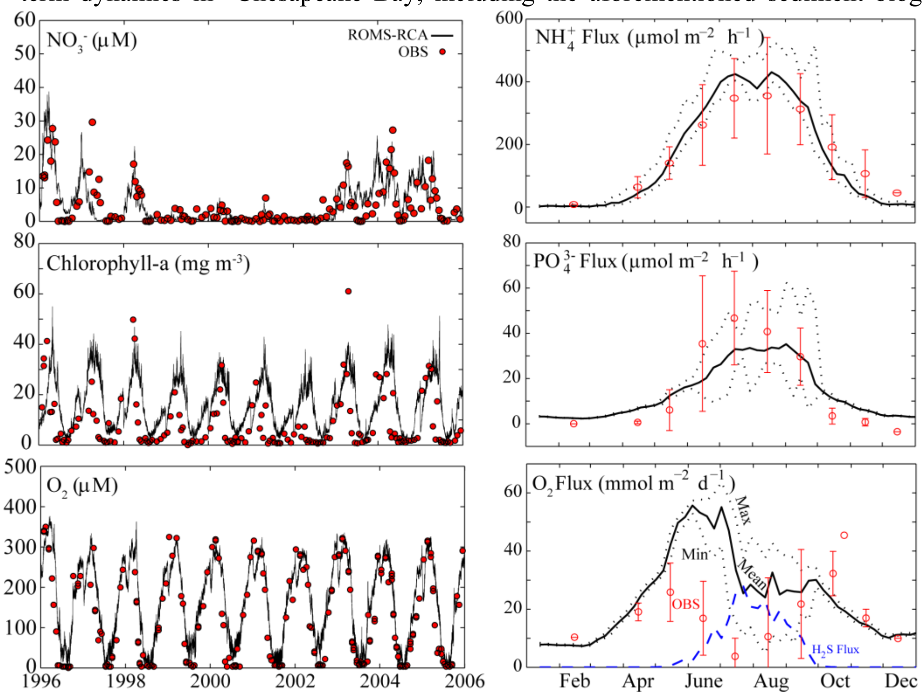

Figure 5: Model-observation comparisons of ROMS-RCA in the mainstem Chesapeake Bay (CIMS station CB4.3C) for bottom-water concentrations of NO_3^-, chlorophyll-a, and dissolved O_2 (left panel; data are red circles and model is black line) and sediment-water fluxes of NH_4^+, PO_4^{3-}, and dissolved O_2 (right panel). For sediment fluxes, the black line is model mean and dashed black lines are the minimum and maximum of model simulations, while red circles are observed fluxes (sediment fluxes courtesy of Walter Boynton).

ROMS-RCA has also shown promise for reproducing short temporal and spatial-scale hydrodynamic and biogeochemical patterns in Delaware's Coastal Bays, a shallow-water ecosystem (Kemp and others 2012). As is typical of shallow water systems, Delaware's Coastal Bays water column-concentrations of chlorophyll-*a*, suspended sediments, and O_2 vary markedly over the course of a day, and although remote forcing (nutrient load, eutrophication legacy) is important, local and proximal forcing (cloudiness, wind stress) are key drivers in this and similar systems (Tyler, et al. 2009). Reasonable characterizations of the physical transport associated with tides and local wind stress in very shallow-systems are necessary to properly simulate biogeochemical dynamics, which can be highly sensitive to advection and turbulent mixing. In contrast to the mainstem of Chesapeake Bay, Delaware's Coastal Bays are shallow and relatively poorly flushed, creating an ideal testbed for a shallow-water numerical modeling. In these shallow-water systems, diel-cycling of algal production and respiration create more ephemeral hypoxic zones in tidal tributaries (see Fig. 6; black indicates O_2 below the acute criteria (2.3 mg O_2 L^{-1}) and blue indicates O_2 below the chronic criteria (4.0 mg O_2 L^{-1})). These diel dynamics are likely characteristic of the shallow-systems we propose to model in this agreement, rather than a seasonal hypoxic 'dead zone' as in the open waters of Chesapeake Bay. To compare spatial patterns in O_2 between the model and observed data, results from 2001 multiparameter sonde deployments were used to create spatiotemporal contour plots of O_2. A three-dimensional plot (bottom water O_2, time in days, and distance along the tributary axis) illustrates key scale-dependent aspects of the diel O_2 cycle from July 12 to July 26, 2001 (Fig. 6). These spatiotemporal contour plots of both the model and observed data (Fig. 6) illustrate the spatial extent of diel-cycling hypoxia along the length of Pepper Creek, an isolated tributary of Delaware's Coastal Bays, and show that severe hypoxic conditions tended to occur more frequently, and persisted longer, in the uppermost area of the creek. The temporal view (y-axis of Fig. 6) of the observed data shows the typical diel O_2 cycle along the length of the tributary. Smooth transitions between hypoxia (in black and blue) and normoxia (red and orange) in the model output (Fig. 6b) demonstrate that shallow water models should be run with fine temporal scale forcing functions as shallow water systems tend to be coupled to synoptic conditions more than seasonal models. That is, whereas summer hypoxia may be caused by spring phytoplankton production in deeper seasonally stratified systems, in shallow water, brief periods (hours) of low insolation may be the proximal cause of hypoxia. Note that extreme events (e.g. days 201 and 202; Fig. 6) can reduce O_2 in the entire tributary to ≤ 2 mg O_2 l^{-1}. Overall, model dynamics along the axis of the creek reflect observed conditions; however improvement could be made to more adequately capture short term fluctuations in O_2.

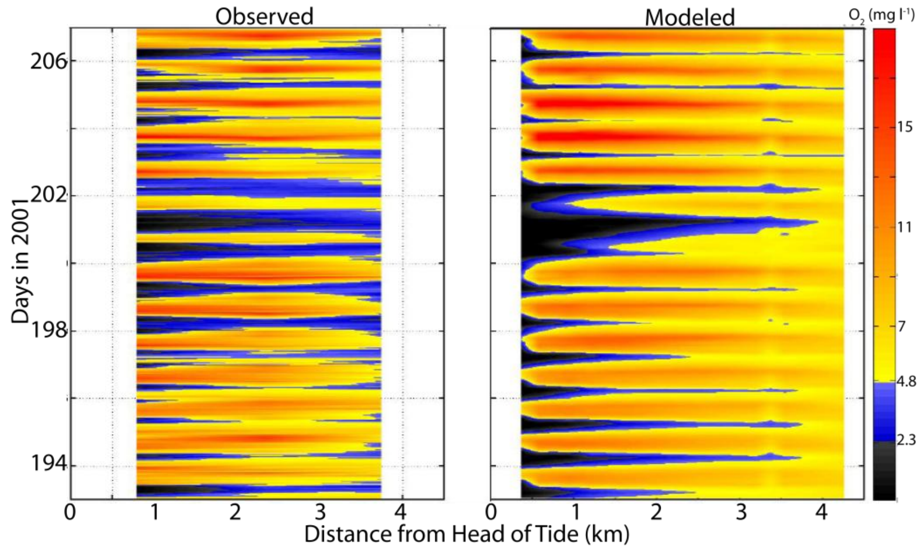

Figure 6: Validation of diel O_2 cycles in the Delaware's Coastal Bays over a two-week period in July 2001. The left panel includes observations (Tyler, et al. 2009), while the right panel is a simulation made with ROMS-RCA.

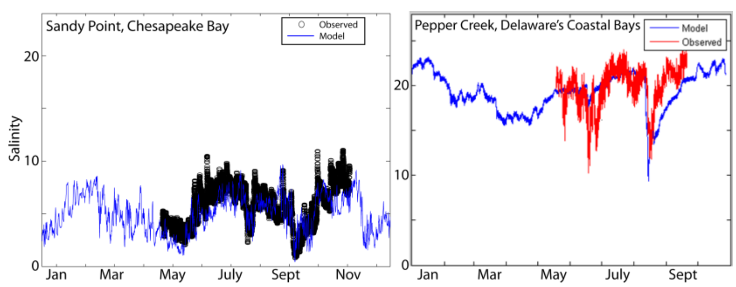

Figure 7: Comparison of observed (black circles, red lines) and ROMS-modeled (blue lines) salinity at a shallow (<4m) site in Chesapeake Bay and in Delaware's Coastal Bays.

Adequate hydrodynamic simulations are also a necessity for simulating shallow-water systems, as current and mixing fields can play a large, if not dominant role in the distribution of dissolved and particulate materials. ROMS has shown the ability of capturing observed salinity variability in shallow coastal systems over daily and seasonal time-scales (Fig. 7; Jia and Li 2012a). These results give confidence that ROMS can be effectively applied in new shallow-water systems with adequate calibration and validation data.

We believe our current ROMS-RCA modeling package will require additional or improved processes to adequately capture the important dynamics within shallow-water systems, including: (1) sediment transport and resuspension and (2) benthic algal production, nutrient uptake, and respiration. Given budget and project duration constraints, we propose to utilize and update previously implemented formulations for these two processes.

Sediment Resuspension and Transport Model: ROMS-RCA will be used to compute wind- and current-driven circulation and bed shear stress that redistributes sediments and associated nutrients. Although a dynamic sediment transport module is available for ROMS and has been implemented in Chesapeake Bay by co-PI Li, this model is computationally demanding, data intensive, and will require substantial effort to implement in a new system. ROMS-RCA currently includes a basic mechanism to incorporate resuspension effects, via a spatially-explicit control on the fraction of deposited organic carbon that remains in sediments (i.e., "net" carbon deposition) versus remaining suspended in the water-column. Although this formulation has proved useful in modeling efforts to date, it is likely too simplistic for the needs of this proposed effort. Therefore, we propose to implement an empirical formulation for sediment resuspension that is driven by wave and current-driven shear stress at the sediment surface. In this scheme, wave data provided by the CBP will be used to compute wave-generated bottom stress, which when added to current-generated bed stress as computed by ROMS, will yield a total shear stress (e.g., Chen, et al. 2007). Empirical formulations between shear-stress and the erodibility of organic particles will then be used to estimate the amount of resuspended material, assuming a limited sediment supply (e.g., Dickhudt, et al. 2009, Sanford and Maa 2001). We will focus on the organic fraction of resuspended sediments, which will allow the sediment formulation to interact directly with the biogeochemical model, but inorganic particles could be incorporated given available data for these materials to better represent the suspended solids pool. Comparable formulations have been applied in Chesapeake Bay with reasonable results (Cerco, et al. 2010), supporting the implementation of a simplified model.

Benthic Algal Model: Benthic algal communities residing within or just above the sediment surface can have large impacts on the biogeochemistry and stability of sediments, which impacts processes occurring in the overlying water-column (McGlathery, et al. 2007, Miller, et al. 1996). For example, sediment-water fluxes of O_2 and NH_4^+ are reduced in sediment cores that are exposed to light (Fig. 3). PIs Brady and Testa have successfully integrated a benthic algal model into a stand-alone version of the sediment flux model, and we will integrate this model into the ROMS-RCA package and validate simulations of nutrient flux against observations (see Letter of Support from Dr. Jeffrey Cornwell in Appendix A). In short, this model predicts benthic algal photosynthesis, respiration, and associated nutrient uptake and release for a benthic algal mat residing on the sediment surface, where algal growth is a function of light, temperature, and nutrient availability.

We have assembled a team that can successfully execute the model simulations required for Activity 1. PIs Jeremy Testa and Damian Brady have extensive expertise applying ROMS-RCA in Chesapeake Bay, its tributaries, and Delaware's Coastal Bays. PIs Brady and Testa will be responsible for executing ROMS-RCA, implementing the new model formulations, and validating model simulations. PI Li will provide guidance and support for the implementation of ROMS in a shallow-water system and/or the refinements of the current ROMS-RCA grid to better resolve shallow habitats. Our specific work plan is as follows. Once the model testing site(s) are chosen, we will determine if our existing model domain adequately represents this system. If it does, we will configure ROMS-RCA to accept the common-forcing data and boundary conditions provided by CBP. If our current domain fails to adequately represent the system, we will implement a ROMS simulation specific to the new system using the CBP-provided forcing, boundary, and bathymetry data. ROMS-RCA is currently configured to utilize the CBP Partnership's Phase 5.3.2 Chesapeake Bay Watershed Model, which will ease the watershed-estuary model-coupling. ROMS-RCA currently makes accurate predictions on water clarity in Chesapeake Bay (Testa, et al. 2013b), and simulates the variables required by the empirical SAV habitat model provided by the CBP (e.g., temperature, salinity, O_2, the light field, etc.), although explicit SAV modeling is not currently included in ROMS-RCA. Thus, ROMS-RCA meets the functional requirements participation in this project (Friedrichs, et al. 2012).

Task	Lead PI	Year 1				Year 2			
		1	2	3	4	1	2	3	4
Model Setup									
Assemble Forcing and Boundary Data	Brady	■	■		■				
Assemble Validation Data	Testa	■	■		■				
Implement and Calibrate ROMS	All	■	■	■					
Model Simulations									
Implement ROMS-RCA	Testa			■	■	■	■		
Validate Model and Organize Output	Brady			■	■	■	■		
Implement Resuspension Model	Testa,Li				■	■			
Post-Processing and Scenarios									
Implement Benthic Algal, SAV Model	Testa				■	■			
Execute Nutrient Load Scenarios	Brady				■	■			
Sensitivity Analysis	All				■	■	■	■	
Integration & Outreach									
Modeling Workgroup Meetings	All		■	■	■	■	■	■	■
Team Meetings and Assessments	All		■	■	■	■	■	■	■
Publication	All							■	■

Figure 8: Timeline of proposed work.

We propose a timeline to achieve the outcomes and products required by this activity (Fig. 8). The implementation of ROMS-RCA will be achieved primarily in the second half of Year One, while the assembly, organization, and integration of the forcing and validation will be done in the months prior to model execution. We expect to have the structure and output ready toward the end of Year One to begin making predictions with the empirical SAV model and to prepare for the nutrient loading scenarios. This will require the implementation of the resuspension and benthic algal formulations by the end of Year One. Sensitivity analyses will be performed throughout the project (calibration, validation, simulation), as will meetings within our group and with CBP and modeling partners. Calibration and validation exercises will be carefully documented since it is during this process that the most salient recommendations can be made to future CBP modeling activities in shallow waters. We expect the dissemination of our results to the scientific and modeling community to occur somewhat continuously (i.e., STAC Technical Modeling Subcommittee Quarterly Meetings), but more formally toward the end of year 2.

ii.) Budget:	*Federal Portion*		*UMCES Cost Share*		
	Year 1	Year 2	Year 1	Year 2	Total
Personnel	9,695	6,348	1,100	900	18,043
Fringe	3,393	2,222	385	315	6,315
Travel	500	500	0	0	1,000
Computing Services	40	40	0	0	80
Sub-Contracts	13,459	13,459	0	0	26,918
Indirect Costs	14,356	10,945	787	644	26,732
Total	**41,443**	**33,514**	**2,272**	**1,859**	**79,088**

The budget developed for this proposal is largely for salaries and fringe of key personnel (Testa, Brady, & Li) and travel. The travel budget is to facilitate collaboration and exchange between UMCES (Horn Point Laboratory and Chesapeake Biological Laboratory) and UMaine personnel, to travel to the CBP Partnership Modeling Workgroup's Quarterly Reviews, and to present results at conferences. This proposal includes a subaward of $26,918 to the University of Maine to support salary, fringe, and travel for PI Brady. UMCES has a Federal negotiated Facilities and Administrative Cost Rate Agreement (F&A Rate) dated October 9, 2012. The UMCES on-campus rate for federally sponsored research is 53% of the modified total direct costs (MTDC). UMCES will provide a cost share equivalent to 5%, which will be met by salary and fringe support for PIs Testa and Li distributed equally over the project and totals $2000 in salary, $700 in fringe benefits, and $1431 in indirect costs, for a total of $4,131. A total of $80 is requested for enhanced IT services for research computer systems, provided through a recharge center at Horn Point Laboratory. Budget details are included in form SF-424A.

iii). Environmental Results - Outputs and Outcomes

1. *Output*: The proposed modeling efforts described above will ultimately provide a complementary modeling system to simulate hydrodynamics, primary production, respiration, and nutrient cycling in shallow-water habitats of Chesapeake Bay. Such a system, in concert with existing modeling tools, will improve confidence in predictions of ecosystem responses to nutrient loading reductions towards compliance with TMDL mandates. This effort will also identify the relative role of key biogeochemical processes in controlling shallow-water quality via sensitivity analyses. This new information will help improve our scientific understanding of shallow-water processes while improving the reliability and predictive strength of modeling tools and will be communicated in agency reports, scientific literature, data products, and meeting presentations. We intend to make our model code, output, and validation data available to agency partners.

2. *Outcome*: One key outcome of this effort will be the continued development of a model that will diversify the suite of numerical models available for analysis and scenario simulations in the Chesapeake region, which will presumably increase confidence in model predictions. The proposed validation effort using continuously measured water-column variables, as well as available rate measurements will surely challenge the models, leading to model refinement and the addition of additional key processes. This validation effort, along with the model inter-comparison, will push model capability forward. Secondly, the shallow-water systems residing at the interface of land and open-water in Chesapeake Bay are relatively poorly studied considering their potential importance as transformation centers of land-derived sediments and nutrients. If we consider models to be tools to synthesize our understanding of a system, the advanced model applications described here will improve our understanding, and thus management, of these important littoral habitats.

iv). Review Criteria

Section IV.1: Organization Capacity and Program Description

PIs Testa, Brady, and Li have collaborated on several previous projects in the last five years and have displayed high productivity in reporting results in a timely fashion in the scientific literature (see Section 2 *iv*) and in project reporting. They have collaborated in developing and enhancing several water-quality modeling tools for Chesapeake Bay, all of which have been contributed to the scientific literature and presented to EPA-CBP scientific workgroups. As all of these modeling tools are operational, they can be readily applies and refined in new applications in shallow-water systems. PIs Testa, Brady, and Li each have the institutional support and computing resources necessary to execute the modeling experiments required by this agreement.

Section IV.2: Programmatic Capability and Environmental Results Past Performance
PIs Testa, Brady and Li have displayed consistent achievement in meeting the deadlines and goals of past federally- and non-federally funded projects that they have participated in, with documented products. PI Testa is a very early career researcher and has not been a lead PI on any previous assistance agreements. PI Testa has played key roles in several recent projects with PIs Brady and Li, a subset of which includes:

(1) NSF (Award 0618986)– A Prototype System for Multi-Disciplinary Shared Cyberinfrastructure: Chesapeake Bay Environmental Observatory (CBEO; 2006-2011): PIs Testa and Brady were participants in this project, which aimed to assemble a prototype testbed of environmental observing data for Chesapeake Bay and to develop analytical tools to integrate the varied datasets toward gaining new insights into the controls on hypoxic volume in Chesapeake Bay (Ball, et al. 2008). Key products of this effort were the creation of the CBEO (with > 20 independent datasets), the transfer of the CBEO to the data management center at Horn Point Laboratory to assure continued development, and the timely completion of project reports and peer-reviewed publications that display the synthesis and analysis of linked, complex environmental datasets and model simulations (e.g., Brady, et al. 2013, Testa and Kemp 2012, 2014, Testa, et al. 2013b).

(2) NOAA CHRP07 (NA07NOS4780191-) Modeling Hypoxia and Ecological Responses to Climate and Nutrients (2007-2013): PIs Testa, Brady, and Li collaborated on this project to develop statistical and numerical models to predict aspects of hydrodynamic and biogeochemical controls on dissolved oxygen in Chesapeake Bay. Key products from this effort include a suite of new predictive modeling tools for Chesapeake Bay (Brady, et al. 2013, Li and Li 2011, Testa, et al. 2013b), including the implementation, calibration, and validation of the ROMS-RCA model in Chesapeake Bay and the shallow Delaware Coastal Bays to investigate nutrient and oxygen dynamics in shallow ecosystems. Implementing ROMS-RCA required the integration of several varied input datasets, development of model skill metrics, and further enhancement of model processes.

(3) NOAA Sea Grant Aquaculture Research Program (NA10OAR4170072): Predicting spatial impacts of bivalve aquaculture on nutrient cycling and benthic habitat quality (2010-2013): PIs Testa and Brady participated in this project, which aimed to understand the spatial aspects of the biogeochemical impact of shellfish aquaculture on local sediments, with a focus of guiding site selection for aquaculture operations in Chesapeake Bay and coastal Maine. Key products of this analysis include (1) an application of a sediment flux model to understand aspects of nutrient cycling and organic matter transport and deposition in shallow-water system, and (2) the development of a numerical tool to quantify the spatial footprint of a potential ecosystem stressor (e.g., oyster farm).

(4) NOAA CSCOR Feasibility Study for Operational Regional Coastal Ecosystem Management Models (2011-2013). PI Brady is a collaborator in this project with James Fitzpatrick (HDR|HydroQual), Dominic M. Di Toro (University of Delaware), Don Scavia (University of Michigan), Joseph De Pinto (Limno-Tech, Inc.), and W.M. Kemp (UMCES), where an upcoming workshop will address the potential for operational numerical model implementation in the coastal ocean to address management-related questions.

Section IV.3.: Cost-effectiveness
An extensive effort was made to propose a work plan whose scope is obtainable given the resources allocated for this project. We have purposely proposed to utilize modeling tools that we are currently applying in Chesapeake Bay and its tributaries, which will allow us to streamline our efforts in meeting the demands of this agreement. In addition, UMCES and UMaine PIs will contribute their effort in overseeing and managing the project(s) to meet the required cost share (including salary, fringe benefits and indirect costs), which provides additional time and effort to meet the project goals. UMCES in particular is in an ideal position to increase the cost effectiveness of these activities by virtue of existing library, computing, and communication tools. Indirect cost recoveries are budgeted at the federally approved off-campus rate of 53%.

Section IV.4.: Transferability of Results to Similar Projects and/or Dissemination to the Public
UMCES has a long and broad tradition of working with stakeholders and the public in ensuring they have the information needed to make informed decisions. PIs Testa and Brady have been participants in EPA-CBP workgroups and have presented research to the CBP partnership on several occasions. We plan to continue in this vein by attending each CBP Modeling Quarterly Review during and after the course of the project. Given the proximity of PIs Li and Testa to Annapolis, additional exchanges are easily achieved. Each PI in our project is currently involved in delivering management-focused, timely scientific information to agency partners and the public, including PI Li for the Chesapeake Inundation Prediction System (CIPS); (Stamey and others 2007), PI

Brady for a DOE-funded offshore wind project in Maine (http://www.umaine.edu/marine/research/clusters-ocean-energy.php) and the State of the Bay Report card for Delaware's Coastal Bays, and PI Testa for the summer hypoxia forecast for Chesapeake Bay (http://ian.umces.edu/ecocheck/forecast/chesapeake-bay/2013/). In addition, the UMCES Director of Public Relations, Amy Pelsinsky, has extensive experience in the Chesapeake Bay region and a good working relationship with CBP. If appropriate, she will work with the CBP partners as well as the employee responsible for this activity in the development of briefing materials for partners, stakeholders, NGOs, citizens, and/or the press. She has a very strong working relationship with many of the relevant journalists in the region. We proposed a calendar of milestone achievements in our work plan (see Section 3*i*) that will guide our accomplishment of tasks and timely delivery of materials to CBP.

Section IV.5.: Modernization of Methods Over Time

We expect the modeling exercises described in this application will lead to new insights for the development, application, and analysis of shallow-water (and more general ecosystem) models in Chesapeake Bay. Toward this end, we plan to offer specific recommendations to how both biogeochemical (key processes and variables) and hydrodynamic modeling tools may better represent shallow-water habitats in the future. Although many of these recommendations will naturally emerge from the model inter-comparison aspect of this project, we intend to perform sensitivity and scenario analyses to determine key controlling processes and parameters in our own model. In addition, we consider our models to be part of our ongoing scientific toolkit, thus we have a strong desire and incentive to incorporate new processes into our models and test current formulations in new systems. We plan to report these improvements as they arrive at CBP workshops, in white paper reports, and the scientific literature.

Section IV.6.: Timely Expenditure of Grant Funds

Given the fact that our budget provides individual salary support for no greater that one month per year, we are confident that we will utilize this support immediately to achieve the modeling tasks as proposed in the narrative.

4) Letters of Support

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Horn Point Laboratory

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January 6, 2014

Dear Dr. Testa:

This letter is in support of your work on modeling of shallow water biogeochemical processes in Chesapeake Bay. I have had a strong interest in the influence of light on benthic biogeochemical processes in the Chesapeake Bay, Maryland Coastal Bays, and a number of shallow water environments on both east and west coasts (San Francisco Bay, Maine, Florida). We have developed data sets for light/dark incubations of sediments with benthic microalgae on the sediment surface, with net fluxes of O_2, N_2-N (denitrification), nitrate, ammonium, and soluble reactive phosphorus. Your incorporation of benthic microalgal dynamics into the sediment flux model will be of particular value in shallow water tributaries where substantial parts of the ecosystem have light at the sediment surface.

My laboratory will provide you with a number of appropriate data sets and provide any insights you deem valuable for model development. In the Chesapeake Bay, we have several data sets well suited to calibration/validation of SFM models. I look forward to interacting with you on incorporating our observations into the sediment flux model; your efforts will enhance the value of our observational efforts and help turn these observations into a form most useful for managing shallow water coastal systems.

Best wishes,
Jeffrey Cornwell
Research Professor

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January 8, 2014

U.S. Environmental Protection Agency
ATTN: Dr. Tim Roberts
Chesapeake Bay Program Office
410 Severn Ave., Suite 109
Annapolis, MD 21403

Re: Proposal "Application and Analysis of a Coupled Hydrodynamic-Biogeochemical Model (ROMS-RCA) in Shallow-Water Habitats of the Chesapeake" in response to RFP EPA-R3-CBP-14-2

Dear Dr. Roberts:

This is to confirm that the University of Maryland Center for Environmental Science will provide a minimum of five percent of the total cost of the project as cost sharing for the referenced proposal should it be funded in full. Drs. Jeremy Testa and Ming Li, as co-principle investigators, will provide the required match. Their effort (percentage of salary, fringe benefits, and indirect costs) will be tracked to meet the cost sharing requirement.

UMCES has a federal negotiated F&A Rate Agreement dated October 9, 2012. The UMCES on-campus rate for federally sponsored research is 53% MTDC and has been applied to this project. The MTDC base of expenses includes all direct costs except equipment (each item over 5k), tuition remission, rental of off-site facilities, capital expenditures, scholarships and fellowships, portion of each subaward/subgrant in excess of 25k and UMCES research vessel operations.

The consideration of this proposal by the EPA's Chesapeake Bay Program will be greatly appreciated. If you have questions, please do not hesitate to contact me at 410/221-2014, or rhoades@umces.edu.

Sincerely,

Phyllis Rhoades
Assistant Director, Office of Research
Administration and Advancement

For your info:

Bob Adams

US Treasury Department

Internal Revenue Service

Date: NOV 21 1969

In reply refer to: Au:R:3030:DLK

University of Maryland
Office of the Comptroller
College Park, Maryland 20742

Gentlemen:

This is in regard to your exemption application, Form 1023, claiming exemption from Federal income tax.

The University of Maryland is a State Institution and a wholly owned agency or instrumentality of the State of Maryland. Federal income tax laws do not apply to it and contributions to it are deductible under the provisions of section 170(c)(1) of the Internal Revenue Code.

Accordingly, no further action is necessary with respect to your application.

Very truly yours,

F. D. Duehay

Francis G. Duehay
Acting District Director