1-4-2011

Collaborative Research: Interannual Variability of Coastal Phytoplankton Blooms in the Gulf of Maine and Their Relationships to Local and Remote Forcings

David W. Townsend
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Final Report for Period: 10/2009 - 09/2010 **Submitted on:** 01/04/2011
Principal Investigator: Townsend, David W. **Award ID:** 0726577
Organization: University of Maine
Submitted By:
Townsend, David - Principal Investigator
Title:
Collaborative Research: Interannual Variability of Coastal Phytoplankton Blooms in the Gulf of Maine and Their Relationships to Local and Remote Forcings

Project Participants

Senior Personnel

Name: Townsend, David
Worked for more than 160 Hours: Yes
Contribution to Project:

Post-doc

Graduate Student

Name: Rebuck, Nathan
Worked for more than 160 Hours: Yes
Contribution to Project:
based dissertation on this project

Undergraduate Student

Technician, Programmer

Name: Thomas, Maura
Worked for more than 160 Hours: Yes
Contribution to Project:
Technical support

Other Participant

Research Experience for Undergraduates

Organizational Partners

Other Collaborators or Contacts

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)
General:

My responsibilities on this component subproject were to provide input to the development of biological-physical models, and in particular to work with my biological modeling team members (Davis, Ji, Durbin and Runge) to couple the dynamics of the zooplankton with that of nutrient and phytoplankton dynamics. In addition, I was to work with the physical oceanographic models and the physical oceanographic team members (Beardsley, Flagg and Chen) to better understand and model nutrient fluxes.

My own participation on the project (with one month of summer salary per year for three years) was in addition to that of my research associate, Maura A. Thomas and my University of Maine graduate student, Nathan.D. Rebuck, each of whom participated on this project in various capacities at no cost to NSF.

Background:

One of the biggest obstacles to modeling phytoplankton dynamics in the Gulf of Maine ? Georges Bank region is the lack of a fundamental understanding of nutrient fields and nutrient fluxes, and how to incorporate those kinds of data into models of phytoplankton production. Prior to the nutrient database developed as a result of this project, all such modeling efforts relied on either the extremely sparse nutrient climatology produced by Dr. Brian Petrie of the Bedford Institute, or the overly simplified relationship between water density and nitrate, developed by the late Chris Garside of the Bigelow Laboratory. Each suffered from woefully incomplete data coverage.

As we reported in our last Progress Report we have made significant progress in compiling the most complete nutrient database for use in driving the numerical models. To the best of our knowledge we have incorporated all electronically-available data for the region. While this database is continuing to grow as we include data from samples we continue to collect as part of our other projects here at the University of Maine, it now serves the needs of the of all the modeling groups in the region.

Our database includes more than 100,000 samples, compiled from sources listed in the Table below (pdf). The majority of data comes from two public sources: the World Ocean Database maintained at the National Oceanographic Data Center, and data assembled at the Marine Environmental Science Division at the Bedford Institute of Oceanography and the Marine Environmental Data Service in Ottawa, both a part of the Department of Fisheries and Oceans Canada (updated from the published Petrie et al. 1999). The two public sources were supplemented with additional data that have remained in provisional or unreleased status. Much of the new and unreleased data come from samples collected and processed by the Townsend Lab at the University of Maine (DWT) [although we have some 10,000 samples from our recent survey cruises (2008-2010) that we have not yet entered]. In addition, observations were provided by the Atlantic Zone Monitoring Program (AZMP), the University of New Hampshire Coastal Ocean Observing Center (UNHCOOA), data collected on Alexandrium and other survey cruises by D. McGillicuddy at the Woods Hole Oceanographic Institute (WHOI), the Massachusetts Water Resource Authority (MWRA), and the Marine Monitoring and Assessment Program at the Northeast Fisheries Science Center of NOAA (MARMAP).

The station locations, color-coded by year of collection, are given in the Figure below (pdf).

Additional details including a description of methods used in QA/QC efforts are given in Rebuck et al. (2009) at: http://grampus.umeoce.maine.edu/nutrients/.

Those data have been analyzed to produce a Nutrient Climatology of monthly averaged nutrient fields that will form a starting point for the phytoplankton bloom models. Nathan Rebuck is in the final stages of preparing a manuscript on the nutrient climatology of the Gulf of Maine (Rebuck et al., in prep).

An example of the objectively-analyzed fields are given in the Figure here for all nitrate samples collected from surface waters of the Gulf of Maine since 1960.

Findings: (See PDF version submitted by PI at the end of the report)

Based on the result just discussed, Townsend and his graduate student, Nathan D. Rebuck, and Research Associate Maura A.Thomas, have finished an historical analysis of changes in the nutrient field in the Gulf of Maine since the 1960s (Townsend et al., 2010). Basing our analyses on T-S diagrams and nutrient correlations, we found that since the 1970s, the deeper waters in the interior Gulf of Maine (>100m) have become fresher and cooler, with lower nitrate but higher silicate concentrations. Prior to the most recent decades, nitrate concentrations in the Gulf normally exceeded silicate by 4-5 ?M, but now (the 2000s) silicate and nitrate are nearly equal. We show that these changes only partially correspond with that expected from deep slope water fluxes correlated with the North Atlantic Oscillation, and are opposite to patterns in freshwater discharges from the major rivers in the region. As for the mechanism behind these changes, we speculate that accelerated melting in the Arctic and concomitant freshening of the Labrador Sea in recent decades have likely increased the equatorward baroclinic transport of the inner limb of the Labrador Current that flows over the broad continental shelf from the Grand Banks of Newfoundland to the Gulf of Maine. That current system now brings a greater fraction of colder and fresher deep shelf waters into the Gulf than warmer and saltier offshore slope waters which were previously thought to dominate the flux of nutrients. Those deep shelf waters reflect nitrate losses from sediment denitrification and silicate accumulations from rivers and in situ regeneration, which together are altering the nutrient regime and potentially the structure of the planktonic ecosystem.

In addition to this paper focused on changes in nutrients, Townsend has also incorporated aspects of this work into a manuscript on the changes in deep water masses in the Gulf of Maine (Smith et al., ms), in that we have evidence that deep water flows into and out of the Gulf of Maine through the Northeast Channel frequently flow in the opposite direction to that expected.

Finally, we have included the role of such changes in water masses and nutrients on the recruitment of fishes (Runge et al., 2010).

Training and Development:

Mr. Nathan Rebuck, a Ph.D. candidate in the University of Maine's School of Marine Sciences has worked on this project, but at no cost to the grant (he is supported on other funds).

His dissertation research focused on nutrient dynamics in the Gulf of Maine and surrounding regions of the NW Atlantic Ocean.

Outreach Activities:

Outreach Activities:

We have published/submitted multiple papers in international journals. We have made several presentations at different meetings. Recently, Ji has initiated and chaired a workshop session on plankton phenology and life history at the 3rd GLOBEC Open Science Meeting (Victoria, Canada, June 2009) to facilitate an extensive discussion from both observation and modeling points of view. By working with two top scientists in this field (David Mackus, Fisheries and Oceans Canada, and Martin Edwards, Sir Alister Hardy Foundation for Ocean Science), we had a very successful workshop, with 13 multi-authored talks that represent a broad geographic distribution of study areas. A small follow-up workshop will be held at WHOI in November at which these and other observations will be fleshed out for publication as a 'Horizons' article in Journal of Plankton Research.

The project website has been maintained at http://www.whoi.edu/sites/ji_bloom, with a link to C. Chen's FVCOM website at http://fvcom.smast.umassd.edu. These sites have created windows to communicate with the research community and interested public. The model results from the project were added into this website with clear explanations. Particular attention has been given to providing context for this audience by communicating background information about the study region and by explaining the research goals and objectives as they apply to the newly developed ocean literacy essential principles.

See Townsend's activities in the pdf file.

Journal Publications

Ji, R., C.S. Davis, C. Chen, D.W. Townsend, D.G. Mountain, R.C. Beardsley, "Influence of ocean freshening on shelf phytoplankton dynamics", Geophys. Res. Letters, p. , vol. , (2007). Published, doi:10.1029/ 2007 GL032010

Ji, R., C.S. Davis, C. Chen, D.W. Townsend, D.G. Mountain, R.C. Beardsley, "Modeling the influence of low-salinity water inflow on winter-spring phytoplankton dynamics in the Nova Scotian Shelf - Gulf of Maine region", Journal of Plankton Research, p. , vol. , (2008). Submitted,

Rebuck, N., D.W. Townsend, K. Smith and M.A. Thomas, "A Nutrient Climatology for the Gulf of Maine − Georges Bank Region", Continetnal Shelf Research, p. , vol. , (2008). In Preperation,

Townsend, D.W., N.D. Rebuck, M.A. Thomas, L. Karp-Boss, and R. M. Gettings, "A changing nutrient regime in the Gulf of Maine", Continental Shelf Research, p. 820, vol. 30, (2010). Published, Smith, P.C. N.R. Pettigrew, P. Yeats, D.W. Townsend and G. Ha, "A regime change in the Gulf of Maine", Trans. Amer. Fish. Soc. (Proceedings of a Scientific Symposium on the Gulf of Maine), p. , vol. , (2011). Submitted,

Rebuck, N.D., D.W. Townsend and M.A Thomas, "Gulf of Maine Region Nutrient and Hydrographic Database", http://grampus.umeoce.maine.edu/nutrients/, p. , vol. , (2010). Web Database,

Books or Other One-time Publications

Web/Internet Site

URL(s):
http://grampus.umeoce.maine.edu/nutrients/
Description:
Rebuck, N.D., D.W. Townsend and M.A Thomas. 2009. Gulf of Maine Region Nutrient and Hydrographic Database.

Other Specific Products

Contributions

Contributions within Discipline:
1) Contributions within Discipline:
The project's modeling study, led by the lead PI, Rubao Ji of Woods Hole Oceanographic Institution, provides a new high-resolution unstructured-grid, finite-volume coupled biological-physical modeling system for use in regional circulation and climate change studies. This model is significantly different from existing structured-grid models due to the great geometric flexibility inherent in the unstructured-grid approach and the local mass, heat, salt, and tracer conservation and computational efficiency inherent in the finite-volume approach. The coupled modeling study provides new insights into the influence of large-scale forcing on the dynamics and productivity of coastal ocean ecosystems. This could be a significant advance in our understanding of phytoplankton blooms dynamics, which has been traditionally studied with a focus on local forcing and seasonal changes. Consequently, the linkage between climate change and coupled atmosphere/ocean oscillations and ocean productivity can be explored in a more quantitative way, rather than more empirical approaches.

Contributions to Other Disciplines:

Contributions to Human Resource Development:
Research opportunity for one Ph.D. graduate student at the University of Maine (Nathan D. Rebuck).
Contributions to Resources for Research and Education:

Contributions Beyond Science and Engineering:

Conference Proceedings

Categories for which nothing is reported:

Organizational Partners
Any Book
Any Product
Contributions: To Any Other Disciplines
Contributions: To Any Resources for Research and Education
Contributions: To Any Beyond Science and Engineering

Any Conference

National Science Foundation

FINAL PROJECT REPORT

Project Title: Collaborative Research: Interannual Variability of Coastal Phytoplankton Blooms in the Gulf of Maine and Their Relationships to Local and Remote Forcings

PI: David W. Townsend

Awardee: University of Maine

Award Number: 0726577

Award Expires: 09/30/2010

Program Officer Name: David L. Garrison

This is the Final Project Report for our three-year grant that covered the period 1 October 2007 to 30 September 2010.

General:

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Source	Number	Years
WOD	17,001	1956-2003
Petrie	24,988	1966-2005
DWT	20,247	1998-2007
MWRA	29,934	1992-2008
WHOI	6,350	2003-2006
MarMAP	4,098	1969-1981
UNHCOOA	815	2004-2007
AZMP	1,461	1999-2005
Total	**100,735**	**1956-2008**

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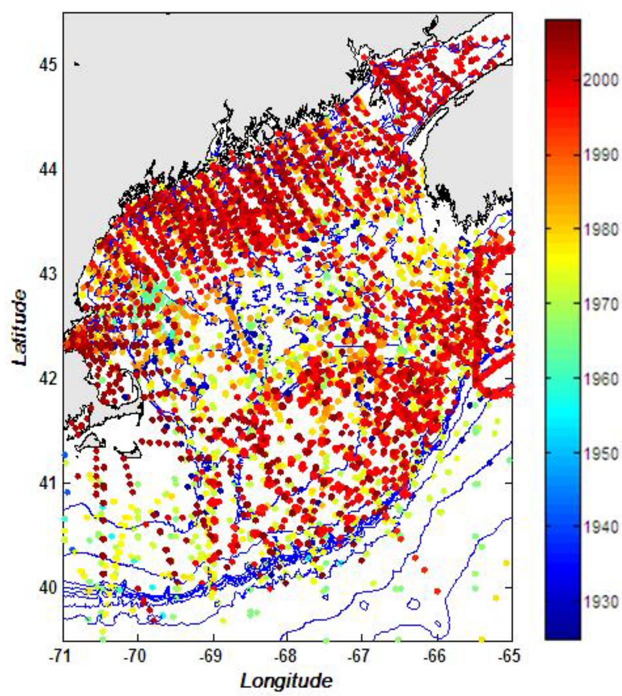

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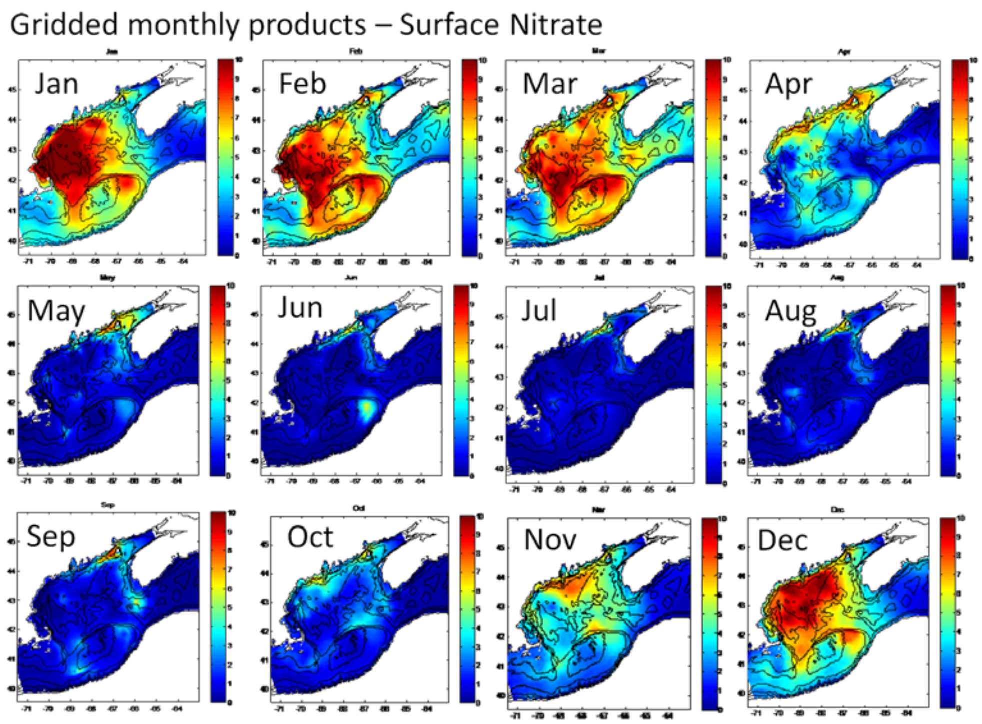

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Finally, we have included the role of such changes in water masses and nutrients on the recruitment of fishes (Runge *et al.,* 2010).

Presentations:

Townsend has presented aspects of that work at a number of venues, including invited talks and seminars at:

- Woods Hole Oceanographic Institution, July 2009.
- Bigelow Laboratory, July 2009;
- Scientific Symposium on the Gulf of Maine, St. Andrews, N.B., October 2009;
- The University of Massachusetts SMAST, December 2009;
- Bowdoin College, March 2010;
- The University of Maine Augusta, April, 2010;

Presentations at the Ocean Sciences Meeting in Portland, Oregon, 2010:

- Rebuck, N.D., **D.W. Townsend**, M.A. Thomas. Spatial and temporal patterns described by a dissolved nutrient climatology for the Gulf of Maine.

- **Townsend, D.W.,** N.D. Rebuck, M.A. Thomas, L. Karp-Boss, R. M. Gettings. A changing nutrient regime in the Gulf of Maine.

Student Theses:

Nathan D. Rebuck (A.B. Princeton University) has finished writing his Ph.D. Dissertation, which is based on this work, and will defend in late January 2011.

Title: Nutrient Dynamics in the Gulf of Maine: An Analysis of Spatial and Temporal Patterns of Dissolved Inorganic Nitrate and its Proportion to Silicate in the Waters of the Gulf of Maine and Georges Bank Region.

Resulting Publications:

Ji, R., C.S. Davis, C. Chen, **D.W. Townsend**, D.G. Mountain, R.C. Beardsley. 2007. Influence of ocean freshening on shelf phytoplankton dynamics. *Geophys. Res. Letters* 34, L24607, doi:10.1029/ 2007 GL032010.

Ji, R., C.S. Davis, C. Chen, **D.W. Townsend**, D.G. Mountain, R.C. Beardsley. 2008. Modeling the influence of low-salinity water inflow on winter-spring phytoplankton dynamics in the Nova Scotian Shelf - Gulf of Maine region. *Journal of Plankton Research* 30: 1399–1416.

Rebuck, N.D., **D.W. Townsend** and M.A Thomas. 2009. Gulf of Maine Region Nutrient and Hydrographic Database. http://grampus.umeoce.maine.edu/nutrients/

Rebuck, N.D., **D.W. Townsend**, K. Smith and M.A. Thomas. Ms. A Nutrient Climatology for the Gulf of Maine − Georges Bank Region. (Manuscript in prep.)

Runge, J.A., A. Kovach, J. Churchill, L. Kerr, J.R. Morrison, R. Beardsley, D. Berlinsky, C. Chen, S. Cadrin, C. Davis, K. Ford, J.H. Grabowski, W.H. Howell, R. Ji, R. Jones, A. Pershing, N. Record, A.C. Thomas, G. Sherwood, S. Tallack, **D.W. Townsend.** 2010. Understanding Climate Impacts on Recruitment and Spatial Dynamics of Atlantic Cod in the Gulf of Maine: Integration of Observations and Modeling. *Progress in Oceanography* 87: 251–263.

Townsend, D.W., N.D. Rebuck, M.A. Thomas, L. Karp-Boss, and R. M. Gettings. 2010. A changing nutrient regime in the Gulf of Maine. *Continental Shelf Research* 30: 820-832.

Smith, P.C. N.R. Pettigrew, P. Yeats, **D.W. Townsend** and G. Han. Ms. A regime change in the Gulf of Maine. *Trans. Amer. Fish. Soc.* (*Proceedings of a Scientific Symposium on the Gulf of Maine*, In Review)

Reference Cited:

Petrie, B., P. Yeats and P. Strain. 1999. Nitrate, silicate and phosphate atlas for the Scotian Shelf and Gulf of Maine. *Can. Tech. Rep. Hydrog. Ocean Sci.* 203, vii, 96 pp.

Findings:

1) Biological Data Mining and Analysis

We mapped the climatological spatial distribution of peaking timing of spring and fall phytoplankton blooms in the Scotian Shelf and the Gulf of Maine region (Fig. 3. ***a, b***).

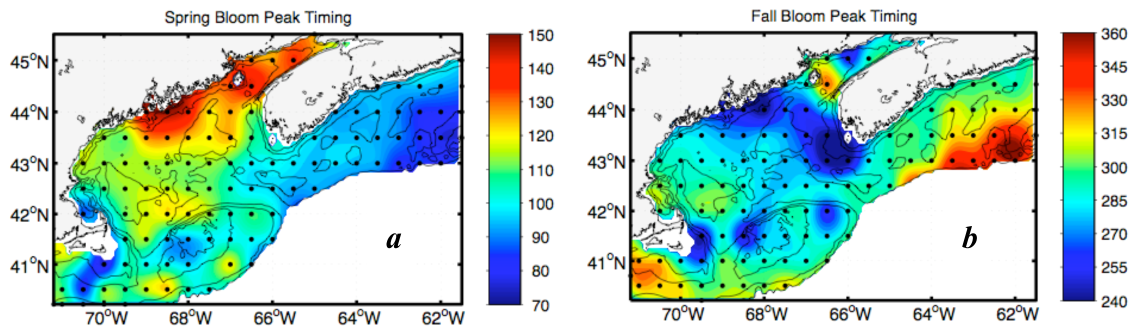


Fig. 3: The spatial distribution of bloom timing in the Scotian Shelf and Gulf of Maine region. ***a***: spring bloom peak timing; ***b***: fall bloom peak timing.

The correlation between spring and fall bloom timing using data from the entire domain (Fig 4, left panel) suggested a significant negative correlation, indicating that regions with earlier spring blooms are associated with delayed fall phytoplankton bloom. The results are in line with our previous findings. Basically the spring phytoplankton bloom in the Scotian Shelf occurs much earlier than that in the Gulf of Maine region, but opposite for the fall phytoplankton bloom, suggesting the possible influence of salinity gradient

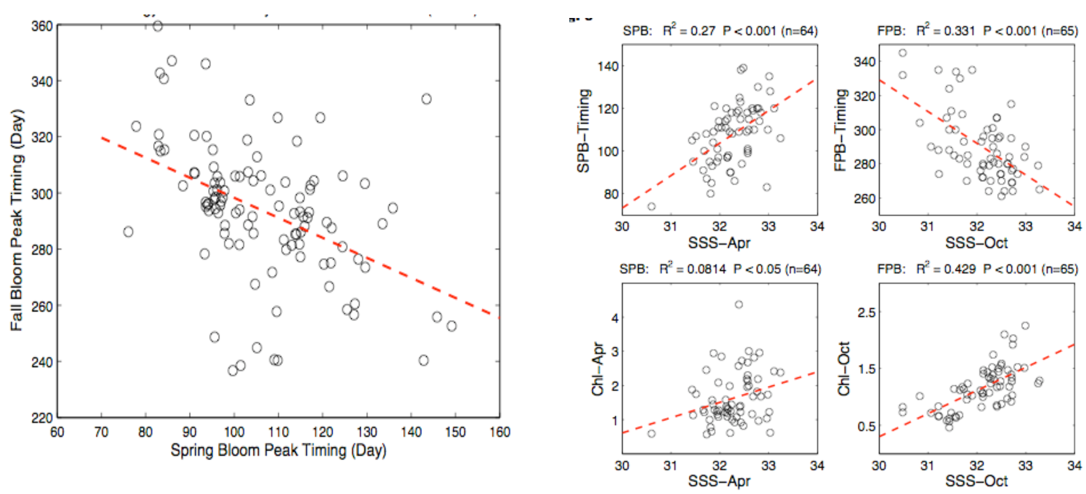


Fig. 4: Left panel: relationship between spring and fall bloom timing; Right panel with 4 subplots: relationship between sea surface salinity (SSS) in April and October and spring phytoplankton bloom (SPB) timing and fall phytoplankton bloom (FPB) timing and Chl-a concentration in April and October.

from the Scotian Shelf to the Gulf of Maine. Further data analyses on the relationship between salinity of bloom timing/magnitude support this argument (Fig. 4, right panel).

Nutrients data have been analyzed to produce a climatology of monthly averaged nutrient fields that will form a starting point for the phytoplankton bloom models. Nathan Rebuck is in the final stages of preparing a manuscript on the nutrient climatology of the Gulf of Maine (Rebuck et al., in prep).

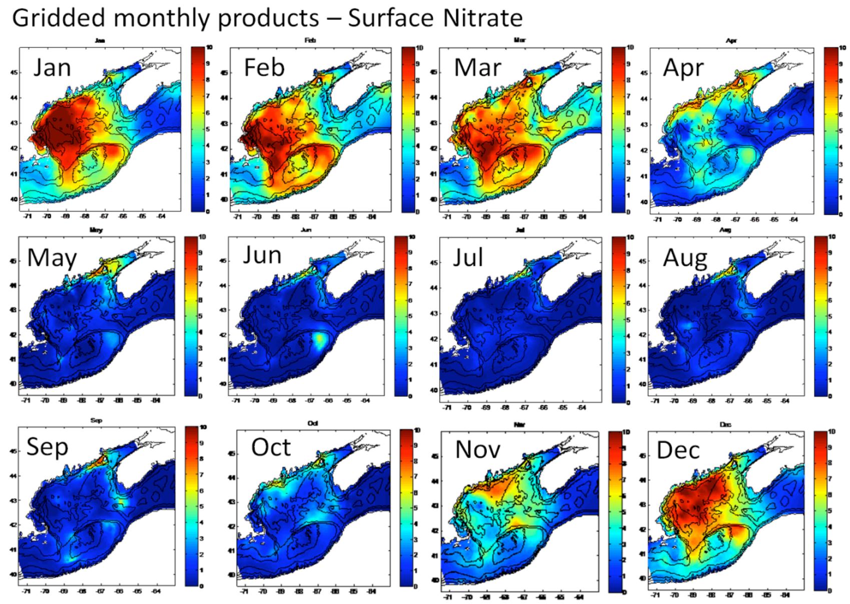


Fig. 5: Objectively-mapped surface nitrate monthly climatology in the Gulf of Maine.

An example of the objectively-analyzed fields are given in the Fig. 5 for all nitrate samples collected from surface waters of the Gulf of Maine since 1960.

2) Physical Modeling:

We have re-run the GoM-FVCOM in a hybrid vertical coordinate system with inclusion of data assimilation for 1995 to 2008. The purpose of this exercise is to improve the accuracy of model-computed temperature and salinity fields through correcting of river discharges, upstream open boundary conditions and vertical resolution. Unlike our previous works, 29 rivers were added into the model system, and freshwater discharges of all rivers were

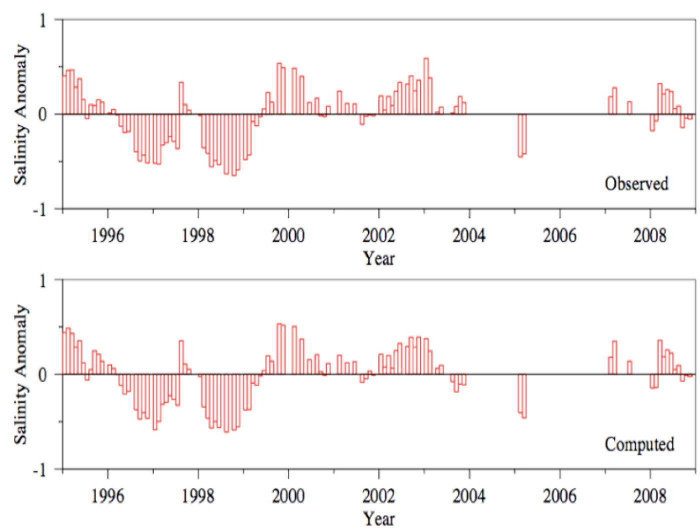


Fig. 6: Comparison between observed and model-computed salinity anomalies over Georges Bank from 1995 to 2008 .

adjusted to consider the influence of the wetland and springtime ice melting in the downstream areas that were not counted at USGS monitoring sites. We successfully implemented non-hydrostatic dynamics into FVCOM [Lai et al., 2009a, b]. This new model is called FVCOM-NH. Two major efforts have been made to improve the accuracy and ability of FVCOM-NH for the study of ecosystem processes. The first is to build multi-subdomain grids that allow us to run the non-hydrostatic model over Georges Bank through a nesting approach from our existing GoM-FVCOM. The second is to validate FVCOM-NH by simulating the internal wave-induced phytoplankton distribution over a bank with steep bottom topography. These two steps are possible following the success of implementing semi-implicit time-stepping and a generalized terrain-following vertical coordinate into FVCOM-NH, work performed during this funding period.

Resolving multi-scale dynamics is a major challenge to ocean modeling, because the scales of interest range from a few meters to kilometers. FVCOM-NH is the first three-dimensional model that is capable of resolving these multi-scale processes in the Gulf of Maine/Georges Bank. Since many non-hydrostatic processes occur around steep topographic banks where nonlinear internal waves are dominant features and in the interior basin where convection is important, it is not impractical to run FVCOM-NH in the entire Gulf of Maine region due to the limitation of current computing power. Multi-subdomain grid nesting approach, which we have developed, has made a big progress to achieve our task to apply FVCOM to study the high-frequency internal waves and its impact on plankton dynamics.

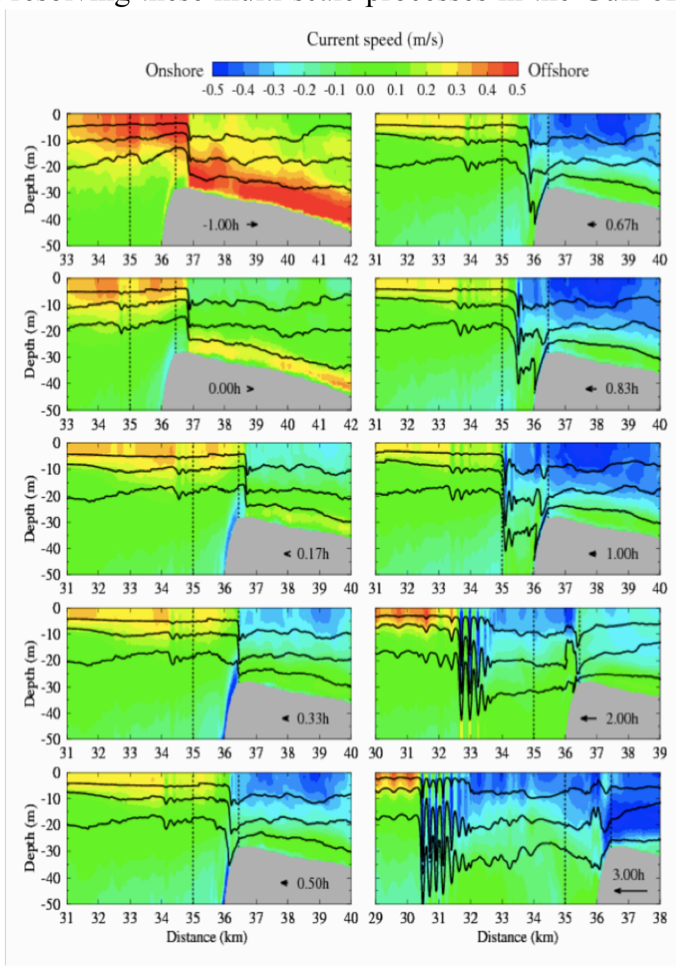


Fig. 7: Snapshot of the cross-bank distribution of density contours σt=22.5,23.5 and 24.5 and cross-bank currents at -1.00, 0, 0.17, 0.33, 0.50, 0.67, 0.83, 1.00, 2.00 and 3.00 hours relative to the ebb-flood transition.

In addition to the fields of water temperature and currents, the model has successfully reproduced the interannual variability of the salinity in the GoM. An example is shown in Fig. 7 for Georges Bank. This interannual pattern was also observed in the other regions of the GoM and captured by the GoM FVCOM, indicating that the re-assimilated model results have provide realistic fields of both currents and hydrograph in the

GoM/GB. This model results make it possible to examine the influence of surface freshening on the population dynamics in this region.

The model reproduced well the characteristics of the high-frequency internal waves observed in Mass Bay in August 1998. The model-guided experiments suggest that the internal wave over the Bank is generated by the interaction of tidal currents with steep bottom topography through a process of forming an initial density front on the western flank near ebb-flood transition; steeping of the front as density depression develops in early flood phase on the bay-side slope; and disintegrating of the density depression into a wave train. The earth's rotation tends to transfer the cross-bank tidal kinetic energy into the along-bank direction and thus reduces the intensity of the density front at ebb-flood transition and density depression in the flood period. The internal wave packet propagates as a leading edge feature of internal tidal waves, and the faster phase speed of the high-frequency internal waves in Mass Bay is caused by the earth's rotation. Ignoring bottom friction significantly enlarges the cross-bank scale of the density front, produces larger vertical density displacement, and weaker dissipation during the wave's shoaling. The Mellor-Yamada level 2.5 turbulence closure model tends to cause an over-damping of the high-frequency internal waves. The model results support the internal wave theory proposed by *Lee and Beardsley* [1974] but disagree with the mechanism proposed by *Maxworthy* [1979].

Two papers are in revision for the Journal of Geophysical Research-Ocean. This project is a part of Zhigang Lai's Ph.D. thesis work.

3) Biological Modeling:

Our 3-d process-oriented model results (Ji et al., published on Journal of Plankton Research 2008) revealed that observed levels of surface freshening could significantly change water column stability and therefore control the winter-spring phytoplankton bloom dynamics in different regions. Freshening caused earlier blooms both on the Scotian Shelf and in the eastern Gulf of Maine, agreeing with inferences drawn from prior empirical analyses. Earlier phytoplankton blooms in the low surface salinity case were followed by earlier depletion of nutrients at the surface along with earlier decline of blooms compared with the high surface salinity case (Fig. 8). The model results also suggested that surface water freshening can impede vertical nutrient exchange between surface and deep waters, thus reducing the overall spring primary productivity throughout the region. The coupled model described in this study provides a unique tool to quantify

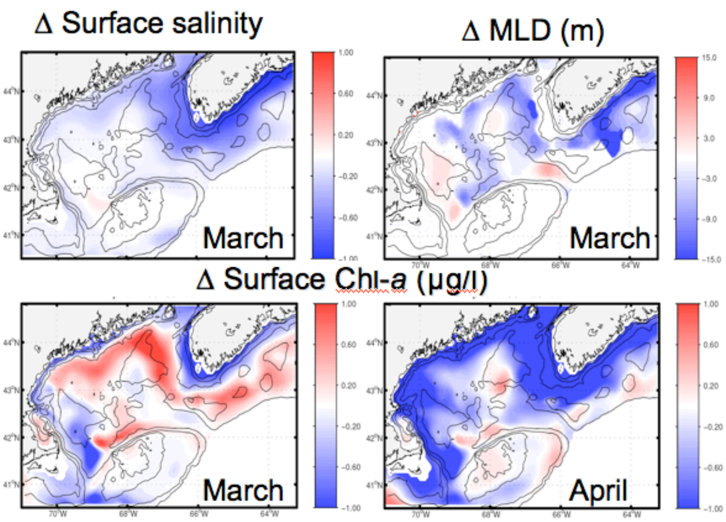


Fig. 8: Modeled impact of freshening on mixed layer depth (MLD), and surface Chl-a in March and April.

the response of lower trophic level production to climate-scale environmental disturbances in a complex but ecologically important shelf ecosystem that has a history of such alternations in surface salinity.

The results from the nine-compartment 1-D model supported the 3-D NPZD model result. The timing of the spring phytoplankton bloom is significantly correlated with the variability of the sea surface salinity (SSS) and associated mixed layer depth (MLD) as shown in Fig. 9. The duration of the fall phytoplankton bloom in the low SSS scenario seems to be longer and extended towards the end of December.

By coupling FVCOM-NH with a simple Nutrient-Phytoplankton-Zooplankton (NPZ) model, we were able to examine the impact of internal wave propagation and dissipation on the phytoplankton distribution over Stellwagen Bank (Fig. 10). This effort was made based on our success of simulating high-frequency internal waves that were observed over the Bank in the past. Since the internal wave dynamics over Stellwagen Bank are very similar to Georges Bank, this exercise allows us to validate the capability of FVCOM-NH to simulate small-scale variability of phytoplankton over Georges Bank. This work is still in progress. Preliminary results clearly show that internal waves are one of key physical processes to transfer biological fields on and off the bank. The rapid dissipation of the waves can lead to the formation of patchy distributions of phytoplankton over and off the Bank.

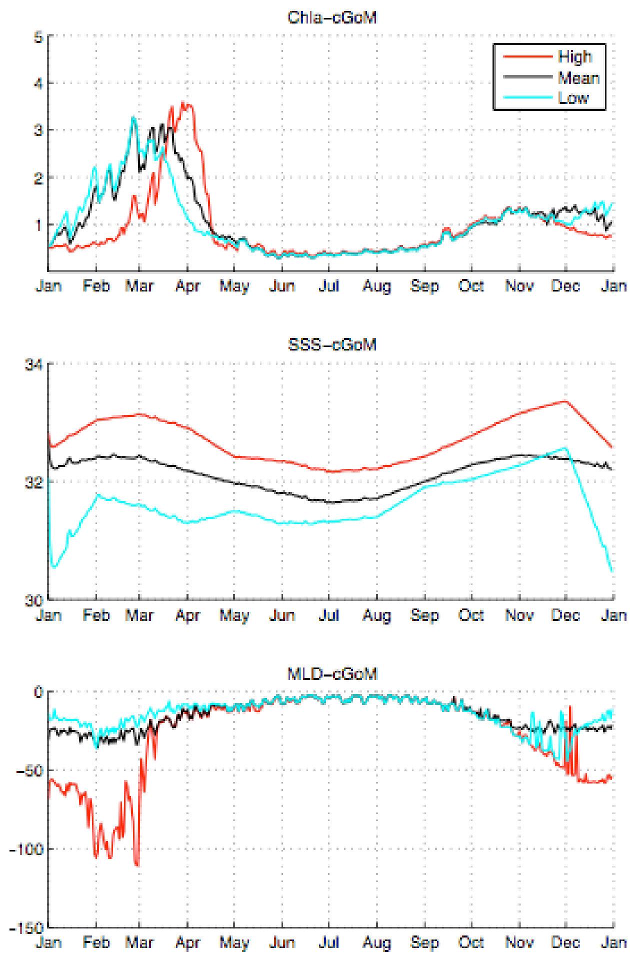


Fig. 9: 1-D Model results of surface Chl-a using different sea surface salinity cycle in central GoM. Top panel: chl-a; mid panel: sea surface salinity; bottom panel: mixed layer depth.

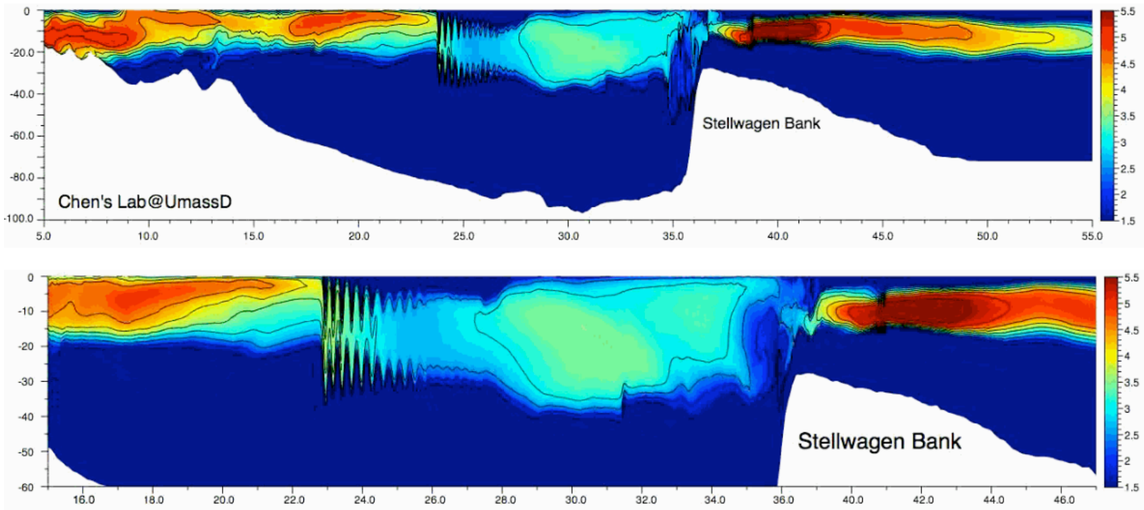


Fig. 10: Results from FVCOM-NH coupled with NPZ model showing the impact of internal wave propagation and dissipation on the phytoplankton distribution over Stellwagen Bank.

National Science Foundation

FINAL PROJECT REPORT

Project Title: Collaborative Research: Interannual Variability of Coastal Phytoplankton Blooms in the Gulf of Maine and Their Relationships to Local and Remote Forcings

PI: David W. Townsend

Awardee: University of Maine

Award Number: 0726577

Award Expires: 09/30/2010

Program Officer Name: David L. Garrison

This is the Final Project Report for our three-year grant that covered the period 1 October 2007 to 30 September 2010.

General:

My responsibilities on this component subproject were to provide input to the development of biological-physical models, and in particular to work with my biological modeling team members (**Davis, Ji, Durbin** and **Runge**) to couple the dynamics of the zooplankton with that of nutrient and phytoplankton dynamics. In addition, I was to work with the physical oceanographic models and the physical oceanographic team members (**Beardsley, Flagg** and **Chen**) to better understand and model nutrient fluxes.

My own participation on the project (with one month of summer salary per year for three years) was in addition to that of my research associate, **Maura A. Thomas** and my University of Maine graduate student, **Nathan.D. Rebuck**, each of whom participated on this project in various capacities at no cost to NSF.

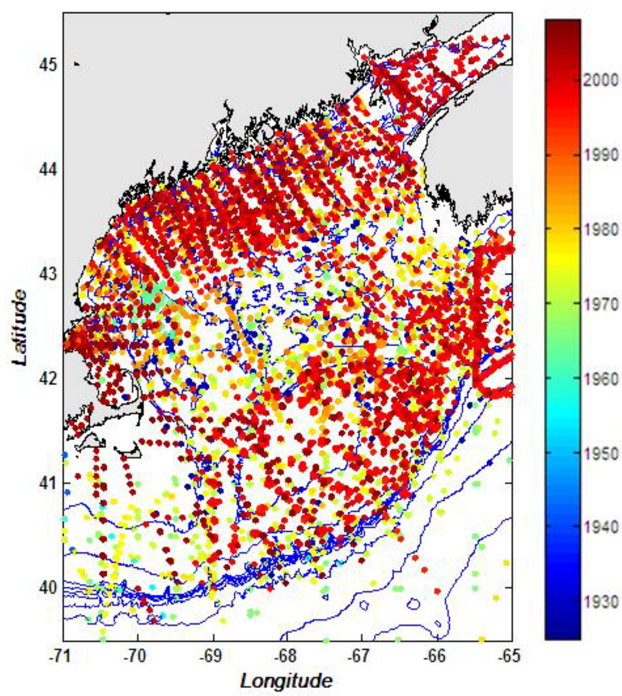
Background:

One of the biggest obstacles to modeling phytoplankton dynamics in the Gulf of Maine – Georges Bank region is the lack of a fundamental understanding of nutrient fields and nutrient fluxes, and how to incorporate those kinds of data into models of phytoplankton production. Prior to the nutrient database developed as a result of this project, all such modeling efforts relied on either the extremely sparse nutrient climatology produced by Dr. Brian Petrie of the Bedford Institute, or the overly simplified relationship between water density and nitrate, developed by the late Chris Garside of the Bigelow Laboratory. Each suffered from woefully incomplete data coverage.

Source	Number	Years
WOD	17,001	1956-2003
Petrie	24,988	1966-2005
DWT	20,247	1998-2007
MWRA	29,934	1992-2008
WHOI	6,350	2003-2006
MarMAP	4,098	1969-1981
UNHCOOA	815	2004-2007
AZMP	1,461	1999-2005
Total	**100,735**	**1956-2008**

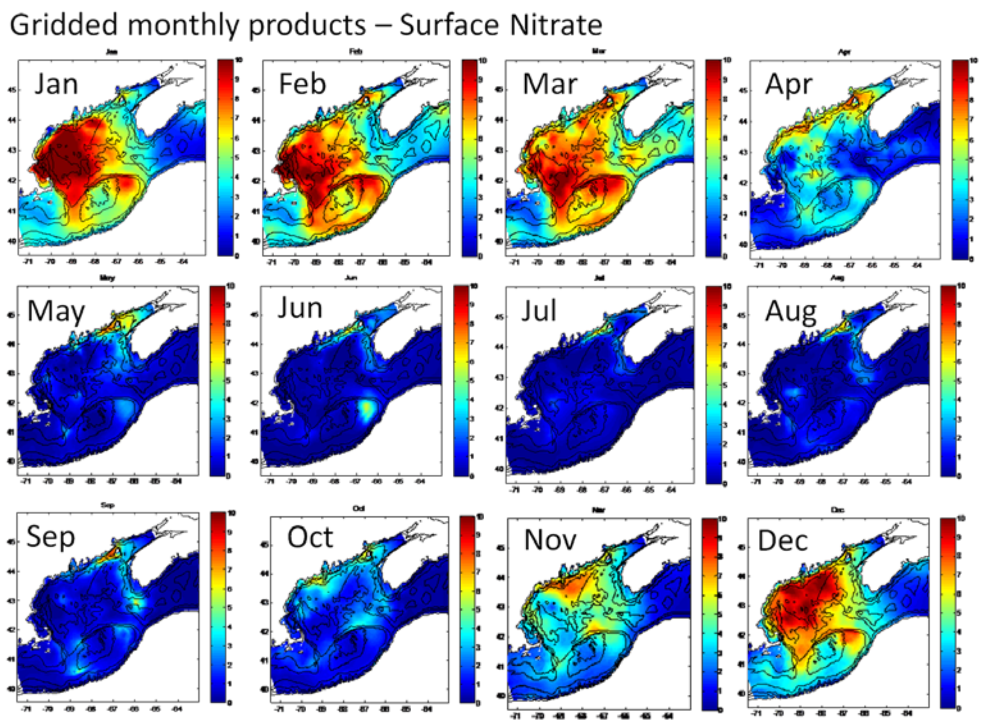
As we reported in our last Progress Report we have made significant progress in compiling the most complete nutrient database for use in driving the numerical models. To the best of our knowledge we have incorporated all electronically-available data for the region. While this database is continuing to grow as we include data from samples we continue to collect as part of our other projects here at the University of Maine, it now serves the needs of the of all the modeling groups in the region.

Our database includes more than 100,000 samples, compiled from sources listed in the Table here. The majority of data comes from two public sources: the World Ocean Database maintained at the National Oceanographic Data Center, and data assembled at the Marine Environmental Science Division at the Bedford Institute of Oceanography and the Marine Environmental Data Service in Ottawa, both a part of the Department of Fisheries and Oceans Canada (updated from the published Petrie et al. 1999). The two public sources were supplemented with additional data that have remained in provisional or unreleased status. Much of the new and unreleased data come from samples collected and processed by the Townsend Lab at the University of Maine (DWT) *[although we have some 10,000 samples from our recent survey cruises (2008-2010) that we have not yet entered]*. In addition, observations were provided by the Atlantic Zone Monitoring Program (AZMP), the University of New Hampshire Coastal Ocean Observing Center (UNHCOOA), data collected on *Alexandrium* and other survey cruises by D. McGillicuddy at the Woods Hole Oceanographic Institute (WHOI), the Massachusetts Water Resource Authority (MWRA), and the Marine Monitoring and Assessment Program at the Northeast Fisheries Science Center of NOAA (MARMAP).



The station locations, color-coded by year of collection, are given in the Figure above. Additional details including a description of methods used in QA/QC efforts are given in Rebuck et al. (2009) at: http://grampus.umeoce.maine.edu/nutrients/.

Those data have been analyzed to produce a Nutrient Climatology of monthly averaged nutrient fields that will form a starting point for the phytoplankton bloom models. Nathan Rebuck is in the final stages of preparing a manuscript on the nutrient climatology of the Gulf of Maine (Rebuck et al., in prep).



An example of the objectively-analyzed fields are given in the Figure here for all nitrate samples collected from surface waters of the Gulf of Maine since 1960.

Based on these results, Townsend and his graduate student, Nathan D. Rebuck, and Research Associate Maura A.Thomas, have finished an historical analysis of changes in the nutrient field in the Gulf of Maine since the 1960s (Townsend *et al.,* 2010). Basing our analyses on T-S diagrams and nutrient correlations, we found that since the 1970s, the deeper waters in the interior Gulf of Maine (>100m) have become fresher and cooler, with lower nitrate but higher silicate concentrations. Prior to the most recent decades, nitrate concentrations in the Gulf normally exceeded silicate by 4-5 µM, but now (the 2000s) silicate and nitrate are nearly equal. We show that these changes only partially correspond with that expected from deep slope water fluxes correlated with the North Atlantic Oscillation, and are opposite to patterns in freshwater discharges from the major rivers in the region. As for the mechanism behinfd these changes, we speculate that accelerated melting in the Arctic and concomitant freshening of the Labrador Sea in recent decades have likely increased the equatorward baroclinic transport of the inner limb of the Labrador Current that flows over the broad continental shelf from the Grand Banks of Newfoundland to the Gulf of Maine. That current system now brings a greater fraction of colder and fresher deep shelf waters into the Gulf than warmer and saltier offshore slope waters which were previously thought to dominate the flux of nutrients. Those deep shelf waters reflect nitrate losses from sediment denitrification and silicate accumulations from rivers and *in situ* regeneration, which together are altering the nutrient regime and potentially the structure of the planktonic ecosystem.

In addition to this paper focused on changes in nutrients, Townsend has also incorporated aspects of this work into a manuscript on the changes in deep water masses in the Gulf of Maine (Smith *et al.,* ms), in that we have evidence that deep water flows into and out of the Gulf of Maine through the Northeast Channel frequently flow in the opposite direction to that expected.

Finally, we have included the role of such changes in water masses and nutrients on the recruitment of fishes (Runge *et al.,* 2010).

Presentations:

Townsend has presented aspects of that work at a number of venues, including invited talks and seminars at:

- Woods Hole Oceanographic Institution, July 2009.
- Bigelow Laboratory, July 2009;
- Scientific Symposium on the Gulf of Maine, St. Andrews, N.B., October 2009;
- The University of Massachusetts SMAST, December 2009;
- Bowdoin College, March 2010;
- The University of Maine Augusta, April, 2010;

Presentations at the Ocean Sciences Meeting in Portland, Oregon, 2010:

- Rebuck, N.D., **D.W. Townsend**, M.A. Thomas. Spatial and temporal patterns described by a dissolved nutrient climatology for the Gulf of Maine.

- **Townsend, D.W.,** N.D. Rebuck, M.A. Thomas, L. Karp-Boss, R. M. Gettings. A changing nutrient regime in the Gulf of Maine.

Student Theses:

Nathan D. Rebuck (A.B. Princeton University) has finished writing his Ph.D. Dissertation, which is based on this work, and will defend in late January 2011.

Title: Nutrient Dynamics in the Gulf of Maine: An Analysis of Spatial and Temporal Patterns of Dissolved Inorganic Nitrate and its Proportion to Silicate in the Waters of the Gulf of Maine and Georges Bank Region.

Resulting Publications:

Ji, R., C.S. Davis, C. Chen, **D.W. Townsend**, D.G. Mountain, R.C. Beardsley. 2007. Influence of ocean freshening on shelf phytoplankton dynamics. *Geophys. Res. Letters* 34, L24607, doi:10.1029/ 2007 GL032010.

Ji, R., C.S. Davis, C. Chen, **D.W. Townsend**, D.G. Mountain, R.C. Beardsley. 2008. Modeling the influence of low-salinity water inflow on winter-spring phytoplankton dynamics in the Nova Scotian Shelf - Gulf of Maine region. *Journal of Plankton Research* 30: 1399–1416.

Rebuck, N.D., **D.W. Townsend** and M.A Thomas. 2009. Gulf of Maine Region Nutrient and Hydrographic Database. *http://grampus.umeoce.maine.edu/nutrients/*

Rebuck, N.D., **D.W. Townsend**, K. Smith and M.A. Thomas. Ms. A Nutrient Climatology for the Gulf of Maine − Georges Bank Region. (Manuscript in prep.)

Runge, J.A., A. Kovach, J. Churchill, L. Kerr, J.R. Morrison, R. Beardsley, D. Berlinsky, C. Chen, S. Cadrin, C. Davis, K. Ford, J.H. Grabowski, W.H. Howell, R. Ji, R. Jones, A. Pershing, N. Record, A.C. Thomas, G. Sherwood, S. Tallack, **D.W. Townsend.** 2010. Understanding Climate Impacts on Recruitment and Spatial Dynamics of Atlantic Cod in the Gulf of Maine: Integration of Observations and Modeling. *Progress in Oceanography* 87: 251–263.

Townsend, D.W., N.D. Rebuck, M.A. Thomas, L. Karp-Boss, and R. M. Gettings. 2010. A changing nutrient regime in the Gulf of Maine. *Continental Shelf Research* 30: 820-832.

Smith, P.C. N.R. Pettigrew, P. Yeats, **D.W. Townsend** and G. Han. Ms. A regime change in the Gulf of Maine. *Trans. Amer. Fish. Soc.* (*Proceedings of a Scientific Symposium on the Gulf of Maine*, In Review)

Reference Cited:

Petrie, B., P. Yeats and P. Strain. 1999. Nitrate, silicate and phosphate atlas for the Scotian Shelf and Gulf of Maine. *Can. Tech. Rep. Hydrog. Ocean Sci.* 203, vii, 96 pp.