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December 23, 1992

Dr. Thomas Curtin
Program Manager Arctic Sciences
Office of Naval Research
800 North Quincy Street
Arlington, Virginia 22217-5000

Dear Dr. Curtin,

Please find enclosed a final report for my Office of Naval Research contract N00014-90-J-1880.

If there is anything else you need, please ask.

Sincerely,

Henry Joseph Niebauer
Professor, Marine Science
Univ. Alaska, Fairbanks

Encl.

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Final Technical Report for:

CEAR_EX: Hydrography, Acoustic Doppler Current Studies and Numerical Modeling of Eddies and their Interaction with the MIZ

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Contract #: N00014-90-J-1880

Contract dates: 01 April 90-30 September 92

Goals

The long-term goals are to understand how the marginal ice edge zone (MIZ) interacts with the open ocean in an oceanographic/meteorological/biological sense. This includes understanding the processes and dynamics for the generation, dissipation and role of mesoscale eddies and chimneys in the MIZ (and in the open ocean after the ice has retreated or melted) in the Greenland Sea/Fram Strait. A further goal is to understand how these physical features interact with the biological and chemical oceanography causing enhancement of biological production in the MIZ and adjacent open ocean.

All of this is aimed at understanding the physical and biological controls on the visible and acoustic environment of the MIZ. It is also aimed at understanding the effects of interannual variability and global change which result in variability in flux of carbon, through primary production, to the deep ocean possibly buffering CO^2 in the atmosphere.

Objectives

Our first objective was to construct numerical models of air-ice-ocean interactions. Our initial model (Niebauer and Smith, 1989) is working well. It is being used to help us understand and to test hypotheses concerning the physical and biological oceanographic interactions that have been observed as the ocean and atmosphere interact with the edge of the Arctic sea ice pack in the Fram Strait-Greenland Sea. It is also being used to model the Bering Sea MIZ. The model includes the interaction of ocean currents and eddys with the ice edge as well as the effects of winds, storms and solar radiation.

Our hypothesis is that the physical processes are a key to both the biological phenomena of spring blooms and to bloom variability. Understanding these physical and biological phenomena are critical in understanding the visible and acoustic regime of the marginal ice edge zone. Our objective is to be able to model these processes and their variability and ultimately to <u>predict</u> the phenomena of bio-physical interaction at the edge of the polar ice caps.

A second, fully 3-D, time dependent model of the Greenland Sea is under construction (Maslowski, 1992). The objective here is to model the 3-D aspects of the MIZ (including the biology and ice) but to extend the space scales to basin-wide as well as extending the simulations to interannual and global change time scales using super computer resources. We have made progress as outlined below. Weislaw Maslowski is doing his PhD building this model.

The second objective of this contract was to gather and analyze data from the marginal ice edge zone to test these hypotheses. The data were gathered from the M/V Polarbjorn (April-May, 1989) during the Coordinated Eastern Arctic Experiment (CEAREX). The scientific crew for this part of the project/contract included H.J. Niebauer, Thomas Weingartner and Steve Okkonen. The analyses of these data continues with sections of the data published as outlined below.

Methods

We employ two basic methods to accomplish our objectives: 1) Numerical modeling, and 2) A field program from the M/V Polarbjorn collecting coincident physical and biological oceanographic data during spring 1989 CEAREX program in the Fram Strait marginal ice edge zone.

The numerical modeling was started in 1985 and the basic model was completed and published in 1989. The detailed methods are outlined in Niebauer and Smith (1989). The model has been continuously improved upon with support from this contract.

Basically the model is made up of three interacting sub-models: 1) physical oceanography (including meteorology), 2) biological oceanography and 3) ice. The physical submodel is a series of time- and space dependent coupled non-linear equations of motion which include vertical and horizontal advection and diffusion, density gradients, mesoscale eddys as well as wind and insolation forcing.

The ice submodel provides ice movement, convergence and divergence, and melting and freezing.

The biological submodel includes two separate nutrient pools (nitrate and ammonium), nutrient uptake by two separate phytoplankton size classes, passive sinking of phytoplankton, grazing by both micro- and macrozooplankton on each phytoplankton size class, export via fecal-pellet flux and material transfer to higher trophic levels, and nutrient cycling and regeneration by microzooplankton, macroplankton and bacterioplankton.

The 3-D physical model (with detailed bottom topography) is running in the barotropic mode driven by historical winds. Work is progressing on the baroclinic mode using historical hydrographic and meteorological data. Work is starting on the ice model. The biological modeling will begin within the year but will lean heavily on previous (Niebauer and Smith, 1989) work.

Our methods for the Polarbjorn field data have been to combine our analyses of the physical (temperature, salinity and density vs. depth), biological (chlorophyll or phytoplankton) and chemical (nitrate, ammonium etc.) data gathered on the CEAREX biological cruise with the modeling with the aim of understanding, first, the physics of the eddys, stratification, etc., and second, the physical controls or effects on the biological production.

Results

Numerical Modeling

We have constructed a numerical model of the physical and biological oceanographic interaction at marginal ice edge zones as outlined above. Our experiments have emphasized the Fram Strait in the East Greenland Sea in spring (May and June) when ice is actively melting and solar radiation is increasing, leading to spring blooms. However, the model is generic and we have also applied it to the Bering Sea MIZ (Niebauer, 1991). While much of the following has resulted from previous ONR support, some has been a result of the present support extending the experiments in both the Greenland Sea and Bering Sea.

We have published several sets of experiments on the Fram Strait MIZ (Niebauer and Smith, 1989; Smith and Niebauer, In Press) including 1) a standard case with oceanic stratification and ice melt stratification but no winds or eddys, 2) variations of the standard case with various stratification schemes with and without ice cover, 3) cases with wind forcing and ice cover but no eddys, and finally, 4) a case with a cyclonic eddy under the ice cover.

For the first two sets of experiments, whenever there is stratification there is an accelerated accumulation of phytoplankton biomass and associated reduction in nitrate. When the stratification is due to ice melt only, the bloom is trapped between the ice and the ice-edge frontal structure and stratification as is observed in field studies. When there is additional stratification away from the ice edge, the phytoplankton biomass is spread out but remains spatially correlated with the stratification. Regardless of the source of stratification, the magnitude and timing of the bloom is similar. That is, maximum chlorophyll coincides with minimum nitrate (this occurs in 10 days to two weeks) but lags maximum primary production by two to three days. The stratification, which enhances the bloom, also restricts the introduction of nutrients from below and limits primary production after about one week. Nitrate levels fall from 8-10 uM to less than 1 uM while chlorophyll levels increase from less than 1 ug l^{-1} to over 5 ug l^{-1}. Zooplankton biomass increases in response to the bloom reaching a maximum about two weeks after maximum phytoplankton biomass. Both the maximum primary production rates (>1 gm C m^{-2} day^{-1}) and the maximum zooplankton biomass (>22 mg dry wt m^{-3}) are in quantitative agreement with field estimates. In the absence of stratification, a slow increase in chlorophyll occurs but no nutrient limitation is observed. The nanoplankton and microzooplankton do not play a significant role in these experiments.

In the third set of experiments, with wind forcing, the major finding was that regardless of which way the wind stress was directed, in either the Fram Strait or the Bering Sea, there was enhancement of primary production. When the wind stress was directed on-ice or parallel to the ice edge with the ice to the right of the wind, some ice edge upwelling was observed while when the wind was off-ice or parallel to the ice with the ice edge to the left of the wind, some downwelling was observed. However, the actual upwelling or downwelling advection had a minor effect on the primary production. The reasons for this are that the region of vertical advection is narrow and localized to the ice edge which was moving in response to the winds. In addition, the relatively strong melt water derived density stratification resists vertical movement. For the case of ice being blown over open water (the downwelling cases), the most noticeable effect was that the ice exerts a drag on the surface of the water carrying a nitrate-rich layer seaward. After the winds cease there was a region of about 12 km seaward of the ice edge that was rich in nitrate and melt-derived stratification, and enhanced growth resulted. However, productivity at the initial ice edge decreased due to increased ice cover.

In the cases where the ice was blown off the ocean (the upwelling cases) the most noticeable effect was to increase the light available for photosynthesis in recently ice covered regions that were replete with nutrients leading to increased productivity. Again, upwelling seemed to have little effect on the hydrographic structure and thus had little effect on the productivity at the ice edge.

There is a noticeable difference between the circulation associated with upwelling situations and circulation associated with downwelling. The difference is due to the way the ice reacts to wind stress. When the ice is forced out past the ice edge over open water (the downwelling situation), the ice tends to thicken or "pile up" down wind and so the effect of wind stress on the ocean via the ice is enhanced. When the ice is forced back into the icepack (the upwelling situation) the ice tends to thin at the ice edge. With lower concentrations of ice, less effect of the wind is felt in the ocean and so the mesoscale ice edge ocean circulation is not so strong. In the model the upwelling velocities were 1/3 the downwelling velocities. Biologically, the thicker ice covering more of the ocean restricted light in the photic zone. When the ice was thinned by the wind, productivity was more wide spread due to the increase in light.

In the last of the four initial cases, a cyclonic eddy was spun up under the ice cover for a week and then allowed to relax. (We did not do these experiments for the Bering Sea because eddys have not yet been observed up on the shelf at the MIZ.) During spin up there was upwelling in the center of the eddy with surface divergence which caused a divergence in the ice cover which cleared the ice cover over the eddy. The strongest horizontal currents were at the surface at >20 cm s^{-1} with flow away from the center of the eddy at 0.25 km day^{-1}. Maximum upwelling velocities were 40 m day^{-1} below 50 m in a core about 6 km wide. This core is flanked by columns of downwelling. This circulation gave the hydrographic structure the appearance of upwelling in the upper layers but downwelling below 100 m. Similar structure has been seen in nitrate cross sections from the Fram Strait.

When the eddy forcing was turned off there was downwelling in the center of the eddy and surface convergence but not enough to cause the ice to recover the surface of the ocean. We estimated that the eddy spin-down would take about two months (ie., the conversion of potential energy, stored in the upwelled density structure during eddy spin-up, back to kinetic energy of circulation via Coriolis dynamics).

The eddy circulation swept the ice off surface waters that were high in nitrate concentrations. This caused a sudden increase in the light regime which, when combined with the nutrient rich water, led to increased productivity. The timing and magnitudes of maximum primary productivity, nitrate, chlorophyll and zooplankton were nearly identical with those of the first two sets of experiments. The only real difference was that the bloom was trapped between two ice edges and that the stratification under the open water was reinforced by upwelling.

The experiments in the Bering Sea were basically quite similar to those in the Fram Strait with some exceptions. Nutrient levels in the Bering Sea are twice those in the Fram Strait so typically the primary production is higher (10 mg m^{-3} vs. as high as 40 mg m^{-3} in the Bering Sea). While nutrient levels play a role, this difference is also due to the differences in environment between a shelf (Bering Sea) and a deep, open ocean (Fram Strait) system. The depth of water at the Bering Sea MIZ is much more shallow than the Fram Strait (100 m vs. 3000 m) so that the Bering Sea water is colder (less oceanic) during the spring MIZ bloom which tends to exclude zooplankton (too cold) so that chlorophyll levels are higher (no grazing). Much of this production goes to the shallow benthic communities. In the Fram Strait MIZ, because the water is more oceanic, the average temperature tends to be warmer in the water column so there are more zooplankton biomass grazing the phytoplankton so there is less chlorophyll in the water. So in the Fram Strait we are beginning to look less at passive sinking of phytoplankton to take carbon from the marine atmosphere to the deep ocean, and beginning to look more at modeling aggregation of phytoplankton processes to ship the primary production past the zooplankton to the deep ocean, as well as the more well known fecal pellet sinking.

Field Experiments

A main objective of our contract was to gather and analyze the ADCP data from the M/V Polarbjorn BIO cruise in the Fram Strait. We used the ONR support, as well as NSF support, to develop ADCP processing and analysis methods. We applied this analysis initially to a set of ADCP data from the MIZ in the Bering Sea. Horizontal currents were acquired with an ADCP along 5 cross-sections through the Bering Sea MIZ in April-May, 1987. Tidal current calculations, using a coincident current meter mooring for calibration, were subtracted from the ADCP data to extract the residual horizontal currents. Vertical currents were then calculated through continuity in which along-ice variability was considered to be negligible. Vector plots of the vertical circulation reveal circulation cells within which the most energetic upwelling occurs on the unstratified side of the frontal structure and the most energetic downwelling occurs on the stratified side of the frontal structure.

In support of the observed circulation, the maximum in the mean integrated chlorophyll/nitrogen ratio from these same 5 cross-sections coincides with upwelling while the minimum in the mean chlorophyll/nitrogen ratio coincides with downwelling. The positive correlation between the mean biochemical activity and mean vertical flow corroborates the existence of persistent and relatively well defined vertical circulation cells associated with the Bering Sea MIZ frontal structure as well as suggesting that the technique of using ADCP to calculate vertical flow is valid.

The great disappointment of our work was the failure of the ADCP on the Polarbjorn during the CEAREX BIO cruise. We saw many features in the Fram

Strait MIZ from the hydrographic data as outlined below. In light of our work with the ADCP data from the Bering Sea, I believe that we would have made significant progress had the ADCP not broken down.

There are additional interesting features/processes that show up in the CEAREX BIO cruise data that are being analyzed, modeled and written up (eg., Smith et al., 1991). For example, chlorophyll concentrations were found quite deep in the water column (~100-200 m), which is below the photic zone, that were still taking up nitrate or still photosynthetically viable. We originally thought that this must be the effect of sinking in chimneys but closer examination of the physical data suggests that this may be the result of downwelling in anti-cyclonic eddies (or alternatively, downwelling between 2 cyclonic eddies). The data do not show a clear cut chimney with sinking in the chimney. The data do show strong sinking/downwelling in what look like anticyclonic features. The energetics of these eddies (eddy streets) must still be sorted out and, in fact, progress is being made on the eddy and eddy streets as results from the 3-D model outlined above. Particle aggregation is also being investigated.

We also get the impression from the data that chimneys may form as a result of cyclonic eddy circulation that forces salty but somewhat warmer water to the surface where atmospheric interaction can draw out more heat. The result is cold, salty water at the surface which then sinks. Preliminary results show that the model can handle this type of process. Our aim here is to continue to do model runs to test ideas on whether the chimneys and/or the eddys are causing downwelling of primary production, or some combination. An additional complication is that if ice is present, ice may insulate the ocean from cooling and convection and further, if the ice is melting, the surface water may too fresh to sink.

Work continues.

References

Maslowski, Weislaw, 1992, A High Resolution Three Dimensional Coupled Ice-Ocean Model of the Greenland Sea and Fram Strait, Proceedings of a modeling workshop on Arctic System Science-Ocean-Atmosphere-Ice Interactions, Report No. 1, Joint Oceanographic Institutions Incorporated, pp 68-70.

Niebauer, H.J., and W.O. Smith, Jr., 1989, A numerical model of mesoscale physical-biological interactions in the Fram Strait Marginal Ice Zone. J. Geophys. Res., 94, 16151-16175.

Niebauer, H.J., 1991, Bio-physical oceanographic interactions at the edge of the Arctic ice pack, J. Marine Systems, 2:209-232.

Smith, W.O., Jr., L.A. Codispoti, D.M Nelson, T. Manley, E.J. Buskey, H.J. Niebauer and G.F. Cota. 1991. Importance of Phaeocyctis blooms in the high-latitude ocean carbon cycle. Nature 352: 514-516.

Smith, W.O.,Jr and H.J. Niebauer, 1993, Interactions Between Biological and Physical Processes in Arctic Seas: Investigations Using Numerical Models, Reviews of Geophysics of the American Geophysical Union (In Press).

To achieve the goals outlined above we have published the following accounts of our research for the period 1990-92:

Niebauer, H.J., 1990 (Invited), Bio-physical Oceanographic Interactions at the Edge of the Arctic Ice Pack. Presented at and to be reviewed for publication in the proceedings of the 22nd International Liege Colloquium on Ocean Hydrodynamics entitled Ice Covered Seas and Ice Edges: Physical, Chemical and Biological Processes and Interactions, Liege, Belgium, 7-11 May, 1990.

Niebauer, H.J., 1991, Bio-physical oceanographic interactions at the edge of the Arctic ice pack, J. Marine Systems, 2:209-232.

Smith, O., Jr., L.A. Codispoti, D.M Nelson, T. Manley, E.J. Buskey, H.J. Niebauer and G.F. Cota. 1991. Importance of Phaeocyctis blooms in the high-latitude ocean carbon cycle. Nature 352: 514-516.

(The above paper was also written up in the Aug 13, 1991 New York Times Science Digest section.)

Maslowski, Weislaw, 1992, A High Resolution Three Dimensional Coupled Ice-Ocean Model of the Greenland Sea and Fram Strait, Proceedings of a modeling workshop on Arctic System Science-Ocean-Atmosphere-Ice Interactions, Report No. 1, Joint Oceanographic Institutions Incorporated, pp 68-70.

Smith, W.O.,Jr and H.J. Niebauer, 1993, Interactions Between Biological and Physical Processes in Arctic Seas: Investigations Using Numerical Models, Reviews of Geophysics of the American Geophysical Union (In Press).

Okkonen, S.R. and H.J. Niebauer, 1993, Marginal Ice Edge Zone Circulation in the Bering Sea from Acoustic Doppler Current Profiler Observations, (Reviewed, rewritten and resubmitted to J. Geophys. Res.)

Coordinated Eastern Arctic Experiment (CEAREX): Biological-Physical-Optical Cruise Data Report, M/V Polarbjorn cruise of April 10-May 17, 1989 to the Fram Strait-Greenland Sea. B.G. Mitchell, B.D. Schieber, E.A. Brody, E.J. Buskey, K. Davidson, L.A. Codispoti, T. Manley, D. Nelson, H.J. Niebauer, W.O. Smith, Jr.

Accounts published previously (1987-90) with ONR support aimed at achieving the goals outlined above:

Niebauer, H.J. and W.O. Smith. 1987. A Numerical Model of Physical-Biological Oceanographic Interactions in Marginal Ice Edge Zones. Presented at the Symposium on Marine Sciences of the Arctic and Sub-Arctic Regions. International Council for the Exploration of the Sea (ICES) at Santander, Spain. September, 1987.

Niebauer, H.J. and W.O. Smith. 1988. (Invited) A Numerical Model of Physical-Biological Oceanographic Interactions in Marginal Ice Edge Zones. Presented at the Ocean Sciences Meeting of the AGU/ASLO in New

Orleans in January 1988.

Niebauer, H.J. and W.O. Smith. 1988. A Numerical Model of Physical-Biological Oceanographic Interactions in Marginal Ice Edge Zones. Presented at the American Meteorological Society meeting on Polar Meteorology and Oceanography in Madison, WI in March, 1988.

Smith, W.O., Jr. and H.J. Niebauer, 1988. A Numerical model of eddy-ice interaction in the Fram Strait. Presented at the American Geophysical Union Fall meeting in San Francisco in December, 1988.

Niebauer, H.J. and W.O. Smith, Jr., 1989, A Numerical Model of Mesoscale Physical-Biological Interactions in the Fram Strait Marginal Ice Edge Zone. J. Geophys. Res. 94:16151-16175.

Niebauer, H.J. and W.O. Smith, Jr., 1989, A Numerical Model of Physical-Biological Oceanographic Interactions in Marginal Ice-Edge Zones, (abstract), Rapports et Proces-Verbaux Reun. Cons. int. Explor. Mer, 188:121.