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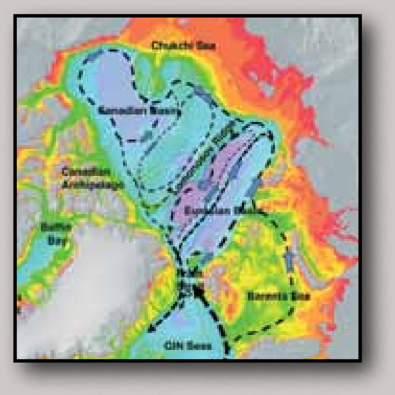
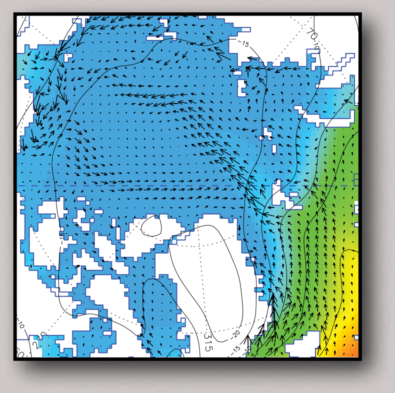
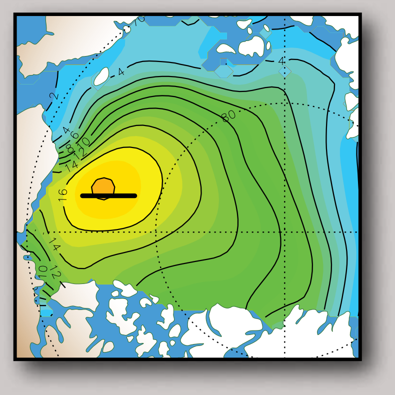
Recent Advances in Arctic Ocean Studies Employing Models from the Arctic Ocean Model Intercomparison Project







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ABSTRACT. Observational data show that the Arctic Ocean has significantly and rapidly changed over the last few decades, which is unprecedented in the observational record. Air and water temperatures have increased, sea ice volume and extent have decreased, permafrost has thawed, storminess has increased, sea level has risen, coastal erosion has progressed, and biological processes have become more complex and diverse. In addition, there are socio-economic impacts of Arctic environmental change on Arctic residents and the world, associated with tourism, oil and gas exploration, navigation, military operations, trade, and industry. This paper discusses important results of the Arctic Ocean Model Intercomparison Project, which is advancing the role of numerical modeling in Arctic Ocean and sea ice research by stimulating national and international synergies for high-latitude research.

ARCTIC OCEAN MODEL INTERCOMPARISON PROJECT MODELS

Modeling has become one of the important instruments for understanding past conditions and explaining recently observed changes in the Arctic Ocean. Models and simulations comprehensively synthesize observations from numerous disciplines (physics, mathematics, and atmospheric, oceanic, cryospheric, and related sciences), enabling hypothesis testing via numerical experiments. Figure 1 explains this philosophy, where synthesis and integration among basic disciplines allows scientists to formulate a basic model, feed this model with initial and boundary conditions, and force it by integrating observational data. We improve models by employing the latest parameterizations of processes, compare models and their outputs, calibrate models and validate their results, and finally obtain advanced models to determine the most probable solutions with reduced uncertainties.

In this context, since 2001, the international Arctic Ocean Model Intercomparison Project (AOMIP; http://www.whoi.edu/projects/AOMIP) has focused on improving Arctic regional models and on investigating various aspects of ocean and sea ice changes. Holloway et al. (2007) and our project website describe AOMIP model specifications, including domains, vertical and horizontal resolutions, initial and boundary conditions, and physical parameterizations. In AOMIP, z-coordinate models that use the original code of Bryan (1969) are the most common. Several AOMIP groups employ different variants of isopycnic (same density; Bleck and Boudra, 1981) and sigma coordinate (topographic; Blumberg and Mellor, 1987) models. The basic configuration for all participating models is driven by coupled ocean and sea ice models using specified atmospheric forcing fields. The sea ice models differ in both dynamics (viscous plastic, general viscous or elastic-viscous-plastic, or cavitating fluid dynamics) and thermodynamics (heat and salt fluxes, number of sea ice categories, layers, and snow parameters). The major AOMIP themes include investigating the variability of Arctic water with Atlantic and Pacific Ocean origins, mechanisms of accumulation and release of freshwater, causes of sea level rise, fate of Arctic sea ice, ecosystem behavior, pathways of contaminants, the role of tides in shaping climate, and many other processes and mechanisms. Whether investigating changes in the Arctic Ocean or working with model improvements, AOMIP uses several different models and runs them under identical coordinated conditions in order to obtain reproducible results and robust conclusions.

SEA ICE

Results from six AOMIP model simulations were recently compared with estimates of sea ice thickness (h) obtained from ICESat (Ice, Cloud, and land Elevation Satellite), moored and submarine-based upward-looking sensors, airborne electromagnetic measurements, and drill holes through ice (recent work of authors Johnson, Proshutinsky, and colleagues). While there are important caveats to keep in mind when comparing modeled results with measurements from different platforms, better agreement was reported for comparisons of model results with moored upward-looking sonars (point data) and satellite data (coarse, gridded data) than for comparisons with data from other platforms. For example, the simulated results are poorest over the fast-ice region of the Siberian shelves (fast ice is ice that is anchored to the shore or seafloor and does not move with winds or currents). In general, most AOMIP models underestimate the amount of thicker ice ($h > 2$ m) and overestimate the amount of thinner ice ($h < 2$ m). The 2 m boundary is a common value separating first-year from multiyear ice. To improve performance, models may need to include better

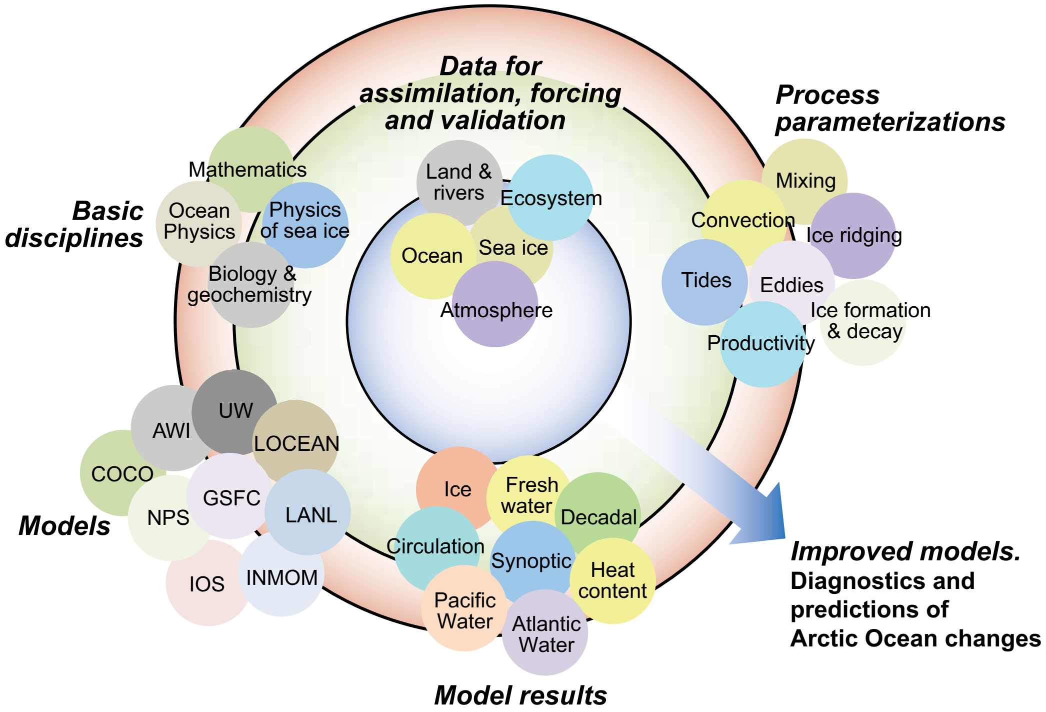

Figure 1. Illustration of synthesis and integration activities employing a modeling approach.

parameterization of first-year ice formation rates and multiyear ice melting rates, and include tidal forcing as well.

Gerdes and Koeberle (2007) evaluated results from one of the AOMIP ocean-sea ice models forced by the atmosphere for the period 1948–2000 and found that most of the IPCC AR4 (Fourth Assessment Report of the Intergovernmental Panel on Climate Change, published in 2007) models do not correctly simulate spatial sea ice thickness distribution during the twentieth century, especially in summer. Some IPCC model deficiencies were related to use of sea ice rheologies that were too simple and to significant biases in the simulated atmospheric forcing.

Biases in twentieth-century sea ice thickness distribution are important not only for future predictions of sea ice (Holland et al., 2010) but also for their important influence on atmospheric conditions over the Arctic (e.g., Budikova, 2009). Furthermore, excessive accumulation of sea ice over the Siberian shelf seas in some model simulations can be important for the formation of the Arctic halocline, the formation of dense waters on the shelves, and the transformation of Atlantic Water in the Arctic that affects the overflows of dense water from the Nordic Seas to the North Atlantic.

Overall, the AR4 IPCC models agree that there is a negative trend in September Arctic sea ice extent over the second half of the twentieth century. However, when compared to satellite observations, most of the AR4 models underestimate the recent trends in the sea ice extent (Stroeve et al., 2007). Interestingly, climate models with more sophisticated sea ice physics (e.g., subgrid-scale ice thickness distribution) more realistically simulate the sea ice distributions (Gerdes and Koeberle, 2007) and sea ice cover changes of the last decades. However, Gerdes and Koeberle (2007) found that even the AR4 IPCC climate models with more sophisticated sea ice models seem to underestimate the internal multidecadal variability of the Arctic sea ice volume compared to forced sea ice-ocean AOMIP models. Note that sea ice in coupled global circulation models (GCMs) is not only determined by the sea ice model but also by atmospheric forcing with its pressure biases (Chapman and Walsh, 2007), which might give unrealistic results for sea ice even if the sea ice model were perfect. Therefore, many of the sea ice thickness distribution problems result from biased atmospheric circulation and from lack (or too low amplitude) of long-term variability in the simulated atmospheric circulation.

WATER CIRCULATION

Below we describe some results of concerted AOMIP experiments to study the pathways and variability of Atlantic Water (AW) and Pacific Water (PW) in the Arctic Ocean. After entering the Arctic, AW and PW lose some heat to the atmosphere and sink to a greater depth. But remaining heat in the Atlantic and Pacific water layers located below the Arctic Ocean's cold and fresh surface layer could melt all Arctic sea ice if released rapidly to the surface. This melting scenario could occur if the cold halocline layer thins as a result of changes in ocean circulation or if mixing changes and the mixed layer deepens as a result of a reduction in sea ice cover.

Atlantic Waters

Observations suggest that AW circulates cyclonically (counterclockwise) in the Arctic Ocean basins at depths between 200 and 800 m (Figure 2). During the earlier years of AOMIP when most models were necessarily run on coarser grids, and hence without eddies, many of the circulation results were confusing. Simulated circulations for AW were sometimes cyclonic and sometimes anticyclonic (clockwise), in conflict with a growing body of observational evidence

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suggesting prevalent "cyclonic rim currents." AOMIP scientists examined the underlying causes for this inconsistency, identified factors influencing AW behavior, and formulated guidelines for model improvements (e.g., Yang, 2005; Karcher et al., 2007; Holloway, 2009).

As a diagnostic for model circulation patterns, Holloway et al. (2007) examined topostrophy ($\tau = f \times V \cdot \nabla D$, where f is the Coriolis force, V is velocity, and ∇D is the gradient of total depth). Topostrophy (the tendency of currents to flow along constant isobaths) recognizes "cyclonic boundary currents" when $\tau > 0$. Analyses from six of the major AOMIP models showed τ (integrated over the volumes of Arctic basins) with small, variable, sign-ambiguous values. Three other AOMIP models included parameterizations of the "neptune effect" (Holloway, 2009), a theory that the many degrees of freedom expressed by ocean eddies will organize mean circulations such as cyclonic boundary currents. The three models that employed the neptune effect showed volume-averaged τ that were large, positive, and persistent. To test these results against observations, an AOMIP project was initiated to gather long-term current meter records. From current meter observations at 2,869 locations, Holloway et al. (in press) estimated Arctic $\tau = +0.57$ (normalized by variances of V and ∇D). One of the newer models for AOMIP, the NEMO model, was run with and without neptune parameterization (Holloway and Wang, 2009); Figure 3 shows the time-averaged results. The neptune run better agrees with inferred flows depicted in Figure 2.

The greater computing resources available in recent years has allowed simulations from fine-grid, eddy-permitting AOMIP models that seem to be approaching more realistic cyclonic rim-current circulations similar to those shown in Figure 2. A resolution-dependence study using the Massachusetts Institute of Technology global climate model ECCO2 is particularly revealing (Holloway et al., in press) because it shows that τ increases when the grid size is reduced. Specifically, in ECCO2, τ increases by 60% when the grid size is reduced from 18 km to 9 km, but it increases by only 13% when the grid is refined from 9 km to 4.5 km. Hence, this study suggests that the model may be improving in the sense of better representation of topographically trapped rim current with respect to further grid refinement.

Pacific Waters

The Canada Basin PW layer occurs at depths between approximately 50 and 150 m (Steele et al., 2004). It originates in ~1 Sv (1.0×10^6 m^3 s^{-1}) of northward flow through Bering Strait, driven by approximately 1 m of sea level difference between the Pacific and Atlantic Oceans (Coachman and Aagaard, 1966). The relatively fresh PW with salinity less than 33.5 comprises about two-thirds of the Canada Basin halocline by thickness and about half by freshwater content (Steele et al., 2004). The exact pathways of PW are not known because of a lack of observations. However, a set of coordinated AOMIP numerical experiments tracked PW using a passive tracer released in Bering Strait to study both cyclonic and anticyclonic circulation. Results of these experiments revealed significant discrepancies among different models, not only in the trajectories of PW waters at different depths (Figure 4) but also in PW layer thickness (not shown).

It was found that the differences among model results are mostly due

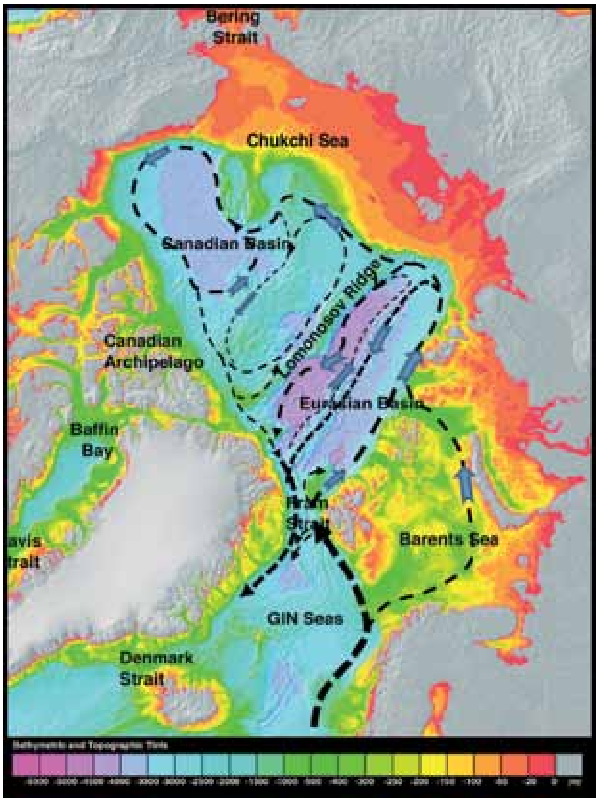


Figure 2. Inferred cyclonic (counter-clockwise) circulation or "cyclonic rim currents" at the intermediate Atlantic water level. *Modified after Rudels et al. (1994). Copyright 1994 American Geophysical Union. Modified by permission of American Geophysical Union*

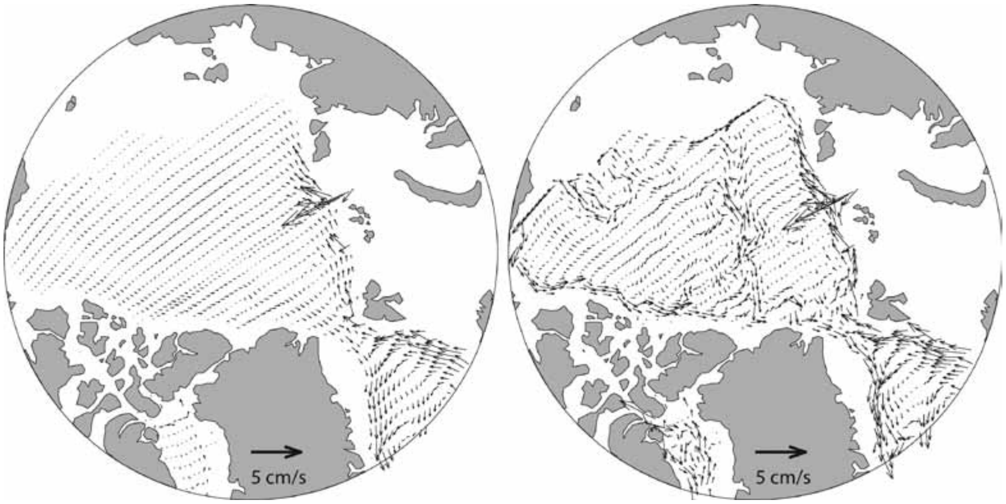
to model resolution, specifically, how models simulate topographically guided rim currents and ocean eddies. Interestingly, higher-resolution models show predominantly cyclonic flow of PW in the Canada Basin, whereas coarser-resolution models mostly show anticyclonic flow. However, the strength of the Bering Strait inflow also has a major influence on PW content and distribution in the Arctic. In models with higher Bering Strait inflow, the Pacific tracer spreads cyclonically through the Canadian Basin, whereas in the models with lower inflow, the tracer spreads anticyclonically. This pattern is likely caused by the sea level difference between the Pacific and North Atlantic noted above, as it influences the volume of Bering Strait inflow and Fram Strait outflow and sets up the density gradients in the subsurface water column, affecting circulation. Another factor is the wind-forced Ekman convergence of the upper-ocean layer that affects the modeled PW distribution in the Canadian Arctic on seasonal and interannual time scales with correlation as high as 80%, in agreement with observations. Thus, the wind regulates PW distribution, which is preconditioned by the strength of the Bering Strait inflow. AOMIP Pacific Water studies will next undertake careful validation of model results against observations available from the Beaufort Gyre Observational Program (see http:www.whoi.edu/beaufortgyre).

ROLES OF WIND AND THERMAL FACTORS INFLUENCING CIRCULATION

Theory, observations, and model results allow us to conclude that both thermal and wind-driven forcing are important for the Arctic Ocean's dynamics and thermodynamics. Unfortunately, the role individual factors play in the circulation and hydrographic fields cannot be easily determined because observed temperature and salinity distributions reflect the combined effects of numerous factors, including forcing (wind and temperature), dependant variables (sea ice, water temperature, and salinity), and dynamic processes (eddy dynamics and topographic interactions). Through numerical modeling, however, the relative roles that different forcing factors play in circulation and hydrography can be assessed. AOMIP scientists designed idealized experiments to investigate the roles of certain factors and eliminate the effects of other factors. To study wind and thermal effects, an idealized Arctic Ocean domain with realistic bathymetry and coastlines was bounded at 55°N; all ocean boundaries were closed to remove inputs of heat, salt, and volume water fluxes from the Pacific and Atlantic Oceans. River runoff and precipitation were disregarded. Initially, the ocean was horizontally uniform (to avoid initial motions driven by horizontal density gradients) but vertically stratified, representing the upper mixed, Pacific, Atlantic, and deepwater layers. In the first wind-only experiment ("wind" experiment), we used annual mean wind stresses derived from National Center for Atmospheric Research/National Centers for Environmental Prediction (NCAR/NCEP) sea level pressure fields following the algorithm recommended on the AOMIP website to force an ice-free ocean for 20 years with 2007 anticyclonic circulation and, in a separate experiment, for 20 years with 1989 cyclonic circulation.

These experiments revealed that wind effects can produce realistic salinity and temperature anomalies. Under the anticyclonic wind forcing of 2007, depending on the model, the simulated

Figure 3. Time mean flow from Nucleus for European Modelling of the Ocean (NEMO) without the "neptune effect" (left) and with the neptune effect (right) at 551 m. The neptune effect (Holloway, 2009) is a theory that the many degrees of freedom expressed by ocean eddies will organize mean circulations. Neptune parameterization intensifies cyclonic (counterclockwise) boundary rim currents and better reproduces the circulation patterns shown in Figure 2. *From Holloway and Wang (2009). Copyright 2009 American Geophysical Union. Reproduced by permission of American Geophysical Union*



ocean accumulated from 14 m to 22 m of freshwater in the Beaufort Gyre (BG) region (Figure 5) due to Ekman pumping. These results were very close to the observed conditions in the Beaufort Gyre region for 2003–2007 (Proshutinsky et al., 2009) and in excellent agreement with the climatology of the Arctic Ocean freshwater content and patterns of salinity and temperature distributions (Arctic Climatology Project, 1997, 1998). Some variation among model results was explained by differences in model parameters such as mixing and vertical resolution (i.e., the model's ability to reproduce the location and strength of the upper ocean halocline). The experiments showed that due to wind forcing alone, freshwater was redistributed and collected in regions with negative wind-stress curl under anticyclonic wind forcing (due to Ekman pumping) and removed from regions where cyclonic wind forcing prevailed with positive wind-stress curl (due to Ekman suction). Approximately 4 m of freshwater was lost from the Greenland Sea Gyre, accompanied by upwelling of deeper layers, whereas surface waters were pushed out of the gyre and diverged, influenced by cyclonic winds. Under a cyclonic wind-driven circulation regime (as observed in 1989), the situation changed: freshwater was removed from the central Arctic Ocean and forced toward coastal regions where downwelling processes became dominant.

It is interesting that during both cyclonic and anticyclonic wind regimes, all models showed recirculation of AW in the vicinity of Fram Strait without water transport into the central basin, indicating that wind forcing does not affect the inflow of AW through Fram Strait in the models. Instead of entering through Fram Strait, AW enters the Arctic basin via the Barents Sea in the models, and this influx is intensified during cyclonic wind regimes. In the Arctic basin, AW circulates mostly cyclonically along the continental slope with varying intensity at different depths, depending on the model and the type of wind regime.

The second idealized experiment (called "thermo") was designed to evaluate the role of air temperature forcing, assuming that all other factors were negligible. Model domain and all other initial and forcing conditions were similar to the "wind" experiment and the ocean was forced only by monthly mean air temperatures derived from NCAR/NCEP reanalysis products for 2007 and 1989. The experiment was

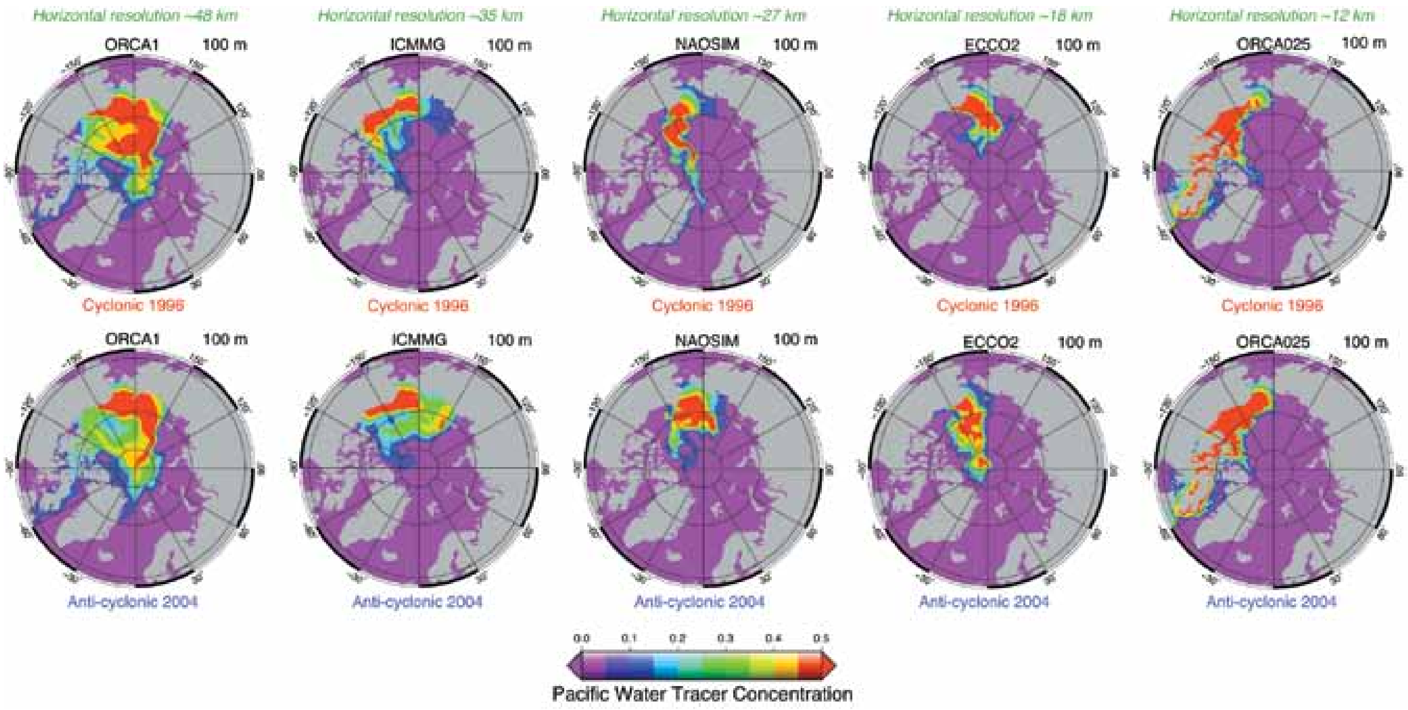


Figure 4. Pathways of Pacific water in Arctic Ocean Model Intercomparison Project (AOMIP) models at the 100 m level for cyclonic (counterclockwise) and anticyclonic (clockwise) types of circulation (recent work of authors Aksenov, Gerdes, Proshutinsky, Watanabe, Golubeva, Ngueyn, Karcher, Platov, and de Cuevas). The models are grouped according to the average horizontal resolution in the Arctic Ocean (shown in green). Passive tracer concentrations are depicted by colors.

initiated with an ice-free ocean, but the models correctly simulated the annual cycle of sea ice formation and growth after 20 years.

The main idea behind the "thermo" experiment was to investigate how horizontally nonuniform seasonal changes in temperature in the Arctic led to the formation of horizontal density and sea surface gradients and current systems in 2007 and 1989. It was expected that after model initialization, sea ice would begin to grow from the center of the ocean toward the coastlines, following the negative radiation balance. In this situation, sea ice transformations should result in the formation of density gradients with higher density in the central Arctic basin and lower density along coasts and a general cyclonic-type of circulation.

Although we are still analyzing results of these experiments to determine the differences between both the model results and the physics behind the simulated effects, we have found that thermal forcing is responsible for AW inflow to the Arctic via Fram Strait at all depths in all models (Figure 6). Comparing 2007 and 1989 thermal forcing and the resulting circulation patterns, we conclude that over the annual cycle, the flux of warm AW to the Arctic should increase in winter to balance the sea level drop in the Arctic basins (associated with cooling), while in summer, the AW flux should be reduced because of sea level rise due to water warming. These simulated changes in AW inflow to the Arctic are in agreement with observations in Fram Strait (Fieg et al., 2010).

FRESHWATER DYNAMICS

The Arctic Ocean receives freshwater from the Pacific Ocean via Bering Strait, from North American and Eurasian rivers, from precipitation over the ocean, and from sea ice melt. It is the largest freshwater storage reservoir in the northern oceans, and it has exhibited substantial changes in all environmental parameters in recent years (Proshutinsky et al., 2009). The volume of freshwater (calculated by Aagaard and Carmack [1989] relative to 34.8 mean salinity of the Arctic Ocean) stored in the Canadian Basin is roughly equal to that stored

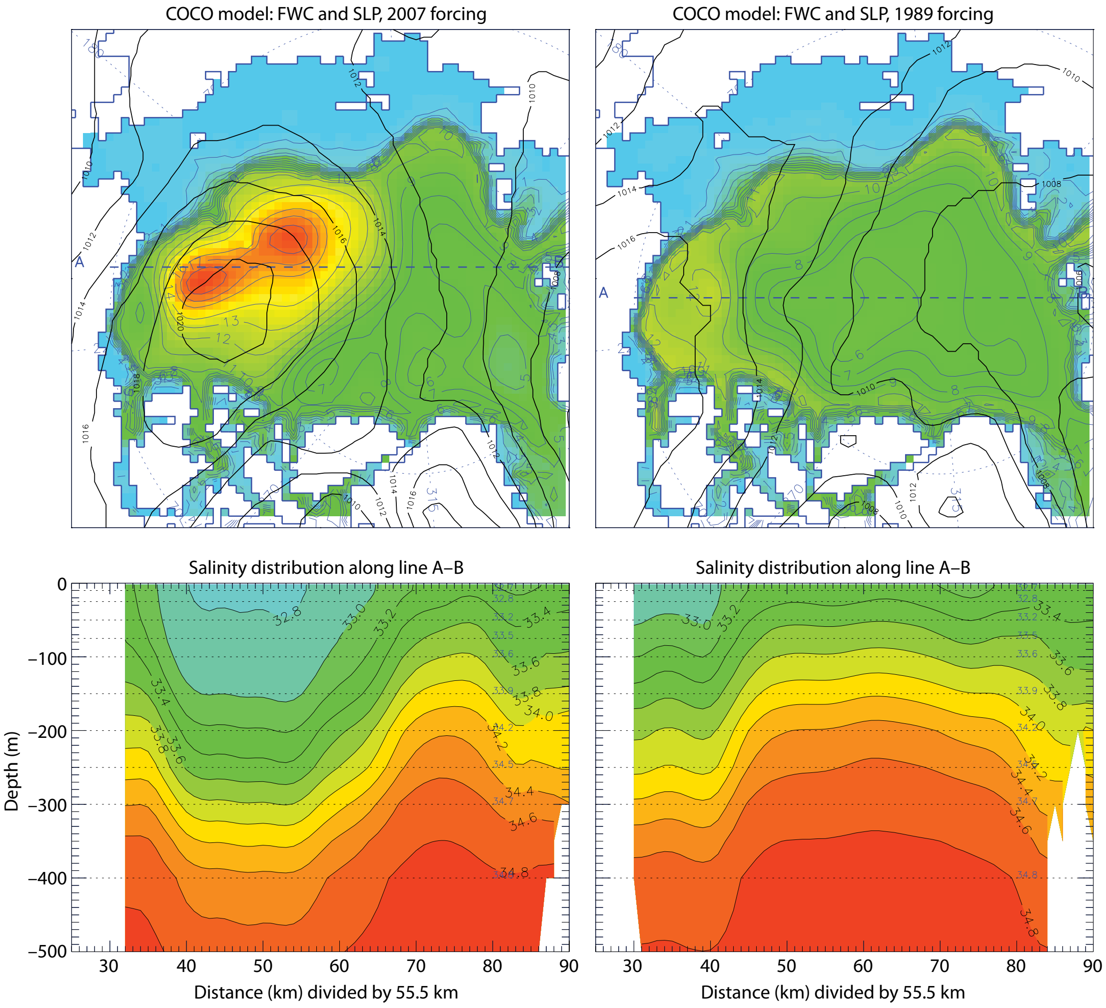


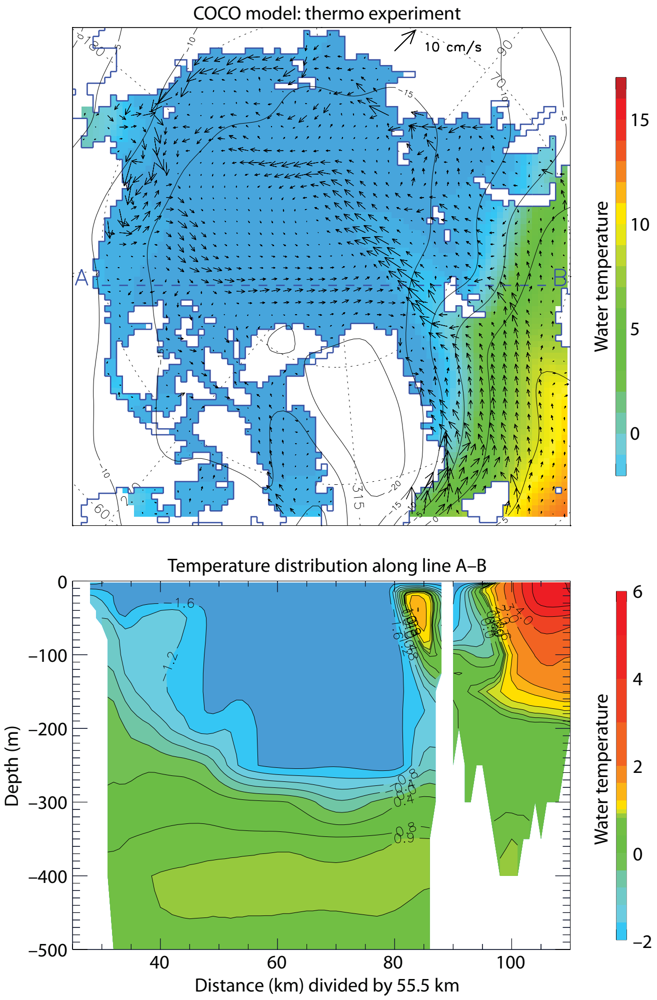
Figure 5. Results of idealized experiments testing the role of anticyclonic (left) and cyclonic (right) winds in the formation of freshwater content anomalies in the Arctic Ocean as simulated by the Center for Climate System Research Ocean Component (COCO) model, version 3.4, developed at the University of Tokyo (Watanabe and Hasumi, 2009). Top panels show freshwater content (m, blue lines and colors) and distribution of sea level pressure (hPa, thick black lines). Bottom panels show distribution of salinity (black lines and colors) along the section depicted as a dashed line in the top panels. Dashed lines in the bottom panels depict initial salinity distributions before applying wind forcing.

in all lakes and rivers of the world and is 10–15 times greater than the annual export of freshwater from the Arctic Ocean. The bulk of this storage is located in the anticyclonically driven Beaufort Gyre (Figure 7) and is related to Ekman convergence (Proshutinsky et al., 2009) of upper-ocean waters from various proximal sources. Hence, the atmospheric and oceanic controls that affect its release and variability are of major importance. For example, the release of only 5% of this freshwater over several years could cause a change in the salinity in the North Atlantic similar to the Great Salinity Anomaly of the 1970s.

Scientific questions that AOMIP collaborators are addressing include: Which circulation regimes are mostly favorable for freshwater accumulation and release? What role does the Beaufort Gyre freshwater reservoir—and the entire Arctic Ocean—play in the generation or suppression of climate changes? AOMIP experiments conducted and integrated with Beaufort Gyre observing system results led to the conclusions that there are significant annual, interannual, and decadal changes in the freshwater content of the Arctic Ocean (water, snow, and ice) and that in addition to freshwater fluxes through boundaries, observations of sea ice thickness, surface freshwater fluxes, and ocean salinity are critically lacking in the central Arctic basin and need year-round monitoring (Proshutinsky et al., 2005).

Another goal of AOMIP freshwater studies is to evaluate the ability of models to accumulate freshwater in the Beaufort Gyre and release it by processes and mechanisms similar to what is observed or revealed by analysis of data collected by the Beaufort Gyre Observational Program (http://www.whoi.edu/beaufortgyre; 2003–present). One lesson from these experiments is that differences in the representation of mixing processes among AOMIP models play a significant role in the ability of the models to represent observed changes in freshwater content correctly. Furthermore, these experiments showed that careful model calibration dependent on a model's horizontal and especially vertical resolution is needed before investigating other elements of ocean freshwater dynamics (Zhang and Steele, 2007; Golubeva and Platov, 2007). Other recent AOMIP activities focused on pathways of freshwater in the Arctic Ocean, such as: How does freshwater enter the Arctic Ocean system? How does it move about, and what phase changes does it undergo? How does it finally exit the system?

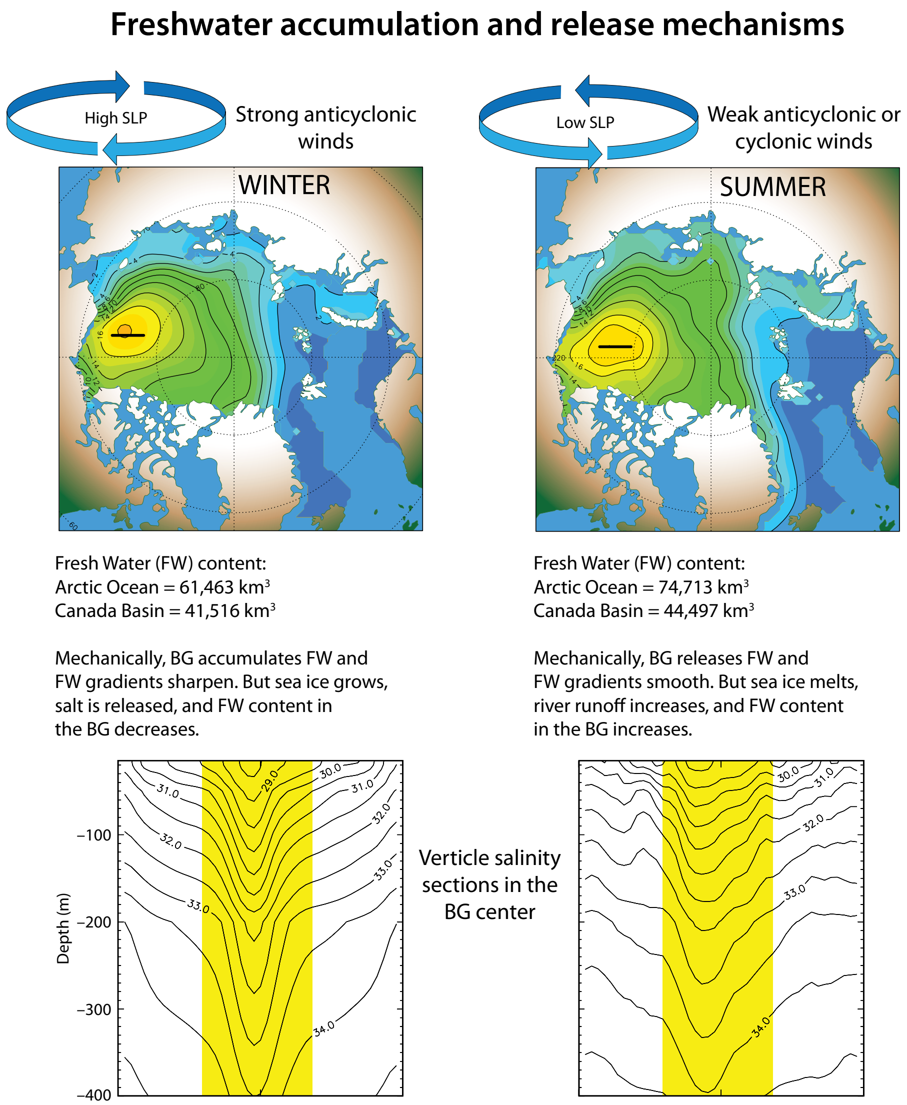
Several experiments have been conducted to answer these questions. For example, it was determined that the northward flow through the narrow and shallow Bering Strait links the Pacific and Arctic Oceans and impacts oceanic conditions downstream in the Chukchi Sea and the western Arctic. AOMIP participants reviewed estimates of the fluxes through Bering Strait at monthly to decadal time scales, including results from coupled ice-ocean models and observations; a synthesis of this review is in preparation. Comparison of data from mooring observations and hydrographic surveys made since the early 1990s with model integrations of the past 26 years


COCO model: thermo experiment

Temperature distribution along line A–B

Figure 6. Results of the "thermo" experiment from the COCO model. The top panel shows surface water temperature (°C, colors), annual air temperature (°C, thin black lines), and surface circulation. The bottom panel shows vertical distribution of temperature (°C, contours and colors) along section A-B depicted as a dashed line in the top panels. Note in the top panel that under thermal forcing, Atlantic Water penetrates to the Arctic Basin through Fram Strait, which is also manifested in the bottom panel via a core of warm Atlantic Water east of Spitsbergen.

indicate that high-resolution models better represent the bathymetry of the region, and thus may more realistically represent flow through the strait. However, in terms of fluxes and mean properties, high-resolution models are not always the most accurate. We find that all models achieve the correct order of magnitude for volume flux and correlate significantly with observations; however, there is still room for improvement, especially in terms of heat and salt fluxes. At the same time, additional measurements with better spatial coverage are needed to minimize uncertainties and better constrain models. Currently, available observational data contain little information on the upper water column and near the coasts.



Fresh Water (FW) content:
Arctic Ocean = 61,463 km^3
Canada Basin = 41,516 km^3

Mechanically, BG accumulates FW and FW gradients sharpen. But sea ice grows, salt is released, and FW content in the BG decreases.

Fresh Water (FW) content:
Arctic Ocean = 74,713 km^3
Canada Basin = 44,497 km^3

Mechanically, BG releases FW and FW gradients smooth. But sea ice melts, river runoff increases, and FW content in the BG increases.

Figure 7. Conceptual mechanisms of freshwater (FW) accumulation and release in the Beaufort Gyre (BG) during an annual cycle. Freshwater content in summer and winter is shown in meters (isolines) calculated relative to salinity 34.8. SLP = sea level atmospheric pressure. The bottom panels show salinity distribution along sections in the center of the Beaufort Gyre region. It is hypothesized that in winter, the wind drives the ice and ocean in an anticyclonic (clockwise) sense so that the Beaufort Gyre accumulates freshwater mechanically through deformation of the salinity field (Ekman convergence and subsequent downwelling; bottom left panel). In summer, anticyclonic winds are weaker (and may even reverse to be cyclonic), and the resultant summer anomaly in Ekman convergence releases freshwater, thereby relaxing salinity gradients (bottom right panel) and reducing Beaufort Gyre freshwater content. *From Proshutinsky et al. (2009). Copyright 2009 American Geophysical Union. Reproduced by permission of American Geophysical Union*

Jahn et al. (2010) completed additional freshwater dynamics studies using a Community Climate System Model Version 3 (CCSM3) simulation that includes passive tracers for freshwater from different sources. They showed that the freshwater exported through the western Canadian Arctic Archipelago comes mainly from Pacific and from North American runoff. In contrast, freshwater export through Fram Strait is mainly composed of Eurasian runoff and freshwater of Pacific origin. Jahn et al. (2010) also found that Eurasian runoff export through Fram Strait depends strongly on the release of freshwater from the Eurasian shelf, which occurs during years with an anticyclonic circulation anomaly. After the freshwater anomaly leaves the shelf, it takes three years to reach Fram Strait. In contrast, variability of Pacific freshwater export through Fram Strait is mainly controlled by changes in Beaufort Gyre storage of freshwater of Pacific origin. There is increased export during years with a cyclonic circulation anomaly (see Figure 4 illustrating dynamics of freshwater of Pacific origin).

TIDAL ROLE IN SHAPING ARCTIC CLIMATE

Holloway and Proshutinsky (2007) introduced parameterizations for tidal influence on ocean mixing and on ice dynamics in a three-dimensional coupled ice ocean model. They showed that tidal forcing leads to enhanced heat loss from the AW layer and ice thinning along continental slopes where tides dominate other motions. This thermodynamic effect competes with net ice growth during rapid openings and closings of tidal leads. Several AOMIP groups have been implementing tides in their models. A spherical coordinate version of the unstructured grid three-dimensional FVCOM (finite volume coastal ocean model; Chen et al., 2009) has been applied to the Arctic Ocean to simulate tides with a horizontal resolution ranging from 1 km in the near-coastal areas to 15 km in the deep ocean. By accurately resolving the irregular coastlines and bathymetry in Arctic Ocean coastal regions, this model reproduces diurnal and semidiurnal tidal wave dynamics very well and captures the complex tidal structure along the coast, particularly in the narrow straits of the Canadian Archipelago. Comparison with previous finite difference models suggests that horizontal resolution and representation of bathymetry are two prerequisites for simulating the tidal energy flux in the Arctic Ocean realistically, particularly in the Canadian Archipelago. Model experiments with realistic forcing and tides are being designed now, and we expect that inclusion of tides will allow us to better understand their role in the dynamics and hydrographic structure of the Arctic Ocean.

ECOSYSTEM QUESTIONS AND MODELING

Physical factors play a disproportionately significant role in plankton productivity in the Arctic Ocean compared with the rest of the world ocean (Smith and Niebauer, 1993; Carmack et al., 2006; Popova et al., 2010). Light and nutrients dominate the control of Arctic primary production. Two main nutrient-supply mechanisms affect the nutrient regime of the surface Arctic Ocean: winter mixing and horizontal exchange with Pacific and Atlantic sectors. In addition to extreme seasonal changes of shortwave radiation, the presence of ice strongly influences light penetration. Two light-limiting characteristics are of prime importance for phytoplankton: the number of days of open water in areas of seasonal ice cover, and ice concentration (rather than ice thickness) in areas covered by multiyear ice (Popova et al., 2010). Recognizing that marine ecosystem modeling is complex and that ecosystems come in many forms, even in the Arctic Ocean environment, AOMIP participants have decided to formulate a set of coordinated experiments to incorporate relatively simple ecosystem modeling in their Arctic Ocean models. Computer models, combined with suitable data-collection programs, can help enhance our understanding of these systems and their reactions to climatic and anthropogenic influences.

Results from five three-dimensional coupled physical and biological ocean models were compared for the Arctic

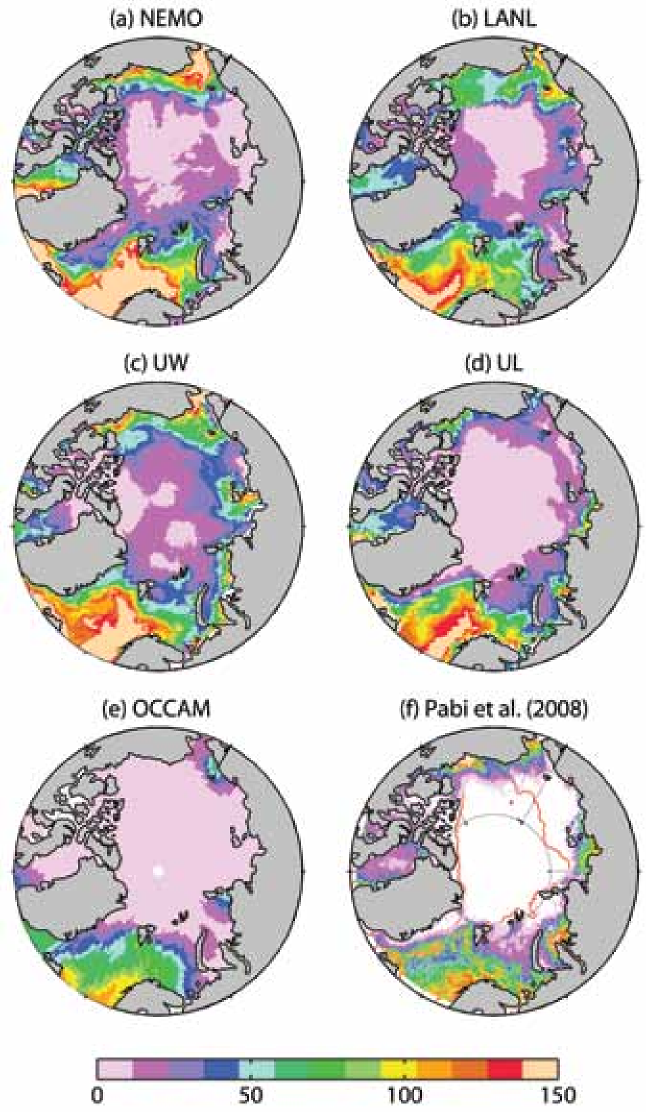


Figure. 8 Mean annual water column primary production (g C m^{-2} yr^{-1}) from different global ocean models: (a) Nucleus for European Modelling of the Ocean (NEMO), (b) Los Alamos National Laboratory (LANL), (c) University of Washington (UW), (d) University of Liège (UL), (e) Ocean Circulation and Climate Advanced Modelling Project (OCCAM), and (f) satellite-derived estimate of Pabi et al. (2008).

domain north of 66.5°N (Figure 8). The global and regional Arctic Ocean models show similar features in the distribution of present-day water column-integrated primary production that are also apparent in the in situ and satellite-derived data. There are substantial variations among models in the depth of winter mixing, a key mechanism supplying inorganic nutrients over the majority of the Arctic Ocean. It is interesting that the amount of nutrients available to plankton is different among models although all models use a similar level of light limitation due to the use of similar ice distributions. Thus, the suite of models being compared disagree in evaluation of which factor (light or nutrients) controls present-day Arctic productivity. These differences between models may not be detrimental in determining primary production, because both light and nutrient limitations are tightly coupled to the presence of sea ice (recent work of authors Popova, Steele, and colleagues). Essentially, as long as at least one of the two limiting factors is reproduced correctly, simulated total primary production will be close to that observed. However, if the retreat of Arctic sea ice continues into the future as expected, a decoupling between sea ice and nutrient limitation will occur, and the predictive capabilities of the models may potentially diminish unless the mechanisms of nutrient supply are better understood.

Although the impact of sea ice on productivity is most immediately evident through its control of the penetration of solar radiation into the ocean, sea ice also affects vertical stratification via salt rejection in winter and freshwater input in summer. Buoyant freshwater from spring and summer melting ice increases water-column stratification and restricts wind-driven mixing of the water column, limiting nutrient resupply from below and thereby constraining primary production (Carmack et al., 2006; Popova et al., 2010). This AOMIP study finds that sea ice impact on primary productivity is perhaps most evident through its direct control of solar irradiance and thus the light available for photosynthesis. However, if sea ice continues to retreat, its impact on stratification, and thus nutrient supply, is likely to be significant. Therefore, we caution against the assumption that reduced Arctic Ocean ice may increase productivity due to elevated light availability. Rather, the Arctic may actually have a limited response because of insufficient nutrients. Care should be taken when forecasting Arctic Ocean ecosystem dynamics during transition to a seasonally ice free ocean until there is sufficient confidence in models' ability to predict the present-day state of Arctic ecosystems.

Circulation, mixing, and freshwater balance play a pivotal role in maintaining the present-day distribution of nutrients in Arctic surface waters, and are probably more important there in controlling plankton productivity than in any other ecological domain of the world ocean (Carmack et al., 2006; Popova et al., 2010). Thus, the fate of the Arctic's ecosystems is tightly coupled to the fate of its unique halocline. Although understanding and modeling Arctic Ocean circulation and water-mass transformation progressed significantly over the last few decades, expansion of this knowledge into biogeochemical cycling is still in its infancy. More studies linking ocean dynamics with biogeochemical tracers are needed to better understand present and predict future changes in Arctic Ocean productivity.

CONCLUDING REMARKS

The next two to three decades will be of great significance in Arctic research as we try to improve understanding of this rapidly changing environment, including external forcing and local and global responses. Increasing interest in the Arctic reflects myriad issues associated with the changing Arctic landscape, including environmental, economic, strategic, and social concerns. New approaches employing innovative technology for making observations along with enhanced complexity and comprehensiveness in models will be necessary in order for us to advance understanding of the Arctic system and decide how to react to the changes taking place there. Arctic Ocean studies based on internationally coordinated experiments through venues such as AOMIP provide unique opportunities for examining the most important processes and interactions. A clear advantage is that each AOMIP participant can draw on the results of all AOMIP models to work with her/his specific research theme and to analyze differences and test hypotheses using a multimodel suite of outputs. The result is a synthesis that integrates observational and modeling efforts toward the overall goal of developing advanced Arctic models that can accurately simulate past, describe present, and predict future Arctic conditions. The goal is to improve models by (1) employing the latest parameterizations of processes, (2) validating the models against observations and comparing them with other model outputs, and (3) determining the most probable solutions with reduced uncertainties. In this regard, we view AOMIP as a collaborative framework that allows modelers and observers to discuss results, problems, and new ideas, working together toward the goals of model improvement and better understanding of the Arctic seas and their role in global ocean change.

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