Impact of Wind-Driven Mixing in the Arctic Ocean

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Vertical Microstructure Profiler being deployed from the icebreaker *Oden* near the North Pole during the Beringia 2005 expedition (Rainville and Winsor, 2008). From similar instruments and more indirect methods, very weak mixing rates are inferred across the entire Arctic Ocean, although this might change as very large areas of the Arctic Ocean become ice-free for a significant fraction of the year. *Photo by P. Winsor*

ABSTRACT. The Arctic Ocean traditionally has been described as an ocean with low variability and weak turbulence levels. Many years of observations from ice camps and ice-based instruments have shown that the sea ice cover effectively isolates the water column from direct wind forcing and damps existing motions, resulting in relatively small upper-ocean variability and an internal wave field that is much weaker than at lower latitudes. Under the ice, direct and indirect estimates across the Arctic basins suggest that turbulent mixing does not play a significant role in the general distribution of oceanic properties and the evolution of Arctic water masses. However, during ice-free periods, the wind generates inertial motions and internal waves, and contributes to deepening of the mixed layer both on the shelves and over the deep basins—as at lower latitudes. Through their associated vertical mixing, these motions can alter the distribution of properties in the water column. With an increasing fraction of the Arctic Ocean becoming ice-free in summer and in fall, there is a crucial need for a better understanding of the impact of direct wind forcing on the Arctic Ocean.

INTRODUCTION

Strong winds blowing over the open ocean typically induce significant surface waves, currents in the surface mixed layer, and often a deepening of the mixed layer itself. The wind-driven inertial (resonant) motions in the mixed layer are responsible for disturbances of the density field at the base of the surface layer. These motions and disturbances in turn generate internal waves, which are supported by the ocean's nonuniform density field, propagate vertically as well as horizontally, and carry a large fraction of the local wind energy input into the deep ocean (D'Asaro, 1985). Together with the internal waves generated by tidal flow over topography, internal waves generated by the wind can break, and therefore mix the interior of the water column. In this context, internal waves are believed to be a major driver of deep-ocean diapycnal (i.e., across density gradients) mixing (Ferrari and Wunsch, 2009).

In the Arctic, however, the sea ice acts as a lid, damping the ocean response to atmospheric forcing. Generally speaking, very strong upper-ocean stratification and greatly damped atmospheric forcing lead to isolated water masses and slow redistribution of properties. Mixing processes in the Arctic are weaker than in the rest of the world's oceans. However, dramatic decreases in summertime minimum sea ice extent, a prominent signal of Arctic change, may significantly amplify upper-ocean response to atmospheric forcing, which would, in turn, affect stratification, sea ice formation, and melting. Recent observations suggest that the marginal ice zone and ice-free areas behave differently and are sites of internal wave generation and enhanced vertical mixing. Because regions of open water are subject to direct wind and atmospheric buoyancy forcing, the impact of storms will likely increase with decreasing ice extent.

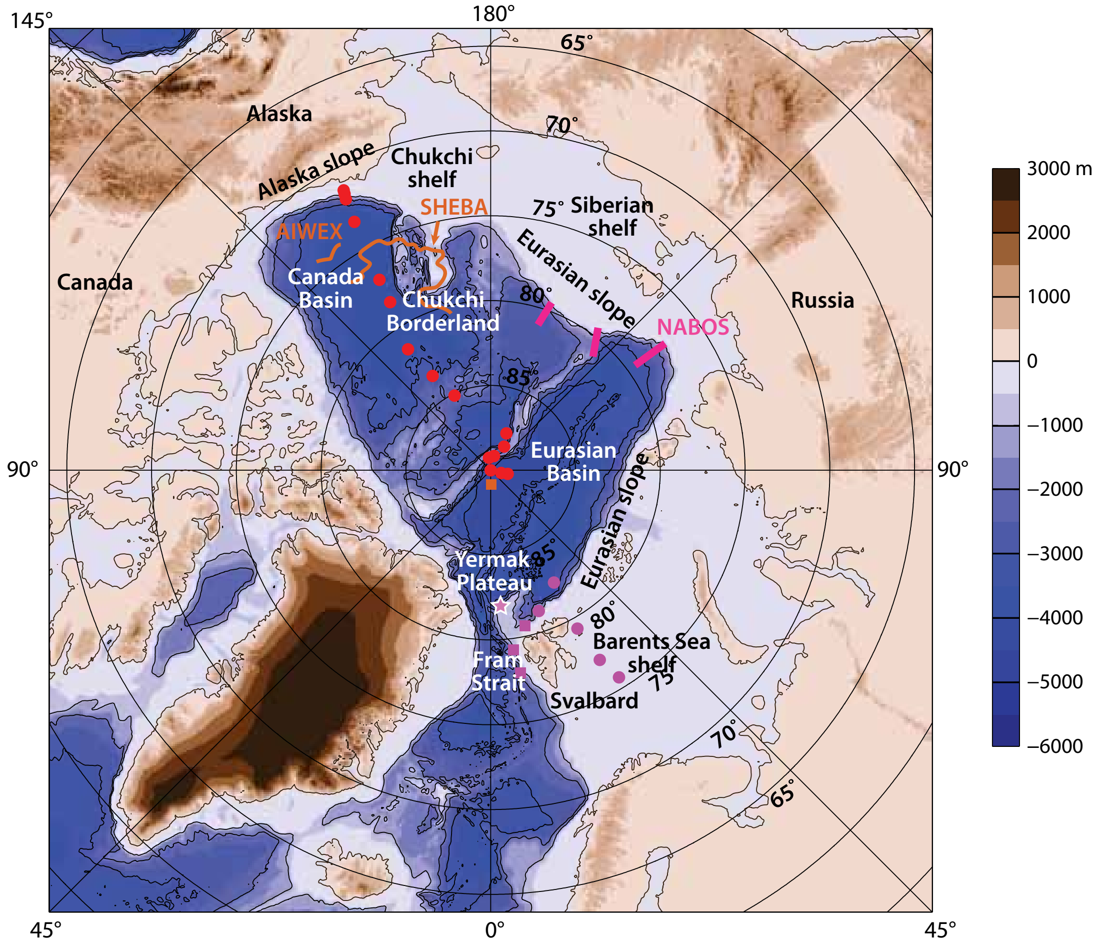
This paper reviews previous studies of Arctic Ocean mixing processes (Figure 1) and compares them with recent investigations that provide evidence for enhanced mixing associated with declining sea ice extent. The observations suggest that wind-driven mixing will likely become increasingly important and could have profound effects on Arctic circulation, sea ice, and climate, particularly in the context of the continued decrease in summer sea ice cover and potentially ice-free summers (Comiso et al., 2008; Perovich, 2011, in this issue).

INTERNAL WAVES AND MIXING IN THE ICE-COVERED ARCTIC

Scattered observations of Arctic internal waves show that, at least in the presence of extensive ice cover, the internal wave field is temporally and spatially nonuniform, with typical energy levels one to two orders of magnitude below that observed in other, ice-free oceans (Levine et al., 1985; D'Asaro and Morison, 1992; Plueddemann, 1992; Halle and Pinkel, 2003; Pinkel, 2005). Because of large internal stresses (rigidity of the ice; McPhee and Kantha, 1989), sea ice inhibits transfer of wind energy to the water and damps the internal wave field in the ice-ocean boundary layer (Morison et al., 1985; Pinkel 2005). This is consistent with the observations of Plueddemann et al. (1998), who report that the energy of inertial motions in the upper 100 m of the Canada Basin generally peaks in late summer when the ice pack is looser and contains more leads, and reaches its minimum at the end of the winter. Despite showing a seasonal cycle, the observed signal is always at least an order of magnitude smaller than typical inertial currents measured at lower latitudes.

Direct and indirect estimates indicate very weak vertical mixing in the ice-covered basin interior, consistent with observed weak internal wave

Figure 1. Map of the Arctic Ocean, indicating the sparse coverage of Arctic microstructure measurements: vertical mixing is estimated to be very small along the drift of ice camps (orange lines: AIWEX, Padman and Dillon, 1987; SHEBA, Shaw et al., 2008), and from deep profiles of the interior (red dots: Rainville and Winsor, 2008; orange square: Fer, 2009). There is some evidence of elevated mixing near the boundaries (pink star: Padman and Dillon, 1991, and Fer et al., 2010; pink dots: Sundfjord et al., 2007; pink squares: Sirevaag and Fer, 2009), but values are still very weak, even in the boundary current (magenta lines from the Nansen and Amundsen Basins Observational System, NABOS, Lenn et al., 2009). Locations of indirect estimates are not plotted.



energy. Estimates of vertical heat fluxes through the "staircase" structures in temperature and salinity capping the thick (~ 1,000 m) homogeneous bottom layer in the Canada Basin (Timmermans and Garrett, 2006) suggest that small double-diffusive fluxes dominate vertical exchange of interior processes, such that the deep waters are effectively isolated from the layers above. Similarly, in the Eurasian Basin, Björk and Winsor (2006) find thick (300–800 m) bottom layers, infer weak interior mixing, and invoke lateral intrusions along the boundaries to account for (slow) estimated renewal rates. Direct full-water-column microstructure measurements across the entire Arctic (Rainville and Winsor, 2008) confirm that turbulence levels in the deep interior basins are below measurable limits.

Relative to the freezing temperature, the upper Arctic water column carries a significant amount of heat, particularly in the Atlantic Water (AW) layer, found throughout the Arctic between 200 and 800 m depth, and, in the western Arctic basins, in the Pacific Summer Water (PSW) layer, characterized by a temperature maximum typically found between 50 and 100 m. Heat contained in these water masses could drive significant melting if brought into contact with sea ice. Generally, however, studies from the ice-covered centers of basins find the surface mixed layer to be isolated from the influence of the deeper water masses by strong stratification within the halocline (Aagaard et al., 1981). Based on over 400 microstructure profiles collected over two months, Padman and Dillon (1987) conclude that there is no significant upward vertical heat flux from AW in the central Canada Basin. More recently, Toole et al. (2010) and Jackson et al. (2010) analyze measurements from Ice-Tethered Profilers (ITP) and ship-based hydrographic surveys in the Canada Basin and both find that the surface mixed layer is warming and

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freshening, enhancing the stratification and effectively impeding wintertime mixed-layer deepening. In ice-covered regions of the Arctic, despite the presence of large wind stresses in both winter and summer, Toole et al. (2010) never observe the mixed layer deepening enough to tap a significant amount of PSW heat. These results echo the findings of Shaw et al. (2009), who estimate the heat fluxed through the halocline using microstructure profile measurements during SHEBA (Surface Heat Budget of the Arctic Ocean program) and conclude that turbulent diffusion does not significantly contribute to the mixed layer and ice heat balance. Closer to the ice and near the base of the oceanic surface mixed layers, fixed turbulence instrument clusters deployed throughout the Arctic over the years have greatly improved our understanding of the transfer of momentum, heat, salt, and other contaminants across the air-ice-ocean boundary layer (e.g., McPhee, 1990, 1999; Shaw et al., 2008), and their measurements generally indicate that the heat fluxes at the base of the mixed layer are too small to contribute significantly to the heat budget of the ice.

Similarly, in the Eurasian Basin interior, Fer (2009) finds diapycnal eddy diffusivities in the cold halocline on the top of the AW layer to be orders of magnitude too small to contribute significantly to the upper halocline and surface mixed layer heat budgets, or even to changes in the heat content of AW itself. Along the Eurasian slope, Polyakov et al. (2010) and Dmitrenko et al. (2008) show that the AW temperature maximum decays with distance following the shelf break and suggest that changes in AW heat content and depth distribution might have contributed to the extreme ice loss of recent years, although the processes that would increase upward heat flux remain unclear. Indeed, even along the boundary, rates of turbulent diffusivity derived from microstructure measurements are much too weak to account for the observed AW cooling, as are the double-diffusive fluxes through the thermohaline staircase capping the AW layer (Lenn et al., 2009). The observed decay of AW temperature is likely due to processes isolated in time and space: for example, upwelling events can bring AW onto the complex Siberian continental shelf where intense interaction with the atmosphere can remove heat. Elevated fine-scale structure variance (i.e., with vertical scales of 10 to a few hundred meters) has been observed near Svalbard (Sundfjord et al., 2007; Sirevaag and Fer, 2009), on the Yermak Plateau (Padman and Dillon, 1991; D'Asaro and Morison, 1992), and along the Siberian shelf (Dewey et al., 1999), suggesting the importance of turbulent mixing generated by internal waves and topographic interactions in specific locations. Particularly near the Yermak Plateau, the observed correlation between rough bathymetry, internal waves, fine-scale vertical shear, and an elevated microstructure signal demonstrates that locally generated internal waves are a major contributor to local mixing (D'Asaro and Morison, 1992; Fer et al., 2010). This might also be true for the Chukchi Borderland.

Figure 2a summarizes the processes responsible for forming and modifying water masses in the Arctic Ocean with relatively small seasonal ice-free areas. The schematic depicts processes active under the more extensive summertime ice cover typical of previous decades. The Discussion section compares this scenario to one in which certain processes might grow in importance, given the shrinking summertime sea ice extent and the correspondingly large area of open ocean subject to direct atmospheric forcing observed in recent years. In the dominantly ice-covered Arctic, sea ice effectively isolates the Arctic Ocean from direct atmospheric forcing and acts as a frictional boundary layer damping the small-scale motion (including inertial motions, internal waves, and presumably eddies and other mesoscale features). Simplistically, cold and salty halocline water is formed on the shelves during periods of ice formation (fall, winter) or from throughflow waters and spreads in the interior. Internal waves and rates of turbulent diffusion in the interior are weak, and coherent thermohaline staircases exist throughout the basins. Locally, thermohaline processes occurring on or near the continental shelves almost exclusively drive water-mass formation and modification in the Arctic Ocean. The boundary currents are thought to be driven by far-field processes.

Nearly all of the studies summarized above stem from observations collected in ice-covered waters. Observations of Arctic Ocean internal wave variability are thus biased toward the large sea ice extents typical of previous years. This bias suggests that an accurate description of Arctic Ocean mixing might be that it is (on average) very weak **under the ice**. The following section describes recent evidence for the importance of episodic mixing events, which might become more prominent as a large fraction of the Arctic Ocean becomes seasonally ice-free.

WIND-DRIVEN MIXING IN ICE-FREE REGIONS

Ice-free regions of the Arctic Ocean might be expected to respond to wind forcing in a manner similar to that observed in the open ocean. Over the Chukchi shelf (a boundary region subject to seasonal ice cover), mooring observations reveal that inertial wave energy and shear are closely linked to the presence of ice (Rainville and Woodgate, 2009). As in previous studies in the high Arctic, inertial velocities are weak under wintertime ice, and shear levels are comparable to values reported in studies from ice camps (Halle and Pinkel, 2003) and ice-tethered buoys (Plueddemann, 1992). When ice is absent from the mooring sites, local storms generate large inertial motions that rapidly fill the water column and generate velocity shear levels comparable to those associated with large mixing events at lower latitudes (Rainville and Woodgate, 2009).

During the 2003 Western Arctic Shelf-Basin Interactions (SBI) program, the high winds and rough seas associated with a storm interrupted the hydrographic sampling of a section across the Alaska shelf from USCGC *Healy* (Woodgate et al., 2004). Notes from the science log reported "45–50 knot winds (about 25 m s^{-1}), force 7 seas" during the storm, and numerical wind reanalysis products (National Centers for Environmental Prediction Reanalysis project [NCEP], Kanamitsu et al., 2002) showed similar wind speeds (Figure 3a). This storm was associated with an Aleutian low propagating from mid-latitudes and was similar to the 2002 storm Pickart et al. (2011) described. Before the storm, the ice edge was about 500 km from the coast. The storm somewhat rearranged the sea ice cover (derived the Special Sensor Microwave/Imager [SSM/I] product; Cavalieri et al., 1996), but a vast area of ice-free ocean remained in the region (Figure 3b).

The nine stations closest to the coast (spanning the slope, with depths from 45 to 810 m) were sampled before and immediately after the storm, allowing a direct measure of the impact of the wind on the upper ocean (Figure 3).

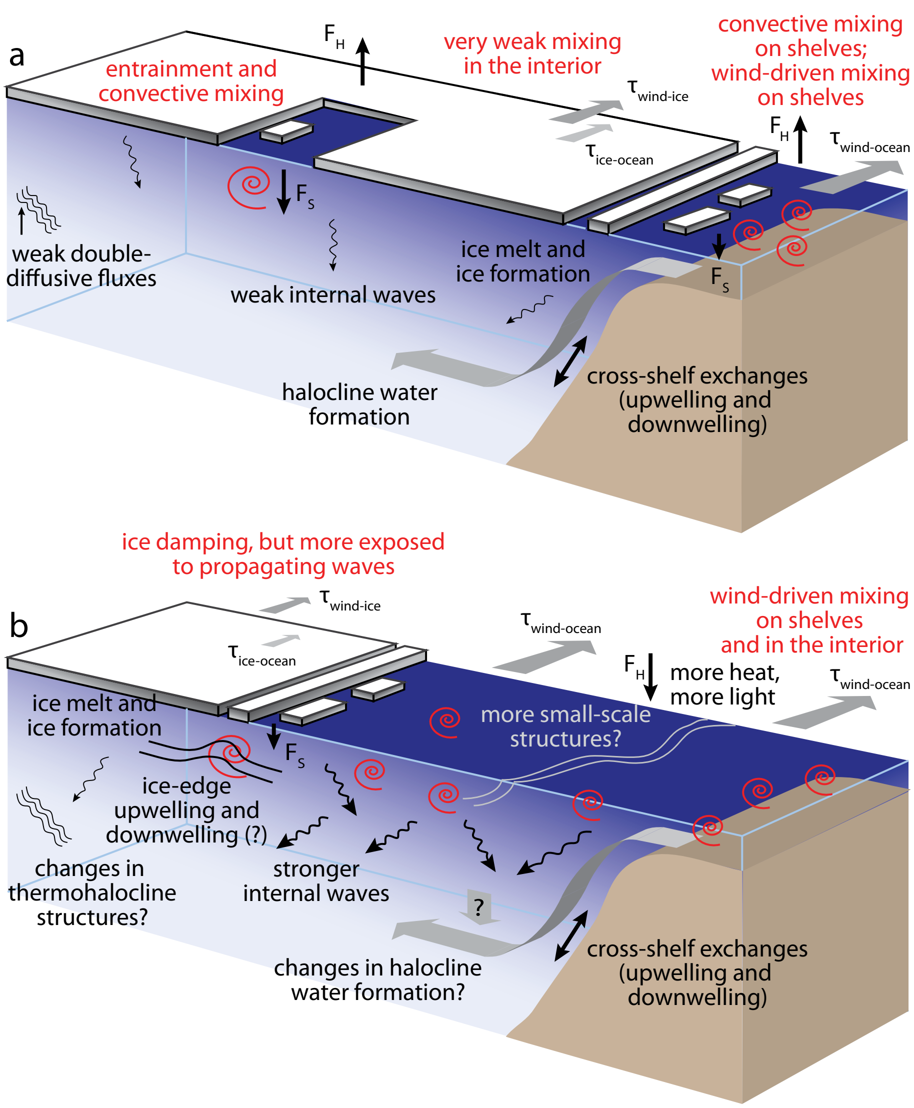

Figure 2. (a) Schematic of the dominant mixing processes in the Arctic Ocean with a relatively small seasonal ice-free area that is more representative of previous decades. Locally, the Arctic Ocean is mostly driven by thermohaline forcing (heat and salt fluxes, F_H and F_S, respectively) associated with ice formation and ice melts on the continental shelves and in polynyas. Wind stress (τ_{wind}) only plays a significant role on the shelves in the summer. Because of its relative rigidity at small scales, the sea ice effectively acts as a frictional boundary layer, both inhibiting internal wave generation and damping existing internal waves as well as small-scale and mesoscale upper ocean features. (b) Schematic of the dominant mixing processes for an Arctic Ocean with large ice-free areas. Both wind and thermohaline forcing are important in driving the ocean. The wind, acting directly over large areas of open water, generates more internal waves and more small-scale structures (fronts, eddies), which would have been damped out by the ice cover. The internal waves propagate to the deep interior, potentially enhancing mixing, modifying stratification and exchange of properties, and eroding the coherent staircase currently observed throughout the Arctic Ocean.

Offshore of the shelf break (~ 10 km), the before and after salinity sections (salinity strongly determines density at these temperatures) showed a deepening of the surface mixed layer—the storm destroyed almost all the stratification in the upper 35 m (Figure 3c,d). There was also strong upwelling and, as described in detail by Pickart et al. (2009), changes in the coastal jet on the shelf and at the shelf break. Optical transmissivity (Figure 3e,f) drastically decreased onshore of the shelf break after the storm, suggesting that the storm disturbed bottom sediment and caused a redistribution of suspended particles throughout the water column, as indeed was observed in water samples taken as part of the hydrographic program. Before the storm, the mixed-layer depth, defined as the depth where salinity differs by more than 0.2 from its surface value, was less than 15 m deep for all stations offshore of the shelf break (12.5 ± 4.4 m for the stations where the bottom depth was larger than 100 m). After the storm, three days later, the depth of the mixed layer for the offshore stations more than doubled (26.0 ± 3.5 m) and did not show a significant decreasing trend toward the interior. The storm significantly deepened the mixed layers over a very large area, from the shelf break to distances of at least 100 km over the deep basin (and presumably to the ice edge). Thus, the impact of summer and fall storms was much broader than coastal.

Prior to the remarkably low summer sea ice extents of recent years, the sea ice edge typically remained near the shelf slopes during the summer, and it is probable that most of the wind-driven mixing historically happened on the shallow shelves. While there is some evidence for storm-driven mixing events in the Canada Basin and north of Fram Strait (Yang et al., 2001, 2004), winter storms do not seem to have a significant impact on the evolution of mixed-layer depths under the ice (Toole et al., 2010). When there is no ice, however, we anticipate that summer and fall wind events will generate large inertial motions in the mixed layers, large shears at the base of the mixed layer, and presumably episodes of deepening of the mixed layers on a regional scale, as in the example presented in Figure 3. It is also possible that the thinner surface mixed layers now observed in the Arctic, and the enhanced stratification at their bases (Jackson et al., 2010; Toole et al., 2010), might lead to a more efficient transfer of wind energy to the internal wave field (i.e., the energy of a given wind stress is distributed over a thinner layer, thus generating larger currents than if the mixed layer were deep, a larger heaving of the base of the mixed layer, and larger inertial internal waves), and therefore lead to more mixing in the interior. Furthermore, even in winter, McPhee (2008) suggests that the ice-ocean boundary layer will couple more strongly with winds as the young, weak ice (which transfers more energy from the wind to the water) replaces strong, multiyear ice (Rothrock et al., 1999).

Another important area to consider is the marginal ice zone. Observational and numerical studies show that the wind stress is often at a local maximum near the edge of the ice (Guest et al., 1995). Indeed, the stress associated with large-scale, upper-level geostrophic winds in the transition zone between 100% ice cover and open ocean is often highly spatially nonuniform due to variations of atmospheric stability on and off ice, wind speed, roughness, and other variables. While surface wind speed generally increases from the ice pack to the open ocean, the maximum roughness associated with broken ice in the marginal ice zone persistently creates a wind-stress maximum right at the ice edge. Combined with upwelling or downwelling associated with the wind-driven Ekman convergence or divergence near the ice edge (Carmack and Chapman, 2003), this observation suggests that the marginal ice zone is a crucial area to study to understand and quantify upper ocean mixing.

DISCUSSION AND CONCLUSIONS

Until only a few years ago, most of our knowledge of Arctic Ocean circulation and dynamics came from a few sparse moorings and isolated field campaigns from icebreakers or ice camps. Despite the surge in observational data collected in recent years (Toole et al., 2011, in this issue), the Arctic Ocean is still one of the most undersampled regions of the world. Arctic Ocean circulation and the dynamics, as well as their year-to-year variability, are often described by tracking changes in the water properties as sampled by a handful of profiles each year. While at lower latitudes the satellite revolution of the last few decades has revealed basin-wide images of oceans filled with small-scale eddies, sharp fronts and jets, spirals, and other features, ice cover prevents much of this satellite imaging of the Arctic. As the summer sea ice cover continues to decrease, it is likely that these processes, and the horizontal and vertical mixing that they produce, will become more obvious and might even play a larger role in Arctic dynamics.

As the Arctic Ocean becomes forced

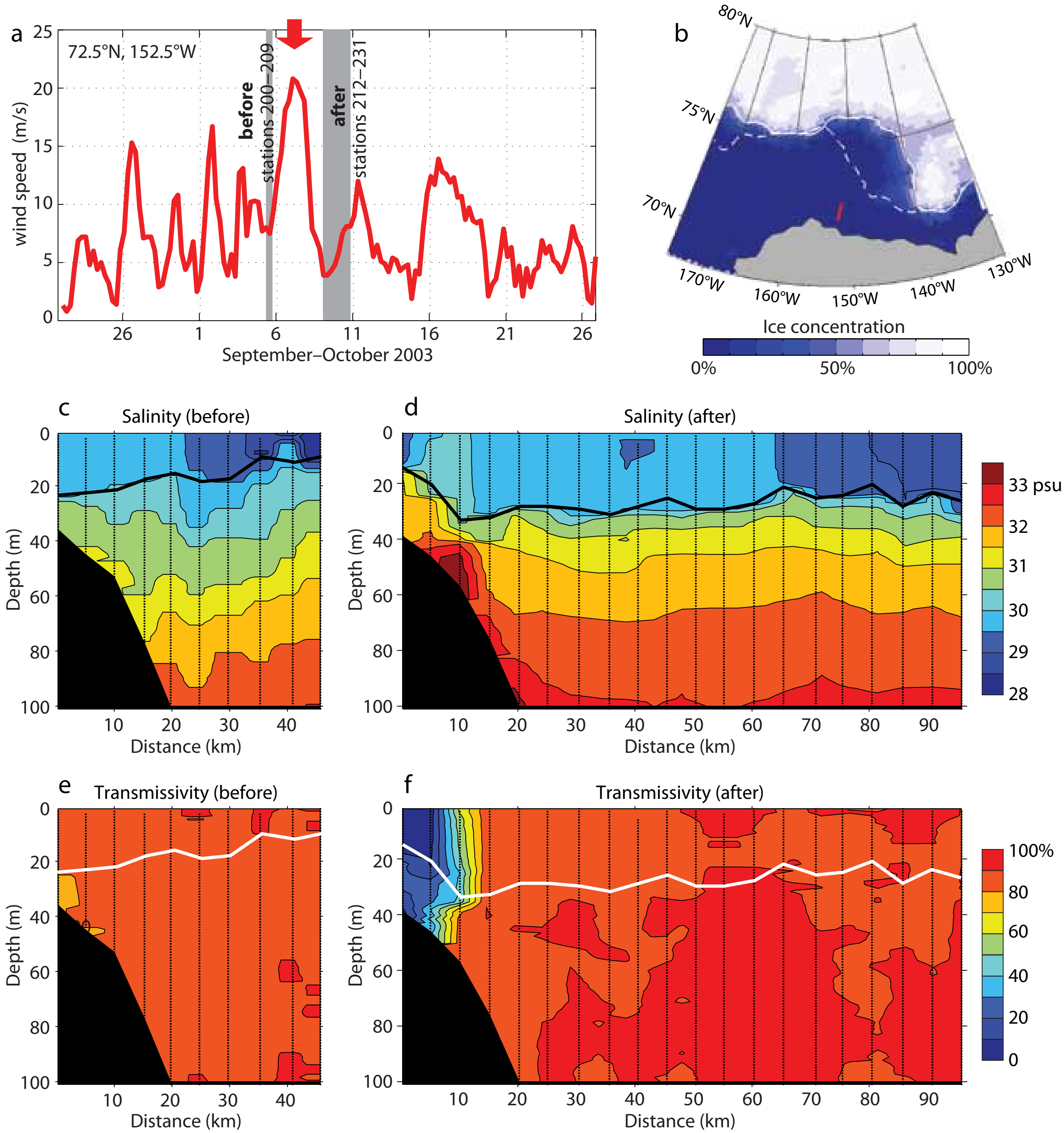

Figure 3. (a) Time series of the 10 m wind speed from NCEP (National Centers for Environmental Prediction) reanalysis at the closest grid point (72.5°N, 152.5°W) to a pair of sections obtained just before and after a strong storm (red arrow). (b) Map of the ice concentration on October 4, 2003, just before the storm. The 50% ice concentration contour is shown in solid white, and that corresponding to sea ice distribution just after the storm, on October 11, is shown in dashed white. The extent of the section is shown in red. (c,d) Salinity and (e,f) optical transmissivity from sections across the Alaska shelf before (left panels, HLY-03-03 stations 200–209) and after (right panels, HLY-03-03 stations 212–231) the storm. The surface mixed layer as defined by salinity is shown in black (c,d) and white (e,f).

more strongly by atmospheric wind during the summer, it is likely that the large-scale properties and the Arctic's "mean" circulation will be affected (McPhee et al., 2009). Although the dynamics of the AW boundary current are still very much debated, many theories suggest it is forced by large-scale wind stress transferred to the ocean through the ice (e.g., Nost and Isachsen, 2003; Karcher et al., 2007). Modifying this coupling will likely lead to changes in the boundary current. Additionally, stronger internal wave mixing may overwhelm the double-diffusive fluxes currently believed to drive spreading of AW from the boundary currents to the interior (McLaughlin et al., 2009).

Eddies observed both in the Canada Basin (Manley and Hunkins, 1985; D'Asaro, 1988; Plueddemann et al., 1998; Muench et al., 2000; Timmermans et al., 2008) and the Eurasian Basin (Woodgate et al., 2001; Schauer et al., 2002) have been linked to instabilities of coastal currents (D'Asaro, 1988), deep and shallow water inflows (Woodgate et al., 2001; Schauer et al., 2002), or frontal systems (Timmermans et al., 2008). As fronts and coastal circulations become more strongly forced and presumably increase in energy, it is possible that the dynamical role of eddies will increase as well. Furthermore, the dynamical response of the ocean to atmospheric forcing and the atmospheric forcing itself are likely to change (Overland and Wang, 2010; Overland, 2011, in this issue). As observed for specific events (Pickart et al., 2011), storms can lead to coastal and slope upwelling, Ekman convergence, and modification of the slope currents. Indeed, by bringing deep and shallow water masses closer together and exposing deeper water to upper-ocean mixing processes (wind- or buoyancy-driven, or boundary mixing associated with bottom drag), upwelling is thought to play a major role in modifying water masses near canyons or on the continental slope (Woodgate et al., 2005; Pickart et al., 2009).

Based on the observations and concepts presented above, we speculate that one of the most profound impacts of climate changes in the Arctic will be the transition from an ocean that is driven locally by thermohaline processes (mainly ice melt and formation) to an ocean that, during the summer, is also strongly wind-driven. Figure 2b schematically depicts the new important mixing processes and expected changes. In the absence of ice cover, wind acts directly on the ocean surface to generate inertial motions and internal waves (and thus mixing), and light (and thus radiative heating) penetrates more efficiently into the upper ocean.

Considerable efforts are underway to understand the effects of sea ice retreat on the radiation balance of the Arctic system, the powerful ice-albedo feedback mechanism, and the thermodynamics of the atmosphere/ice/ocean interface. This paper argues that the dynamical response to seasonal sea ice decrease is also likely to be important.

In summary, without the ice cover, summer and fall storms over the Arctic Ocean generate significant inertial motion and inertial shear (Rainville and Woodgate, 2009). As observed at lower latitudes for many years (e.g., Polland and Millar, 1970; Plueddemann and Farrar, 2006), turbulent mixing due to wind-driven storms deepens the mixed layer and severely impacts mixing in the upper ocean, on the shelves, at the slope, and in the interior (Figure 3). This enhanced wind-driven mixing can also cause oceanic heat to rise, with implications for ice melt and ice formation. In addition, wind-driven turbulence mixes fresher waters from the Arctic Ocean surface downward, changing the structure of waters exiting the Arctic basins through Fram Strait and the Canadian Archipelago, with possible implications for global-Arctic connections. Increased wind-driven energy within the ocean may influence the dynamics of the Atlantic water boundary current and slope-to-basin exchange. If currents strengthen, their potential to generate eddies might also increase, resulting in more eddy-driven exchange within the Arctic.

The processes discussed above and potential resulting changes will directly impact phytoplankton growth, which is controlled by a delicate balance among nutrient availability, light, and stratification. If the Bering Sea may be used as a guide, subtle changes in timing of ice retreat, storm mixing, and shelf-break upwelling relative to spring sunrise may shift the initial bloom from an ice-edge phenomenon, which favors export of material to the bottom and thus promotes benthic food webs, to a later pelagic (water column) bloom that favors retention in the water column and pelagic food webs (Hunt et al., 2002; Carmack et al., 2006). McLaughlin and Carmack (2010) indicate that the recent increase in stratification of the Canada Basin (in part due to ice melt) strongly limits the availability of nutrients and therefore negatively impacts productivity. If wind mixing generates deep mixed layers on the shelves and in the basin interior in the summer (ice-free period), the nutrient replenishment to the euphotic zone might benefit phytoplankton growth in the current fall or following spring.

A fundamental question for the future of the whole Arctic system is how will that larger seasonality in the ice cover impact upper-ocean stratification? Early and enhanced ice melt in the summer leads to thinner and fresher mixed layers over large areas of the Arctic, but, in turn, they make the ocean more susceptible to the generation of large inertial motions, larger shear in the halocline that might be sufficiently large to overcome the stronger stratification, and enhanced mixing in the upper halocline. Given the large amount of heat contained in AW and in PSW, the potentially large feedback processes between ice melt and upper ocean variability, and the subsurface presence of nutrients, it is critical to better understand the upper ocean heat and momentum balances and the potential impacts of a decreased ice cover.

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