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Preface to special section on Beaufort Gyre Climate System Exploration Studies: Documenting key parameters to understand environmental variability

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1. Introduction

[1] The Beaufort Gyre (BG) of the Arctic Ocean is one of the most hostile and inaccessible areas of the globe. Until late 1920s most of it had never been measured or even explored. The region's harsh climate, winter darkness, and thick drifting sea ice deterred potential observers and made this area inaccessible to scientific expeditions. The BG is a unique phenomenon comprising a set of specific atmospheric, sea ice, and oceanic conditions that have significant influence on the Arctic climate. The papers of this special issue focus on the atmospheric, sea ice, oceanographic, and some biogeochemical features of this region and describe the BG system variability at seasonal to decadal timescales, employing historical and the most recent data, simple hypotheses, and models to estimate changes.

2. Brief History

[2] The first modern attempt to investigate the deep Arctic north of Barrow was made by Captain Wilkins and Carl Ben Eielson in 1927 [e.g., *Nasht*, 2006]. Wilkins and Eielson flew 450 nautical miles (1 nautical mile = 1.852 km) northwest from Barrow before being forced down by bad weather at 77°45′N and 175°W. At this location they sounded an ocean depth of 5625 m, which may be the first oceanographic measurement in this region. In the mid-1920s there was thought to be land north of Alaska in the middle of the Arctic Ocean, in an area known as the "blind spot." In the center was the "Pole of Inaccessibility" (84°12′ N and 160°W), a point equidistant from all landmasses and about 400 miles south of the North Pole. On official charts, it was called Crocker Land or Keenan Land, or Harris Land and appeared with question marks. Wilkins' flights in 1927 and 1928 definitively determined that there is no land in this region.

[3] Another attempt to reach the Pole of Inaccessibility was made in April–May of 1941 by Soviet pilots and scientists on "flying observatory" expeditions using "CCCP H-169" airplanes. That year, they landed on the sea ice and made oceanographic, sea ice and meteorological observations at 3 locations (3 April at 81°28′N, 179°12′E; 13 April at 78°28′N, 176°44E′; and 23 April at 79°54′, 179°50W′). They also measured ocean depth and found that it was 2 times shallower than Wilkins' recording. Hydrographic measurements showed the presence of warm waters of Atlantic origin at 500 m depth with temperatures at least 2 times lower than in the Makarov and Nansen basins of the Arctic Ocean; but deep layer water in the Canada Basin was warmer than deep water in the eastern Arctic indicating the presence of a ridge dividing eastern and western parts of the Arctic Ocean [*Timofeev*, 1960].

[4] The existence of this submarine ridge was inferred and, indeed, actually later observed by American scientists in the course of studies in the Arctic Basin after World War II. During ice landings with aircraft north of Alaska in April 1951, *Crary et al.* [1952] found the ocean basin in the Beaufort Sea had a depth of 3838 m at 74°45′N, 150°55′W. *Worthington* [1953] in his "Ski-Jump" expeditions recorded a depth of 2950 m about 300 miles north of this point in March 1952. From the oceanographic data gathered by *Worthington* [1953], the deep water in the Beaufort Sea was shown to be warmer by 0.35°C than that in the ocean north of Siberia and Svalbard as described by *Sverdrup and Soule* [1933]; similar to what was observed by participants of the CCCP H-169 expedition. Worthington believed that this could be explained in one of two ways: either the deep water entering the Arctic Basin from the Norwegian Sea had warmed since the earlier observations were made, or "there is a submarine ridge, running roughly from Ellesmere to the New Siberian Islands, which separates the deepest water of the Beaufort Sea from the remainder of the basin." The major oceanic feature discovered by *Worthington* [1953] in the northern parts of the Beaufort Sea was a large anticyclonic circulation gyre (Beaufort Gyre (BG)).

[5] After 1951, many more expeditions were launched to sample water characteristics and bottom sediments in the region including: manned drifting station "T3" (Radar Target 3) which was the designation given when a 7 mile long ice island which protruded 50 ft (1 ft = 0.3048 m) above the surrounding ice pack was first spotted by an U.S. Air Force ice patrol airplane commanded by Joe Fletcher – who went on to promote the island's use for science, so that the "official" name of T3 became Fletcher's Ice Island

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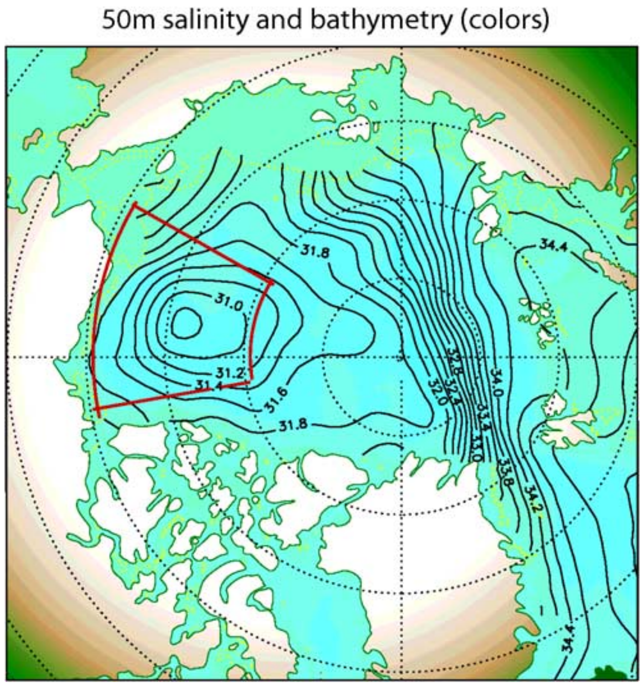

Figure 1. Climatological (1950–1980) water salinity at 50 m from *Arctic Climatology Project* [1997, 1998]. There is a salinity minimum in the center of the BG (region bounded by thick red line). The 50 m bathymetry contour as shown by the yellow dotted line.

(1952–1954, 1955, 1957–1961 and 1965–1974, 1979); International Geophysical Year ice stations Alpha and Charlie (1957–1958 and 1960–1961); the Arctic Research Laboratory ice stations (ARLIS I, 1960–1961 and ARLIS II, 1961–1965); the Arctic Ice Dynamics Joint Experiment (AIDJEX,1975–1976); North Pole (NP, Russian drifting stations, 1950–1991); and Russian airborne surveys (Sever, 1972–1986).

[6] On the basis of the observations obtained during this time period, *Treshnikov* [1954] determined the boundaries of the BG by analyzing geostrophic currents calculated using observed water and temperature fields from the early Russian airborne surveys, and *Gudkovich* [1966] calculated the period of sea ice circulation in the BG (3.5 years) by analyzing Russian drifting station tracks. Meanwhile, *Hunkins* [1966] presented clear evidence of a clockwise (Ekman) spiral structure of ocean currents in the upper layers of the Canadian Basin, and in 1974 *Newton et al.* [1974] and *Hunkins* [1974] reported findings of subsurface eddies after extensive observations during the AIDJEX program.

[7] After AIDJEX, the major features of the water structure and ice dynamics continued to be investigated from manned expeditions and using new technology, including: the Leads Experiment ice camp (LEADEX, 1992); Sea Ice Mechanics Initiative ice camps (SIMI 1993 and 1994); Surface Heat Budget of the Arctic expedition (SHEBA 1997–1998); Canadian Arctic Shelf Exchange Studies (CASES, 2003–2005); Applied Physics Laboratory Ice Stations (APLIS, every 2–4 years since 1978, most recently 2007 and 2008); submarine Scientific Ice Expeditions (SCICEX, 1993–2000); International Arctic Buoy Program buoys (IABP, 1979–present); Salinity Argos buoys (SALARGOS, 1985–1993); Ice-Ocean Environmental Buoys (IOEB, 1996–2000); JAMSTEC Compact Arctic Drifters (JCAD, 2000–2005); Ice-Tethered Profiler buoys (2004–present); and satellite-based observations (1972–present).

[8] The investigations in the 1990s brought new discoveries, for instance: warming of the Atlantic Water layer [*Carmack et al.*, 1997], thinning sea ice relative to the 1970s [*Rothrock et al.*, 1999], a declining trend in sea ice concentrations, a significant reduction of summer sea ice in the Pacific sector [*Barber and Hanesiak*, 2004], and a change in the rate of bioproductivity [*Melnikov*, 2000]. Very interesting and unexpected results were obtained in 1997–1998 from the SHEBA drift experiment which included more that 180 researchers who participated in an interdisciplinary measurement program motivated by the questions of global warming. Detailed measurements were made to investigate the processes that affect ice albedo and cloud radiation feedbacks over the annual cycle. Some SHEBA results were published in the special collection of JGR papers in 2002 [see *Moore et al.*, 2002].

3. Scientific Questions and Major Goals for BG Exploration Studies

[9] Despite the numerous observations carried out during the relatively long period of BG exploration there still remained a number of important scientific questions related to this region. The major reason for the initiation of the BG Exploration Project in 2003 was to field an experiment designed to test the hypothesis of *Proshutinsky et al.* [2002, hereinafter referred to as *P2002*] on the origin of the salinity minimum in the center of the BG (Figure 1). Hydrographic climatology shows that because of this salinity minimum, which extends from the surface to ~400 m depth (Figure 2), the Canada Basin contains approximately 45,000 km^3 of fresh water [*Aagaard and Carmack*, 1989]. This value calculated relative to a reference mean salinity (34.8) of the Arctic Ocean specifies how much fresh water is accumulated in this region from different sources (ice melting and freezing, rivers, atmospheric precipitation and water transport from the Pacific and Atlantic Oceans via straits).

[10] *P2002* hypothesized that in winter, the wind (a dynamic factor) drives the ice and ocean in a clockwise (anticyclonic) sense so that the BG accumulates fresh water mechanically through a deformation of the salinity field (Ekman convergence and subsequent downwelling). In summer, winds are weaker (and may even reverse to be counterclockwise) and the summer resultant anomaly in Ekman convergence releases fresh water, thereby relaxing salinity gradients and reducing BG Fresh Water Content (FWC). *P2002* tested this mechanical hypothesis for fresh water accumulation and release by employing a relatively simple model where wind was the major driving force (the influences of sea ice and ocean thermodynamics were neglected). At the same time, *P2002* pointed out that thermodynamic processes may also be important – in winter, ice growth and subsequent salt release reduce the FWC of the BG, and in summer ice melt increases the FWC. The interplay between dynamic and thermodynamic forcing is no doubt complicated.

[11] Starting in August 2003, a team of Woods Hole Oceanographic Institution scientists in collaboration with

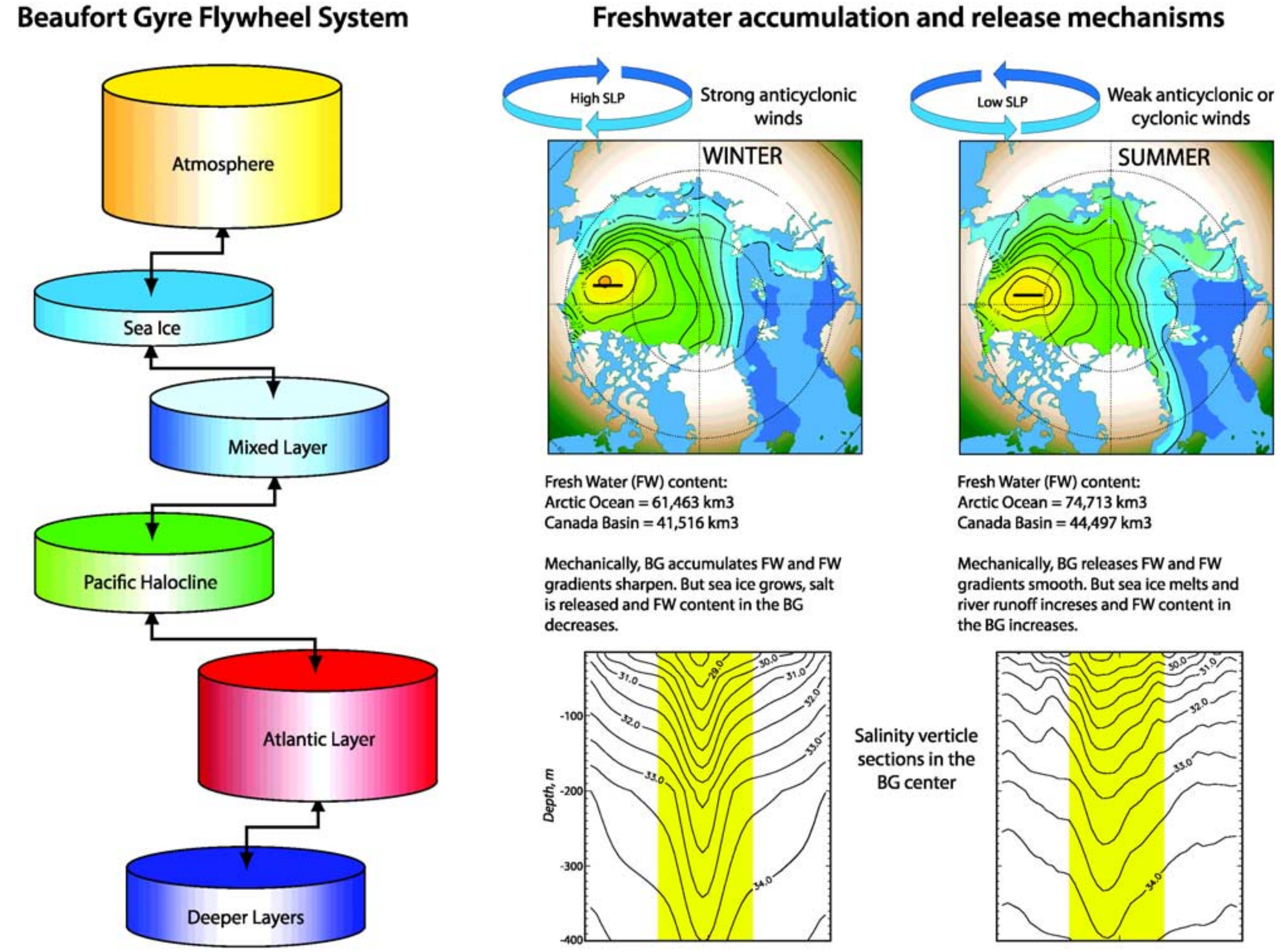

Figure 2. (left) Coupling diagram of the BG system. Each component (or wheel of the system) stores and exchanges mass and energy differently during different climate regimes. Conceptually, the size of each block in the diagram represents the relative amount of momentum and energy stored by the particular wheel. Quantifying and describing the state and variability of these wheels and their couplings is essential to understand the state and fate of the present-day Arctic climate. (right) Conceptual mechanisms of freshwater accumulation and release in the BG during a seasonal cycle. Freshwater content in summer and winter is shown in meters (isolines) calculated relative to salinity 34.8. SLP, sea level atmospheric pressure.

researchers from the Institute of Ocean Sciences, Canada and the Japan Agency for Marine-Earth Science and Technology began to acquire time series of temperature, salinity, currents, geochemical tracers, sea ice draft, and sea level on JWACS (Joint Western Arctic Climate Studies) cruises. Measurements were made using moorings, drifting buoys, shipboard, and remote sensing techniques. The mooring data allow estimation of sea level variability, sea ice draft, and variations in the vertical distribution of FWC [see *Proshutinsky et al.*, 2009]. Repeat hydrographic sections have examined variability of ocean and ice characteristics in the region in time and space. Remote sensing techniques examine the broader spatial variability of the sea ice thickness and horizontal structure of sea surface height.

[12] Observations conducted in 2003 and 2004 clearly showed that BG conditions in the early 2000s differed significantly from the pre-1990s FWC climatology: the center of the FWC maximum (which is also the center of the BG geostrophic circulation) shifted to the southeast and appeared to have contracted in area relative to climatology [*Proshutinsky et al.*, 2009]. In spite of this areal reduction, the magnitude of BG FWC increased by approximately 1,000 km^3 relative to climatology, while lateral gradients of dynamic height increased. In addition to a spin-up of the BG, the baroclinic part of the Transpolar Drift current intensified and shifted toward Canada. An unusual seasonal variability in sea ice thickness and oceanic freshwater content [*Proshutinsky et al.*, 2009; *Hutchings and Rigor*, 2009] was also observed. Theoretical studies and relatively simple numerical experiments [*Proshutinsky et al.*, 2005; *Dukhovskoy et al.*, 2004] have shown that in order to understand the important role of the BG in Arctic climate it is necessary to carry out a multifaceted study combining investigations of the BG system composed of several elements depicted as ''wheels'' in Figure 2 (left). The BGOS program has continued through 2005–2008 and all data collected by BGOS are available at the project web site http://www.whoi.edu/beaufortgyre.

[13] The main results based on the publications indicated above are as follows:

[14] 1. The atmospheric wheel (Figure 2) appears to be regulated by both teleconnection patterns (such as the Arctic Oscillation [*Thompson and Wallace*, 1998] and via local scale forcing of cyclones in this region [*Overland*, 2009; *Overland and Wang*, 2007]. In particular the surface pressure patterns appear to cause a reversal of the sea ice gyre [*Lukovich and Barber*, 2005] which is becoming more irregular throughout the annual cycle. Recent work has also highlighted the role which cyclones can play in the reversal of the gyre [*Asplin et al.*, 2009] and how this process propagates through stratosphere-troposphere coupling [*Lukovich et al.*, 2009].

[15] 2. The sea ice wheel, as an intermediate link between the atmosphere and ocean and a product of interactions between the two is responsible for regulating momentum and heat transfer between the atmosphere and ocean [*Hutchings and Rigor*, 2009; *Perovich et al.*, 2009]; accumulating and releasing fresh water or salt during the melting-freezing cycle [*Proshutinsky et al.*, 2009]; redistributing fresh water sources by incorporating first-year ice from the marginal seas into the convergent BG circulation; retaining it there and transforming it into ridged and thick multiyear ice [*Proshutinsky et al.*, 2009; *Hutchings and Rigor*, 2009]; archiving the previous year's conditions; buffering variations; and reducing abrupt changes [*Hutchings and Rigor*, 2009]; protecting the ocean from overcooling or overheating, both of which are extremely important for nutrient dynamics [*Tremblay et al.*, 2008]; and for polar biology [*Hopcroft et al.*, 2005; *Kosobokova et al.*, 2007].

[16] 3. The oceanic wheel is an important part of the BG system and is responsible for stabilizing the anticyclonic circulation of sea ice and upper ocean [*Proshutinsky et al.*, 2002, 2005], accumulating and releasing liquid fresh water and sea ice from the BG [*Proshutinsky et al.*, 2002, 2009], governing the ventilation of the ocean in coastal polynyas and openings along the shelf break (M. Itoh et al., Interannual variability of Pacific Winter Water inflow through Barrow Canyon from 2000 to 2006, submitted to *Journal of Geophysical Research*, 2009), regulating the circulation and fractional redistribution of the summer and winter Pacific waters [*Timmermans et al.*, 2008; *Okkonen et al.*, 2009; Itoh et al., submitted manuscript, 2009], and determining the pathways of fresh water export from the Arctic to the North Atlantic [*Joyce and Proshutinsky*, 2007; *Guay et al.*, 2009].

4. Papers in This BG Special Issue

[17] There are fifteen papers focusing on the atmospheric, sea ice, oceanographic and some biogeochemical features of the BG in this special issue. The majority of these papers have already been cited in the text above. Here we provide some more details and describe how each paper contributes to the scientific framework presented above.

4.1. Atmosphere

[18] This element is described in several papers. *Overland* [2009] provides a review of the Beaufort Sea meteorology with updates on recent research in this area. It is specifically noted that the recent sea ice losses have changed the climatology of the region, especially with increased temperatures greater than 6°C through the autumn months. This new climatology suggests that it would be difficult to quickly return to pre-1990 climate in the Beaufort Sea.

[19] *Asplin et al.* [2009] and *Lukovich et al.* [2009] describe atmospheric forcing of the BG. They investigate the coupling between BG surface and lower troposphere *Asplin et al.* [2009] and relationships between surface and stratospheric processes. These papers analyze synoptic atmospheric conditions which drive different regimes of the BG atmospheric circulation, explain reversals at synoptic timescales and address a question: What is the nature of synoptic weather patterns that have preceded reversals of the BG? Results of these studies are important for understanding of sea ice drift and ocean circulation variability, and changes in the BG freshwater and heat content.

[20] *Pickart and Moore* [2008] analyze synoptic atmospheric conditions responsible for generation of strong upwelling and downwelling events along the BG shelves on the basis of observations of ocean parameters in 2002 from a mooring array crossing the BG shelf, and NCAR/NCEP atmospheric reanalysis data. This paper is well connected with *Yang*'s [2009] studies where the upwelling and downwelling processes are investigated in the center of the BG and are driven by Ekman pumping because of changes of wind curl over the region. These two papers supplement each other regionally and from a physical view point because strong downwelling in the BG center has to be compensated by upwelling along BG shelves.

4.2. Sea Ice

[21] Some characteristics of BG sea ice can be found in the paper by *Perovich et al.* [2009]. In late summer of 2005 in the western Beaufort Sea, extensive areas of undeformed first-year ice with thickness of 0.5–1.0 m were observed. In contrast, there was no ice in this region in 2007. Some additional information about sea ice thickness variability at seasonal to interannual timescales in the central BG region is provided by *Proshutinsky et al.* [2009].

4.3. Ocean

[22] Atmosphere, sea ice and ocean components are analyzed by *Proshutinsky et al.* [2009] in order to better understand the mechanisms responsible for the processes of fresh water accumulation and release in the BG freshwater reservoir. In this study, BG Observational system data (2003–2007) are used to test the *P2002* hypothesis (see section 3 and Figure 2 above). This paper describes the mechanical (Ekman pumping) and thermodynamic (ice melt/freezing) mechanisms, but does not address fresh water composition. Two papers fill this gap, namely, those by *Yamamoto-Kawai et al.* [2009] and *Guay et al.* [2009]. *Yamamoto-Kawai et al.* [2009] analyze surface freshening on the basis of observations of water salinity, δ^{18}O and alkalinity and estimate how much fresh water observed in the BG in recent years is from meteoric and from river runoff sources, and show how contributions from these sources to the BG freshwater balance change from year to year and from region to region. *Guay et al.* [2009] investigate fresh water composition in the upper 200 m layer of the BG region, and employ a salinity-oxygen isotope mass balance to calculate the relative contributions from sea ice melt,

meteoric, and saline end-members. Ba measurements are also incorporated and used to resolve the meteoric fraction into separate contributions from North American and Eurasian sources of river runoff.

[23] The research of *Okkonen et al.* [2009] and Itoh et al. (submitted manuscript, 2009) focus on water circulation in Barrow Canyon, which is considered one of the major sources of Pacific origin waters for the deep ocean in the BG region. *Okkonen et al.*'s [2009] analysis and results are based on late summer high-resolution hydrographic surveys, acoustic Doppler current profiler measured currents, satellite-measured sea surface temperatures and numerical modeling. The findings of Itoh et al. (submitted manuscript, 2009) originate from a thorough analysis of data from several moorings covering the 2000–2006 period and also hydrography. *Okkonen et al.* [2009] are more interested in the analysis of wind-driven circulation changes, while Itoh et al. (submitted manuscript, 2009) examine the interannual variability of Pacific Winter Water.

[24] Changes in the Pacific water mass characteristics (including temperature, salinity, nutrient, and chlorophyll *a* parameters) are described by *Nishino et al.* [2008] and add one more dimension in the picture showing oceanic changes in the BG and its vicinity. The *Timmermans et al.* [2008] study is focused on the analysis of the double-diffusive staircases in the BG thermocline (200–300 m depth) which separates Pacific and Atlantic waters, on the basis of observations in 2004–2007 by drifting Ice-Tethered Profiling instruments. This paper continues studies of the BG system shown in Figure 2 above. It is concluded that the vertical transport of heat from the Atlantic Water in the central basin is unlikely to have a significant impact to the Canada Basin ocean surface heat budget but absence of staircases in the vicinity of continental slope suggests that the heat can escape from the Atlantic layer along continental slopes where it is strongly influenced by frequent upwelling and downwelling events described by *Pickart and Moore* [2008].

[25] *McLaughlin et al.* [2009] investigate changes recently observed in the BG Atlantic Water layer relative to the information obtained in the 1990s. It is hypothesized that two main mechanisms are responsible for the warming of the Atlantic Water layer in the BG, namely: increase in the boundary current and thermohaline intrusions. W. Maslowski and J. C. Kinney (Influence of oceanic circulation, heat fluxes and eddies on recent warming in the western Arctic: Results of a high-resolution ice-ocean model, submitted to *Journal of Geophysical Research*, 2009) synthesize some observational data and very high resolution model results in order to understand how the oceanic dynamics (circulation and eddies) and thermodynamics (heat fluxes from different sources) influence unprecedented warming in the BG region. Their major finding is that at least 60% of sea ice thickness variance in the BG region can be explained by warm waters advected from shelves by mesoscale eddies.

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