

## RESEARCH/REVIEW ARTICLE

## Is there a “new normal” climate in the Beaufort Sea?

Kevin R. Wood,<sup>1</sup> James E. Overland,<sup>2</sup> Sigrud A. Salo,<sup>2</sup> Nicholas A. Bond,<sup>1</sup> William J. Williams<sup>3</sup> & Xiquan Dong<sup>4</sup>

<sup>1</sup> Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, 3737 Brooklyn Avenue NE, Seattle, 98195-5672 WA, USA

<sup>2</sup> Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, 7600 Sand Point Way NE, Seattle, 98115 WA, USA

<sup>3</sup> Institute of Ocean Sciences, 9860 West Saanich Road, Sidney, British Columbia, Canada V8L 4B2

<sup>4</sup> Department of Atmospheric Sciences, University of North Dakota, 4149 University Avenue, Grand Forks, 58202 ND, USA

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### Correspondence

Kevin R. Wood, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, 3737 Brooklyn Avenue NE, Seattle, 98195-5672 WA, USA.  
E-mail: kevin.r.wood@noaa.gov

### Abstract

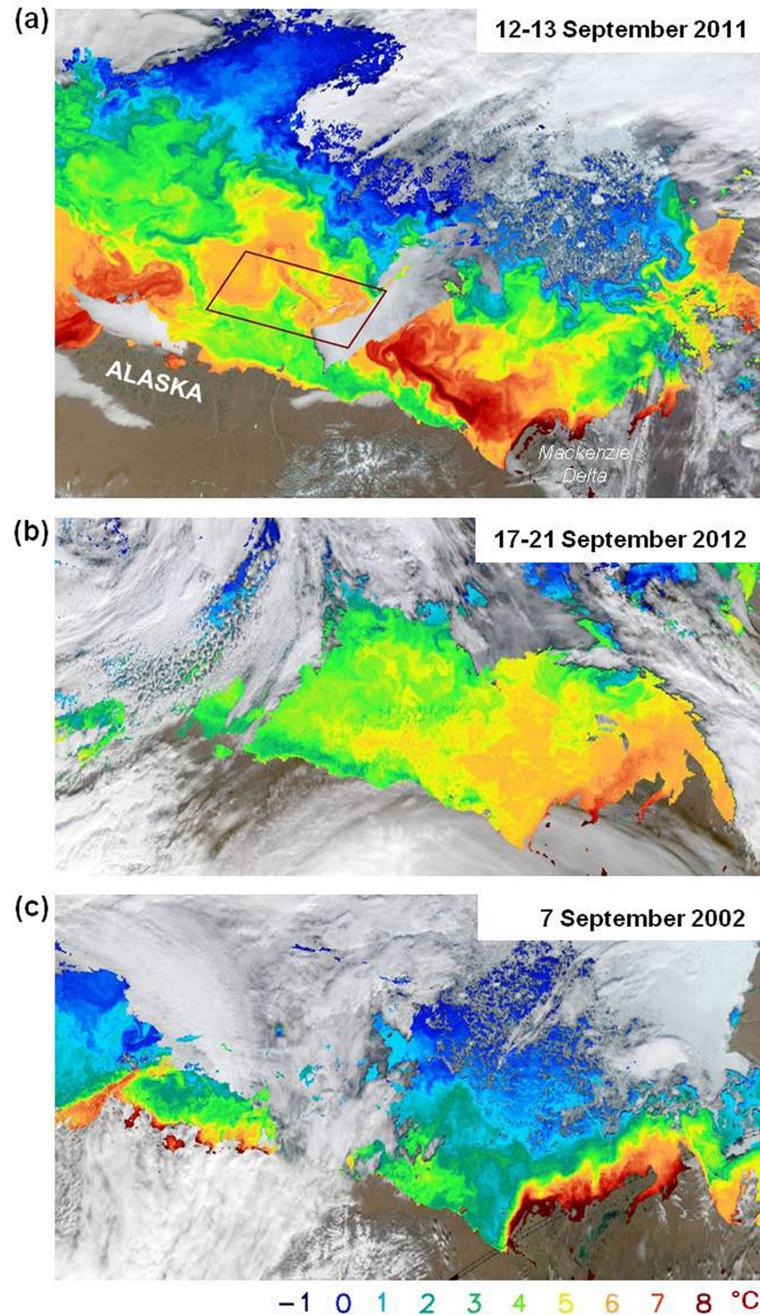
Since 2007, environmental conditions in the Beaufort Sea have appeared to be consistently different from those in the past. Is a “new normal” climate emerging in the region? Sea-surface temperatures (SSTs) have been notably warm during the summer, leading to delayed freeze-up in the fall along with large surface air temperature (SAT) anomalies due to the release of stored ocean heat to the atmosphere. In the autumn of 2011 and 2012, SST and SAT anomalies in Arctic marginal seas were the largest observed in the Northern Hemisphere. Since 2007, there has been an increase in easterly winds, which has helped set the stage for Arctic amplification by advecting sea ice out of the region and enhancing surface stratification due to the offshore transport of fresh water from the large Mackenzie River discharge plume. These winds are linked to an intensification of the Beaufort High and are evident throughout the troposphere. Their occurrence has undoubtedly contributed to the acceleration of sea-ice loss and surface warming in the Beaufort Sea, with additional impacts likely throughout the ecosystem.

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Sea and air temperatures in the Beaufort Sea have been anomalously high in the summer and autumn over the past six years. In July 2011, sea-surface temperatures (SSTs) of up to 12°C were observed over a wide area beyond the continental shelf, where sea ice (and cold water) was once the prevailing condition. The warmest SSTs were located in a strongly stratified surface layer, 6–8 m thick, associated with the Mackenzie River discharge plume. Anomalous SSTs persisted into early autumn (Fig. 1a), where they contributed to regional surface air temperature (SAT) anomalies from 4°C to more than 10°C in September and October (relative to the standard 1981–2010 reference climatology in the US National Centers for Environmental Prediction/National Center for Atmospheric Research re-analysis data set [NNR]). SAT anomalies over the Beaufort and other western Arctic marginal seas during these months were the largest observed anywhere in the

Northern Hemisphere. Similarly elevated SSTs were observed in the autumn of 2012 (Fig. 1b), along with a consistent pattern of large SAT anomalies offshore.

There are multiple factors operating over a range of spatial and temporal scales that contribute to the increased summertime warming of the Beaufort Sea. Arctic sea ice is disappearing faster than climate models have projected (Duarte et al. 2012), and reductions in the Beaufort Sea have been especially dramatic. Here, the ice-free area has increased by an average of 80% since 2007, compared to climatology (1981–2010). There has also been a marked increase in easterly winds during the summer that tend to blow sea ice out of the region, especially now that thicker and less mobile multiyear ice makes up a smaller fraction of the ice cover. The same wind that drives a thinner and more mobile ice pack away also increases the advection of fresh water run-off



**Fig. 1** Beaufort Sea in September. (a) Moderate-resolution Imaging Spectroradiometer composite image obtained on 12–13 September 2011 shows high sea-surface temperatures (SSTs) associated with the Mackenzie River plume persisted into autumn. The Wave Glider operating area is indicated by the box. (b) A more diffuse Mackenzie plume on 17–21 September 2012, after a summer of relatively light mean easterly winds. (c) The same area for 7 September 2002. Westerly winds have contained the plume to the coastal region. Year-to-year variation in the intrusion of warm Bering/Chukchi water carried by the Alaska Coastal Current past Point Barrow can also be seen (Okkonen et al. 2009). In 2011, high September SSTs in the western Beaufort are traceable to both the Alaska Coastal Current and warm water farther offshore that was advected from the east.

from the Mackenzie River far out into the Beaufort Sea. This creates ideal conditions for both rapid surface warming and enhanced ocean heat storage due to reduced albedo and strong surface stratification. Ocean

temperature anomalies thus created may be advected farther to the west and into the path of warm Bering Strait inflow (Okkonen et al. 2009). This collection of processes contributes to Arctic amplification (Serreze &

Barry 2011). Without this combination of factors the Beaufort Sea tends to be much colder, as was the case even in 2002 and 2003 for example (Fig. 1c).

Against this backdrop the idea that a “new normal” is emerging in the Beaufort Sea has become a frequent topic of discussion. There is a sense that the run of warm summers with substantially ice-free conditions that has occurred since 2007 may herald a long-term shift in the regional climate. While the overall thinning of the Arctic sea-ice pack is due in part to large-scale anthropogenic forcing (Laxon et al. 2013) and its influence on local radiation processes, in the Beaufort Sea the recent increase in ice-free area and rapid warming of the surface ocean in the summer, along with consequent impacts later in the season, is also related to the rise of anomalous easterly winds (Fig. 2).

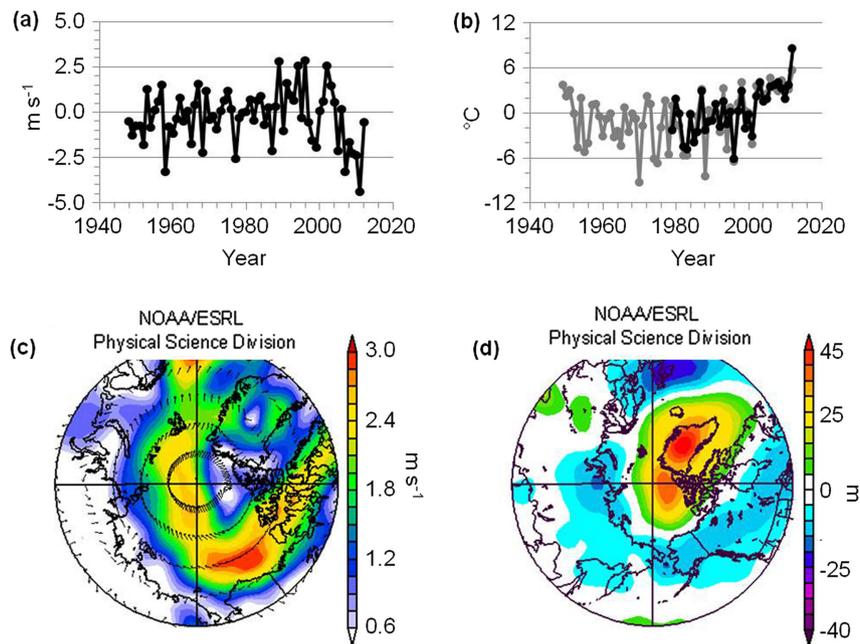
## Methods

Evidence collected from both newly developed and long-established environmental observing systems is used to develop a coherent picture of the fluctuations in the atmosphere and ocean, which have tended to shift the

Beaufort Sea climate away from once familiar seasonal patterns. We utilize in situ and satellite-derived ocean temperature measurements, sea-ice concentration and motion, wind and other meteorological variables extracted from NNR, Mackenzie River run-off and daily radiation climatology.

## Wave gliders

Crucial processes that regulate the flow of heat through the air–sea–ice interface in seasonal ice zones such as the Beaufort Sea have been difficult to quantify because it is such a challenge to make sustained measurements. One option currently under development is to use small, semi-autonomous surface vehicles to collect high-resolution data under difficult operating conditions like those found in the Arctic seasonal ice zone. In a first proof-of-concept experiment, the Pacific Marine Environmental Laboratory (PMEL) of the National Oceanic and Atmospheric Administration (NOAA) deployed two Liquid Robotics (Sunnyvale, CA) Wave Gliders in the Beaufort Sea for 54 days in 2011 (31 July–23 September). The Wave Gliders were equipped with six



**Fig. 2** Recent change in the Beaufort Sea. (a) US National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis data set (NNR) 925-hPa zonal wind anomaly (June–August) over the Beaufort Sea between 70 and 75°N, for the period 1948–2012. (b) Surface temperature anomaly at freeze-up (October) for the same time/region. The black line indicates the 1000-hPa over-ocean temperature from the National Centers for Environmental Prediction—Department of Energy Reanalysis 2 data set and for comparison the grey line is the Barrow temperature record from the Global Historical Climatology Network (Menne et al. 2012). (c) The 925-hPa vector wind anomaly over the Arctic since 2007, showing peak values over the Beaufort Sea. (d) An intensified Beaufort High as indicated by the 925-hPa geopotential height anomaly for the same interval. Anomalies are all based on the 1981–2010 standard climatology, and computed using the online utility (<http://www.esrl.noaa.gov/psd/>) of the Physical Sciences Division, Earth System Research Laboratory, National Oceanic and Atmospheric Administration.

thermistors spanning 0.5–6.0 m in depth. Temperature data have been corrected based on pre- and post-deployment comparisons with well-calibrated SBE-3 instruments (Sea-Bird Electronics, Bellevue, WA). A predetermined track was followed by both Wave Gliders at an average speed of 0.9 knots, with a 12–24 h interval separating them. The operating area north of the Alaskan Beaufort Sea continental shelf is shown in Fig. 1a. Additional hydrographic data collected on the 2011 Joint Ocean Ice Study on the CCGC *Louis S. St-Laurent* were provided by the Department of Fisheries and Oceans Canada. These data were used to confirm the temperature–salinity structure of the surface layer encountered by the Wave Gliders early in the deployment.

### Satellite imagery

All of the Moderate-resolution Imaging Spectroradiometer (MODIS) imagery of the summer Beaufort Sea that has been obtained since 2000 was reviewed to place in situ observations in spatial and temporal context. One hundred and sixteen SST/true-colour composite maps were produced from the beginning of the MODIS—Aqua satellite mission in 2002. An additional 88 MODIS-Terra true-colour images were obtained for 2000–01. The satellite imagery confirmed that the Wave Gliders were primarily operating in an extensive Mackenzie River plume in 2011 and allowed us to determine whether or not the plume was present in some other years, but due to the high degree of cloudiness over the region in summer the useful retrieval rate is only about 10%. This is not enough to allow for a complete analysis of the sea-surface environment based on satellite data alone, and it highlights the utility of continuous all-weather surface and sub-surface sampling provided by the Wave Glider.

### Wind and other data

NNR (Kalnay et al. 1996) and National Centers for Environmental Prediction—Department of Energy Reanalysis 2 data set (R-2; Kanamitsu et al. 2002) were used to investigate the monthly/seasonal zonal wind and other variables for the period 1948–2012. Monthly (June–October) sea-ice concentration and ice-free area was computed from passive microwave sea-ice concentration data from the National Snow and Ice Data Center (NSIDC 2012). Sea-ice motion in the Beaufort Sea was estimated using International Arctic Buoy Program (IABP) data (Rigor 2002). Zonal wind from NNR is well correlated with measured daily mean ice motion in the central Beaufort Sea in summer 2011 ( $r = -0.83$  at 1-day lag).

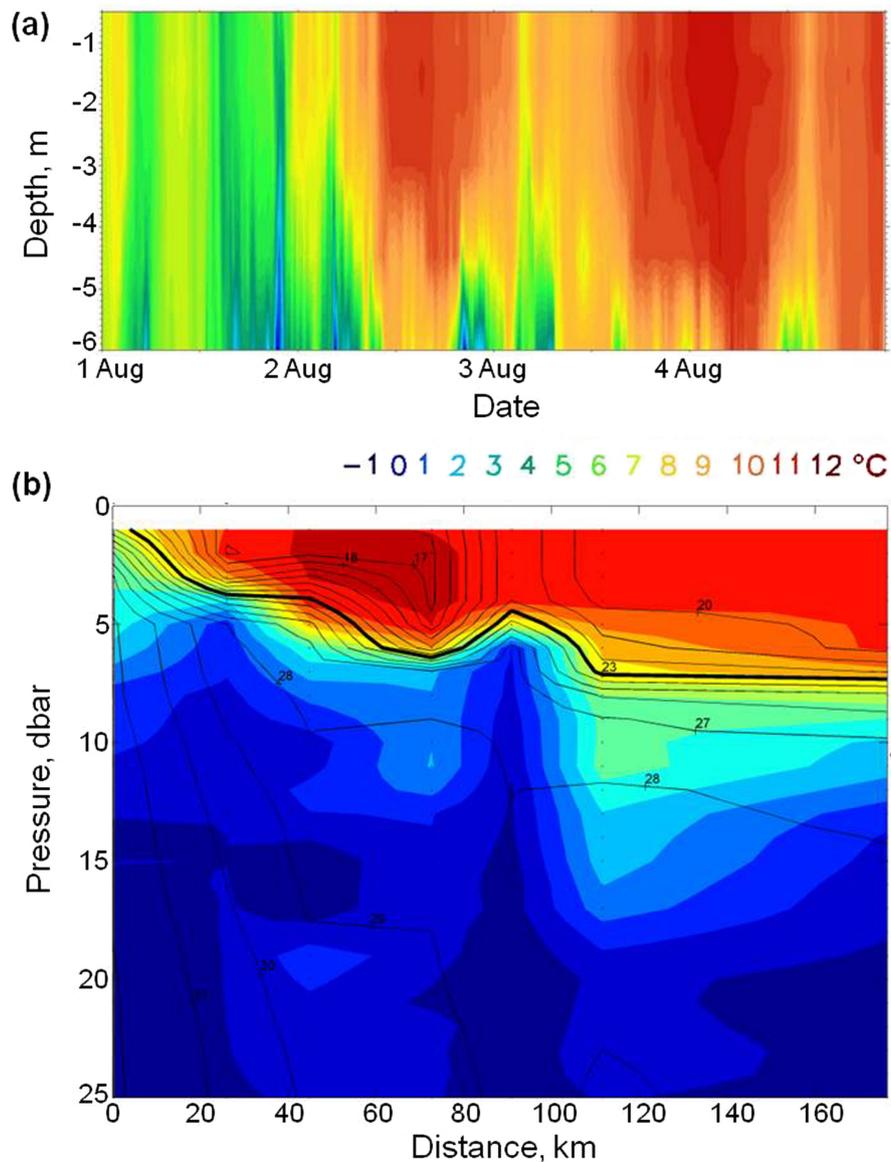
The inflow of freshwater run-off from the Mackenzie River into the Beaufort Sea was calculated from daily mean discharge records for the Mackenzie at Arctic Red River (station 10LC014, 1972–2010; 2011 preliminary) provided by Environment Canada (Environment Canada 1972–2010, 2011). Radiation data from the US Department of Energy Atmospheric Radiation Monitoring and the NOAA Global Monitoring Division observatories in Barrow, Alaska, were obtained and processed at the University of North Dakota (Dong et al. 2010). These data were used, in combination with ice concentration, to estimate the long-term change in energy absorbed by the surface ocean, following Perovich et al. (2007).

Wave Glider sea-temperature data and calibrations, satellite imagery, animations of sea-ice motion in 2011 and plume propagation in 2008, and maps of NNR variables are available at [www.pmel.noaa.gov/arctic/glider](http://www.pmel.noaa.gov/arctic/glider)

### Results

PMEL Wave Gliders were deployed in the Arctic for the first time in the summer of 2011. On 2 August an 11°C surface layer was detected over the continental shelf break, along with a sharp temperature contrast exceeding 8°C between the surface and 6 m depth (Fig. 3a). A review of MODIS SST and true-colour satellite imagery showed that the Wave Gliders had encountered the boundary of a large Mackenzie River discharge plume. In situ temperature observations from the Wave Gliders are consistent with satellite-derived SSTs from MODIS, but more importantly they provide uninterrupted high-resolution monitoring of an undisturbed surface layer at depths not seen by satellite, and above the reach of typical oceanographic moorings. Together the two sources indicate a 6–12°C surface layer associated with the plume that was at least 6 m thick and approximately 74 000 km<sup>2</sup> in extent. A hydrographic transect along 140°W obtained on 26–27 July from the Canadian ice-breaker CCGS *Louis S. St-Laurent* confirmed that the 6°C isotherm was generally  $\leq 8$  m deep and that it coincided with the strong salinity stratification that defines the base of the plume and summer polar mixed layer (Fig. 3b).

By the end of July 2011, an excess heat content of  $2.0\text{--}2.5 \times 10^{19}$  J had already accumulated in the surface layer associated with the Mackenzie plume (relative to a baseline temperature of  $-1.8^\circ\text{C}$ ). A well-stratified surface layer in the Beaufort Sea can warm very rapidly, especially on cloud-free days in late June and July when direct radiation can exceed  $300 \text{ W m}^{-2}$ . A striking example is provided by a rare 23-day sequence of MODIS images from July 2008 that shows heating rates in excess



**Fig. 3** Stratification associated with the Mackenzie River plume. (a) Wave Glider temperature section obtained on 1–4 August 2011 on the shoreward boundary of the plume at 147°W. (b) Hydrographic transect obtained 26–27 July along 140°W confirms the presence of a strongly stratified surface layer 6–8 m thick. Data from the 2011 Joint Ocean Ice Study carried out on the Canadian ice-breaker CCGC *Louis S. St-Laurent* and provided by the Department of Fisheries and Oceans Canada.

of  $0.5^{\circ}\text{C day}^{-1}$  (see the Supplementary File or [go directly to the animation](#)). This rate also implies that heating was distributed over an approximately 12-m-thick surface layer, consistent with plume depths observed along 140°W in 2011.

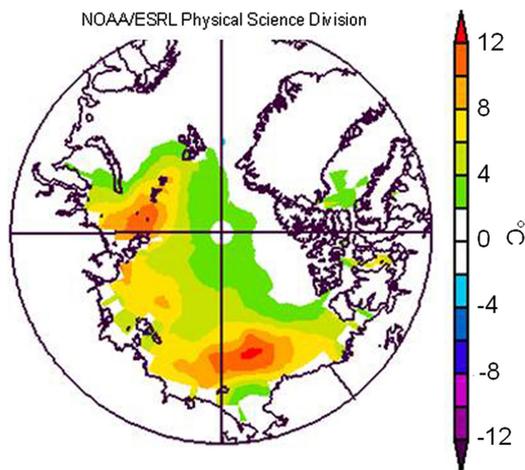
Entrainment of the Mackenzie River discharge under moving pack ice early in the summer can also help set the stage for rapid warming offshore later in the season. MODIS imagery from early June 2011 shows warm and discoloured water flowing under the westward-drifting ice pack. Given that freely moving sea ice amplifies the

effect of wind stress on the underlying water layer (Pite et al. 1995), it is certain that river water was carried along under the ice. Buoy data indicate that the ice pack was moving westward at a mean rate of  $15.1\text{ cm s}^{-1}$  (maximum  $28.6\text{ cm s}^{-1}$ ; Rigor 2002). Counting ca.  $55\text{ km}^3$  of fresh water impounded under coastal fast ice (Macdonald & Carmack 1991; Dean et al. 1994; Dunton et al. 2006), half of the total summer discharge ( $129\text{ km}^3$  of  $246\text{ km}^3$  in 2011) had already entered the Beaufort Sea by mid-July. Although sea-ice melt obviously contributes fresh water to the surface layer, there was

enough Mackenzie River water discharged under the ice cover of the Beaufort Sea early in the season to create a plume of the dimensions described here of an average thickness of 6–8 m and salinity of 20 psu.

Heat supplied directly by the Mackenzie River around break-up in late May and June melts and mobilizes the sea ice near the delta (Macdonald 2000), but as more area opens up offshore due to the combined effect of early melt and wind, solar radiation provides most of the heat in the surface layer. With about 80% more ice-free area compared to the 1981–2010 climatology, the Beaufort Sea south of 76°N has been absorbing much more shortwave radiation than in the past—an average of  $5.1 \times 10^{20}$  J (2007–11) compared to  $2.8 \times 10^{20}$  J during the reference period. This is roughly equivalent to the amount of heat advected through the Bering Strait annually (Woodgate et al. 2010), and is enough to melt about  $1.5 \times 10^6$  km<sup>2</sup> of 1-m-thick sea ice each year. How some of this heat is stored and later released in the autumn is modulated by the Mackenzie plume, as can be inferred from the patterns in the MODIS SST composites in Fig. 1. This warm water contributes directly to the formation of large mean surface temperature anomalies in the Beaufort Sea around freeze-up in September and October (Fig. 4).

Large fluctuations in the summer wind field over the Beaufort Sea provide a common thread linking sea-ice distribution (and ice-albedo feedback), surface stratification amplified by the westward advection of the Mackenzie River plume, higher ocean temperatures and the formation of persistent temperature anomalies that last well into the freeze-up period in the autumn.

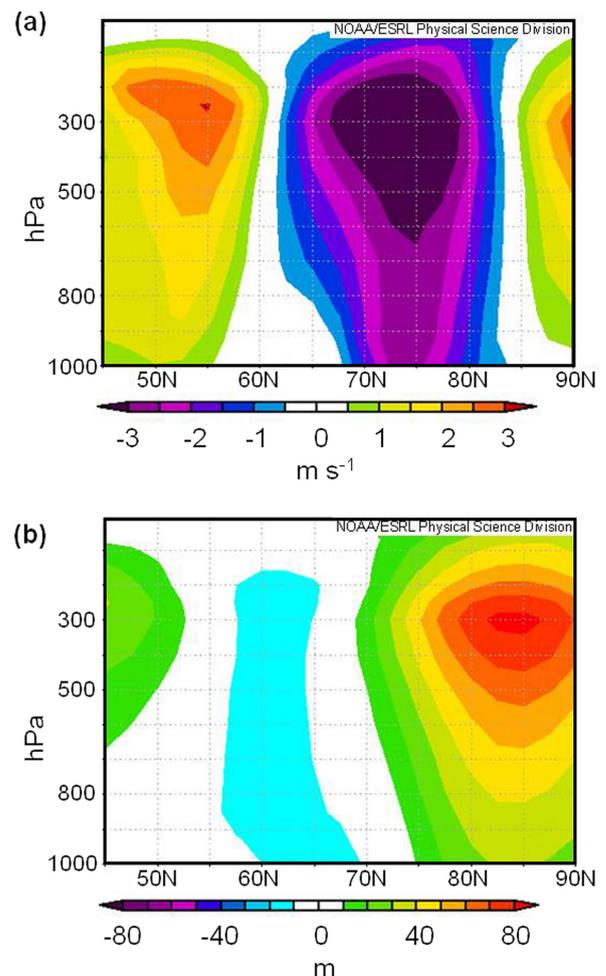


**Fig. 4** Unseasonable warmth at freeze-up. Mean US National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis data surface skin temperature difference in October for the period 2007–12 compared to climatology.

Easterly winds have been stronger and more frequent in this region since 2007 (Fig. 2a, c). These winds are linked to anomalous anticyclonic circulation around an intensified Beaufort High (Ogi & Wallace 2012; Fig. 2d), and the pattern is present throughout the entire depth of the troposphere, reaching a maximum at 300 hPa (Fig. 5). Thus, even though the maximum wind anomaly appears over the Beaufort Sea, it is more than a regional or atmospheric boundary layer phenomenon.

**Discussion**

The perception that a new normal climate is emerging in the Beaufort Sea is rooted in the combined impacts of large-scale anthropogenic warming, represented most clearly by the diminishing Arctic ice pack, and, in the



**Fig. 5** Anomalous winds over the Beaufort Sea. (a) Vertical cross-section of the mean summer zonal wind anomaly from the surface to 10 hPa along 150°W (June–August, 2007–12). (b) Geopotential height anomaly for the same cross-section and season.

Beaufort Sea, the immediate effects of anomalous easterly winds that promote additional sea-ice loss and rapid warming of the surface ocean, especially as amplified by the presence of a well-stratified surface layer produced by an extensive Mackenzie River plume. Relatively strong easterly winds have occurred on occasion over the Beaufort Sea in the past, notably in 1997–98, but there is no period in NNR equivalent to the most recent run of years. The easterly wind anomaly that has occurred lately is part of a deep Arctic-wide pattern of circulation around an intensified Beaufort High.

In the absence of easterly winds and a thinner sea-ice cover, the conditions for rapid surface warming of the Beaufort Sea are not established, and the sea and surrounding area remain relatively cool. When winds are westerly (as in 2002 and 2003, for example, and more often in the past) the ice pack stays closer to the coast, and the Mackenzie River plume is constrained to the continental shelf area, or drifts towards the east into the Canadian Arctic Archipelago (Macdonald & Yu 2006; Yamamoto-Kawai et al. 2009), and as shown by the example in Fig. 1c. In former times, when the ice pack was heavier, it would have been less mobile and less prone to blowing out, and would likely have further limited the movement of Mackenzie water off the continental shelf and to the west. While our historical knowledge of sea-ice conditions in the Beaufort Sea is incomplete, no evidence of a major reduction like 2007 and 2012 in the past 100–150 years has yet come to light (Mahoney et al. 2011; DMI & NSIDC 2012).

The summer of 2011 set the record for the seasonal mean NNR zonal wind anomaly over the Beaufort Sea ( $-4.4 \text{ m s}^{-1} / -2.6 \text{ SD}$  at 925 hPa). These winds caused the advection of both the sea ice and the Mackenzie River plume to the west. The large ice-free area that was created warmed rapidly due to positive ice-albedo feedback supported by strong stratification of the surface layer, in this case due to the plume, as recorded by the PMEL Wave Gliders and other observing systems. Anomalous heat content persisted into the autumn and contributed to the formation of very large surface temperature anomalies around freeze-up; a common occurrence over the past six years here and in other Arctic marginal seas.

It is still unclear how the additional heat input into the Arctic Ocean in recent years is ultimately partitioned (Perovich et al. 2007). Some of the heat absorbed in summer is stored in the ocean and later enters the deepening winter mixed layer where it can continue to melt sea ice during the winter (Steele et al. 2011; Jackson et al. 2012). Another fraction of this heat is released in the autumn, when it may perturb the large-scale atmospheric circulation. Extreme weather events

at mid-latitudes associated with more persistent weather patterns may be set up in this way (Overland & Wang 2010; Francis & Vavrus 2012).

Variants of the fast regional-scale processes that have contributed to the appearance of the “new normal” climate in the Beaufort Sea are probably typical in other Arctic marginal seas, and this may help explain why current climate models under-project the observed rate of sea-ice loss and environmental change in the Arctic. It is likely that gradual large-scale warming associated with anthropogenic forcing is relatively well represented (Mahlstein & Knutti 2012), but rapidly evolving regional interactions between the atmosphere, sea ice and ocean of the type described here may not yet be accounted for properly even by the latest models. In particular, the wind patterns seen recently appear to be well-suited to both remove multiyear ice from the Canadian Arctic Archipelago, where it has been historically concentrated into a warmer Beaufort Sea, as shown by the supplementary animation and consistent with early CryoSat-2 results reported by Laxon et al. (2013), and to accelerate the transport of sea ice from the western Arctic towards Fram Strait (e.g., Ogi & Wallace 2012).

The recent run of anomalous easterlies has undoubtedly contributed to the acceleration of sea-ice loss and surface warming in the Beaufort Sea and is likely to have significantly impacted the broader ecosystem, but can the arrival of a “new normal” climate be declared? The reason the summer Beaufort High has strengthened is largely unexplained (Ogi & Wallace 2012), and as we have shown, this is intimately linked to what has happened in the Beaufort Sea over the past few years. Overland et al. (2012) suggest that the anomalous easterlies are part of a larger climate pattern over North America previously recognized as the Arctic Dipole. However, until this question is answered uncertainty remains over the possibility of continued persistence. Nevertheless, it is clear that the overall decline of the Arctic sea ice has left the Beaufort Sea more susceptible to rapid warming than it has been in the past, and this has also magnified the potential for additional regional and far-field impacts that are only now becoming apparent. If the wind patterns seen lately are reinforced by changes in long-term climate forcing then the Beaufort Sea, already warm and mostly ice-free by late summer, will tend to remain that way.

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