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Wintertime warming of an Arctic shelf in response to large-scale atmospheric circulation

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[1] Observations on the West Spitsbergen Shelf have shown that the dynamic response of the shelf to wind forcing has a profound effect on the heat content of the water. Hydrographic and atmospheric data have been analysed with respect to the relative importance of surface heat fluxes and advective processes on ocean temperature. During the Arctic winter of 2005/06 periods of sustained along-shelf winds generated upwelling and cross-shelf exchange causing extensive flooding of the coastal waters with warm Atlantic Water from the West Spitsbergen Current. The winter temperature of the West Spitsbergen Shelf reverted to that typical of fall, interrupting the normal cycle of sea ice formation in the region. **Citation:** Cottier, F. R., F. Nilsen, M. E. Inall, S. Gerland, V. Tverberg, and H. Svendsen (2007), Wintertime warming of an Arctic shelf in response to large-scale atmospheric circulation, *Geophys. Res. Lett.*, *34*, L10607, doi:10.1029/2007GL029948.

1. Introduction

[2] It is widely understood that Arctic regions will experience amplified climatic change and there is growing evidence for this in many aspects of the high latitude environment [*Serreze and Francis*, 2006]. Sustained oceanic time series are revealing an increase in heat transport into the Arctic basin through Fram Strait [*Schauer et al.*, 2004; *Walczowski and Piechura*, 2006]. In general there has been rather sparse discussion of the mechanisms by which the Atlantic inflow interacts with the adjacent shelf areas, although *Dmitrenko et al.* [2006] illustrated the effect of wind forcing on the dynamics of the warm Atlantic layer at the Siberian slope.

[3] The major heat transport to the Arctic Ocean is through Fram Strait with the passage of Atlantic Water (AW) along the Svalbard margin in the West Spitsbergen Current (WSC) [*Schauer et al.*, 2004]. The Svalbard archipelago is situated in a climatically and oceanographically complex area. Warm AW in the WSC is generally isolated from the Arctic-type coastal waters by the Arctic Front [*Saloranta and Svendsen*, 2001]. Significantly, heat is lost from the WSC as it flows northward through communication with the West Spitsbergen Shelf (WSS) [*Saloranta and Haugan*, 2004]. Observations have shown that shelf-exchanges may occur through short term, localised eddy activity [*Nilsen et al.*, 2006] or extensive occupation of the shelf by AW in summer [*Cottier et al.*, 2005], thus switching the hydrography from an Arctic to an Atlantic dominated system.

[4] The inshore fjord waters of the WSS typically have a fast ice cover during winter [*Svendsen et al.*, 2002] although the link between the variations in ice cover and the local climate is not a simple one. Whilst there has been much interest recently in the magnitude [*Comiso*, 2006] and mechanisms [*Francis et al.*, 2005] of observed reductions in Arctic summer and winter sea ice extent, the discussions concerning these have been strongly biased towards atmospheric forcing. In locations such as the WSS where sea ice exists in close proximity to warm water masses, it is essential to consider the oceanic impacts on shelf hydrography.

[5] The Arctic winter of 2005/06 was notable for its relatively high air temperatures and minimal sea ice extent in the peripheral seas of the European Arctic [*Comiso*, 2006]. Specifically, the mid-winter air temperatures in Svalbard have been reported as anomalously high [*Walker*, 2006]. Whilst the extreme sea ice and atmospheric conditions reported for 2005/06 could be cited as an indicator for a step change toward a warming Arctic, we contribute to this debate by illustrating aspects of the complex interrelationship of the oceanic response to the regional forcing processes. Here we interpret oceanographic observations that show increasing shelf water temperatures during winter in the context of wind-induced coastal upwelling.

2. Data and Methods

[6] Monthly mean surface air temperature data were extracted from the NCEP/NCAR 2.5° grid reanalysis products [*Kalnay et al.*, 1996] over the NE Atlantic, Nordic Seas and Barents Sea sector for January and February for the years 1995–2006. Wind stress data over the same sector and periods were obtained from the Norwegian Meteorological Institute (met.no) hindcast database, every 6 hours at 75 km resolution. Wind stress data were also extracted from the met.no database for the period 1 October 2005 to 31 March 2006 for a grid point at 77.7°N and 8.2°E (Figure 1), which has been shown by correlation studies [*Floor*, 2006] to give a good dynamical representation of the wind stress field over the WSS.

[7] Hydrographic parameters at the inshore side of the WSS were recorded by two moorings during 2005/06. Mooring K was sited inside Kongsfjorden in 210 m water depth and Mooring I was outside the entrance to Isfjorden in 200 m, (Figure 1). Mooring K had 13 temperature sensors over the range 30–200 m to capture variation in the vertical temperature structure of the water column. Mooring I had a current meter with temperature sensor at 50 m. Current

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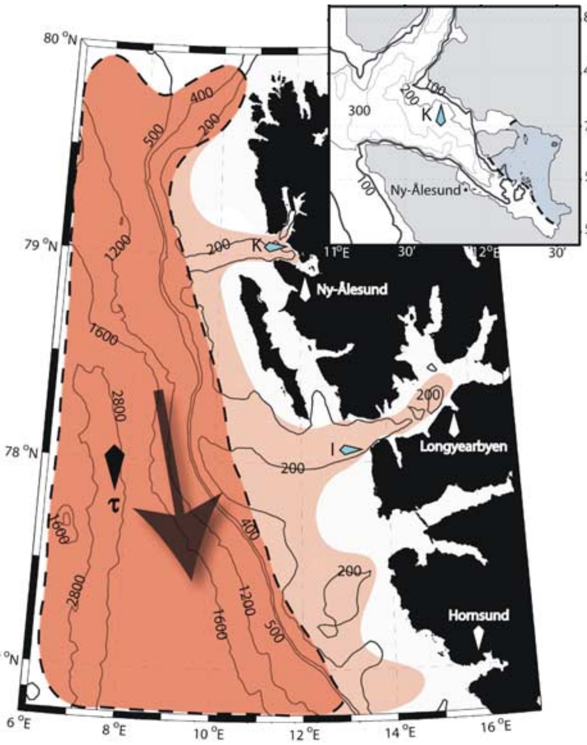

Figure 1. Bathymetric map of West Spitsbergen illustrating the spatial extent of the WSC at the shelf break (dark red) and the occurrence of AW on the shelf (pale red) during an upwelling situation with northerly winds (black arrow). Locations of moorings (blue), met. stations (white), and wind stress data point (black τ) are shown. The inset shows the area of Kongsfjorden (blue) most susceptible to fast ice formation during years of minimal ice extent.

vectors were resolved into two components; parallel and perpendicular to the isobaths. The cumulative displacement of water along the axis of the cross-shelf trench towards Isfjorden was calculated using the component of current parallel to the isobaths.

[8] To simulate the ocean-atmosphere interaction in Kongsfjorden, wind (10 m height), wet and dry bulb temperatures (2 m height) and observed cloud cover from Ny-Ålesund (Figure 1), were used to drive a 1-D ocean mixing model, the so-called 'PWP' model [*Price et al.*, 1986]. Surface heat flux boundary conditions were calculated by coupling the model sea surface temperature at each time step to bulk parameterisations for sensible and latent heat loss [*Fairall et al.*, 1996], and net longwave radiation [*Josey et al.*, 2003]. Wind stress was applied to the model mixed layer at each time step. The initial temperature and salinity profiles were derived from in situ observations made at mooring K. The model was run from 1 October 2005 to 31 March 2006 (Δt = 3 hours, Δz = 2 m). Throughout the model integrations the short wave radiant flux and surface fresh water flux were set to zero. During the winter the first assumption is clearly valid, the second assumption is a good approximation because winter discharge of freshwater in the locality is minimal [*Svendsen et al.*, 2002].

[9] Mean heat content per unit volume (H) of the water column was calculated for mooring K and for the 1-D model output relative to a reference water mass with S = 34.5 (mean salinity at mooring K in September 2005) and T = -1.89°C (freezing point for seawater with S = 34.5). Temporal records of sea ice extent have been constructed from daily visual observations (visibility-permitting) and recorded images of Kongsfjorden [*Gerland and Renner*, 2007].

3. Results

[10] The mean wind stress fields from 1995 to 2005 for January and February are shown in Figures 2a and 2b respectively. These fields are overlaid on the corresponding 11-year mean surface air temperature which show January air temperatures around Svalbard of -25°C and colder in February. The wind pattern is typical of a high North Atlantic Oscillation (NAO) index situation with a low pressure circulation around Iceland and a trough pattern crossing the Nordic Seas towards the Barents Sea. Wind stress over Svalbard and on the WSS has an easterly component in January (Figure 2a) but a weaker easterly component in February (Figure 2b).

[11] Wind stress fields for January and February 2006 are shown in Figures 2c and 2d overlaid on the 2006 surface air temperature anomaly. In January 2006 warm air was transported from the NE Atlantic due to exceptionally large and strong low pressure systems through the Nordic Seas. The greatest air temperature anomaly was centred east of Svalbard and air temperatures on the WSS were approximately 3–5°C warmer than the 11-year mean. In February the situation is reversed with Fram Strait being dominated by northerly winds.

[12] The northerly component of shelf wind stress at 77.7°N, 8.2°E and surface air temperature at Longyearbyen airport (Figure 1) are shown in Figure 3a. The wind stress was rather variable until 18 December when a sustained period of southerly winds and warming began. This situation switched dramatically on 24 January when northerly winds dominated and air temperatures decreased rapidly. Monthly mean air temperatures measured at Longyearbyen airport during December 2005 and January 2006 were typically 7 to 9°C greater than the 10-year mean whilst all other months from September to March were within the 99% confidence limits of the 10-year mean.

[13] The current data at mooring I (Figure 3b) show a persistent long-term flow towards Isfjorden, consistent with topographic steering of currents toward the fjord [see *Cottier et al.*, 2005, Figure 8]. On 24 January 2006 the mean inflow increased significantly from 8.4 km d^{-1} to 30 km d^{-1}. Water temperature at mooring I decreased during the fall and early winter, attaining a minimum by 22 December. Temperature then gradually increased but showed a large step-increase on 24 January followed by a further rise in temperature towards 3°C, the water mass demarcation for AW [*Swift*, 1986]. From mid-February, there was a rather rapid decrease in water temperature.

[14] The water temperature at mooring K is shown in Figure 4a. Of particular note is the large volume of water in October with temperature greater than 2°C. This relatively warm water is detected below 100 m throughout the winter

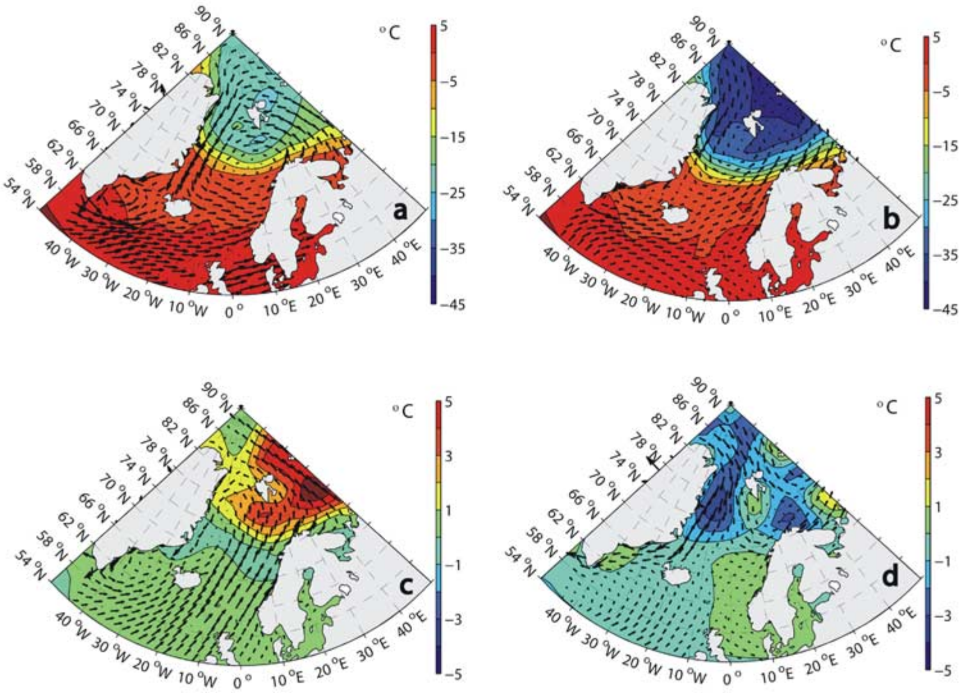

Figure 2. Mean wind stress fields and surface air temperature for the years 1995–2005 in (a) January and (b) February. Monthly mean wind stress fields for 2006 and the surface air temperature anomaly for 2006 compared to the years 1995–2005 in (c) January and (d) February.

and increases in volume during February. Through December and January the water column at location K comprised 2 layers with a distinct thermocline at 100 m. The increase in water temperature in February occurred first at intermediate depths and gradually extended to the surface water. At the end of February there was rapid cooling of the water column over the full depth.

[15] Figure 4b shows H over the depth interval 30–100 m for both mooring K and the 1-D model output. Mooring data show a rapid decrease in H around 1 November followed by rather steady cooling at a mean rate of -0.1 MJ m^{-3} d^{-1}. From 24 January, H increased rapidly at a rate of +0.4 MJ m^{-3} d^{-1} until 27 February when there was cooling over the full depth. Modelled H closely follows the observations until 24 January when there is marked divergence. The model mixed layer temperature on 24 January was -1.87°C, very close to the freezing point (-1.89°C). By January 27th, indicated by the arrow, the model mixed layer temperature was below the freezing point. Values of H from a rerun of the 1-D model, initialised on 27 February followed those calculated from mooring data.

4. Discussion

[16] We have shown data that capture the oceanic response to large scale atmospheric patterns for an Arctic shelf location. Specifically, we have presented a notable and counter-intuitive case of increasing water temperature during

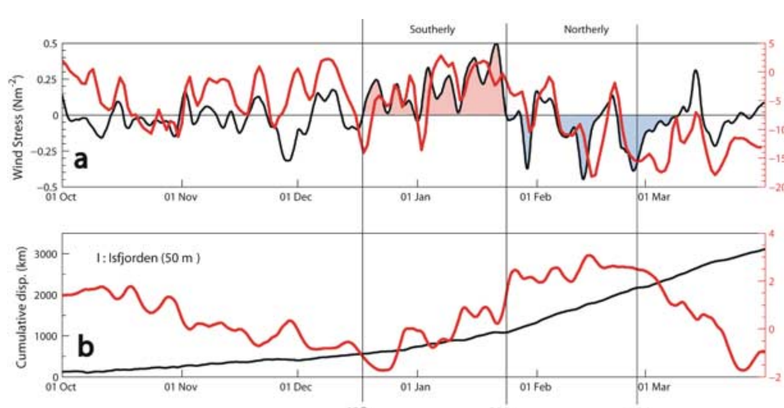

Figure 3. (a) Northerly component of wind stress (black) at 77.7°N, 8.2°E, and daily mean surface air temperature at Longyearbyen airport (red). (b) Cumulative displacement of water (black) and water temperature (red) at mooring I outside Isfjorden (positive values indicate inflow). A 3.5 day box filter has been applied to each series.

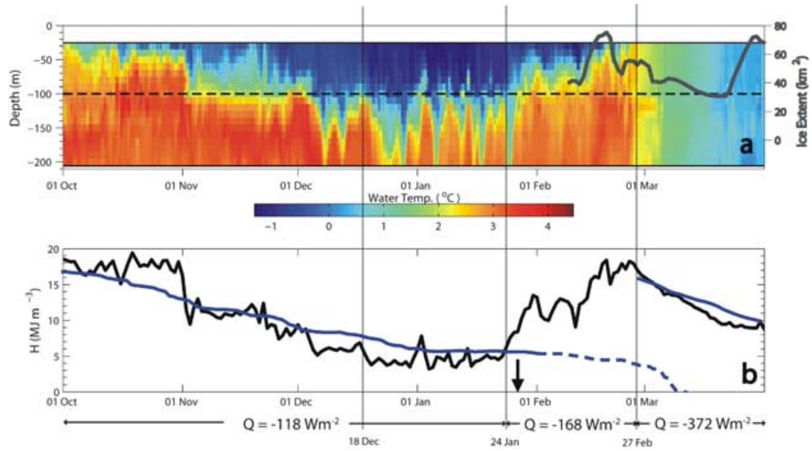

Figure 4. (a) Temperature profile at mooring K between 30 m and 200 m with H calculated over the interval 30–100 m (dashed line). The 7-day running mean of fast ice extent in Kongsfjorden (see Figure 1 inset) is overlaid (grey). (b) Mean heat content (H) from mooring K (black) and from the 1-D model (blue line – dashed when the model diverges from observations) with mean surface heat flux (Q). The model is reinitialised on 27 February 2006 and the arrow marks when the model predicts freezing.

a period of low air temperatures in February 2006. The pressure pattern for January 2006 was an extreme situation for the Eastern Arctic with a large, high-pressure system over Russia and Eastern Europe (not shown). This high tended to block the usual pathway of low-pressure systems to Norway and into the Barents Sea, instead directing them to Fram Strait and the Eurasian Basin. *Rogers et al.* [2005] examined the link between winter cyclone tracks through Fram Strait and the climate of Spitsbergen. They found during relatively mild winters an increased cyclone frequency over Fram Strait associated with anomalous high pressure over Scandinavia and the Barents Sea. Conversely, relatively cold winters had increased cyclone frequency in the Barents Sea. January and February 2006 (Figures 2c and 2d) resemble these warm and cold winter characteristics, respectively.

[17] It is clear that the temperature of water masses on the WSS will be influenced by the surface heat fluxes resulting from changes in air temperature in response to the switch in wind direction. Additionally, we hypothesise that the water masses on the WSS will act as a 2-layer system, in a manner similar to that described by *Dmitrenko et al.* [2006], with downwelling in January and upwelling in February with the potential for transport of AW across the shelf. Although the air temperature over Spitsbergen decreased after January 24 (Figure 3a) water temperatures on the shelf continued to rise. Consequently, the dynamic response to wind direction potentially has a greater effect on shelf water temperatures than changes in air temperature.

[18] From 24 January the wind situation, with strong northerly winds, sets up a favourable situation for upwelling. Significantly, both moorings recorded increases in water temperature (Figures 3b and 4a) and an increased inflow (Figure 3b) commencing on 24 January. These observations are consistent with upwelling of AW from the core of the WSC, from depths down to ∼500 m [*Saloranta and Svendsen*, 2001], and its advection across the WSS and into the fjords. This warm inflow continued until the end of February at both Isfjorden and Kongsfjorden.

[19] Both moorings also recorded pulses of warm inflow during the period of predominantly southerly winds from 17 December to 24 January (Figures 3b and 4a). In a 2-layer system southerly winds over the shelf will tend to force surface water to stack up against the coast [*Klinck et al.*, 1981] developing a pressure gradient force in the offshore direction. When the southerly winds relax, the pressure gradient will move surface water offshore thus generating a compensating onshore transport in the lower layer with warmer, Atlantic-type water detected at the mooring positions. We can interpret the large, stepwise temperature jump on January 24 in Figure 3b as the concerted effects of pressure gradient relaxation and northerly wind upwelling.

[20] Figure 4b shows a close correspondence in H between the mixing model and the Kongsfjorden mooring data until 24 January 2006. This indicates that the fjord cooled in a broadly 1-D sense with a mean surface heat flux (Q) of -118 W m^{-2}. From 24 January to 27 February, Q increased to -168 W m^{-2}, yet water temperatures increased at intermediate depths producing a rapid rise in observed H. Figure 4b shows that during February the waters in the fjord, and potentially the entire shelf, reverted to H values typical for fall. The marked divergence commencing 24 January of the observed H from that calculated with the model is interpreted as the coastal system switching from a simple 1-D atmospheric heat loss state to a 2-D oceanic heat advection state. This supports the assertion of upwelling and shelf exchange occurring over the entire WSS – shown schematically in Figure 1.

[21] Through advection of AW the water column became more weakly stratified such that after 27 February there was rapid cooling (also seen in Figure 3b), with Q = -377 W m^{-2}. During this period the water column appeared to return to a 1-D system. To test this hypothesis, the 1-D mixing model was initialised for 27 February and integrated forward with the same boundary conditions described above. Again, the observed and modelled H values correspond closely, confirming 1-D cooling of the fjord. A CTD survey crossing the shelf west of Kongsfjorden from 25–26 April 2006 found evidence of the winter advection, where mean H on the shelf was 9.3 MJ m^{-3} in the interval 30–100 m (cf. March values in Figure 4a).

[22] Clearly, advection of AW and a return to pre-winter temperatures will impact on local sea ice formation. Figure 4a shows the extent of fast ice over the inner part of Kongsfjorden (blue area in Figure 1 inset map). In 2006 ice formation was restricted to the shallow, protected part of the fjord only. Extent of relatively stable fast ice never exceeded 80 km^{-2} which is typical of spring (May–June) extent in normal ice growth years [*Gerland and Renner*, 2007]. Extent increased at the beginning of February in response to decreasing air temperatures and gradually decreased as the enhanced heat contained in the water column was released at the surface. Despite the low regional air temperatures, we infer that heat released over the entire shelf system prevented ice formation. Ice reformed again in mid-March when air temperatures dropped. A critical contrast between winter 2005/06 and those during the preceding decade was a lack of stable fast ice cover on the southern shore of Kongsfjorden.

[23] We have demonstrated the importance of wind-driven shelf exchange processes in determining the hydrographic conditions on the West Spitsbergen Shelf. The extreme atmospheric conditions during the winter of 2005/06 illustrate the transition in a 2-layer coastal system from 1-D cooling, to warming through advection and then returning to 1-D cooling in response to forcing by shelf winds. Whilst rather intuitive, we regard this as an important shelf exchange process that is particularly relevant in the Eurasian Arctic by virtue of the distinct topographically steered AW core present at the shelf break. It is important to note that sea ice conditions in such areas will be strongly controlled by interactions with both the atmosphere and ocean.

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