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Spatial distribution of air-sea heat fluxes over the sub-polar North Atlantic Ocean

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[1] On a variety of spatial and temporal scales, the energy transferred by air-sea heat and moisture fluxes plays an important role in both atmospheric and oceanic circulations. This is particularly true in the sub-polar North Atlantic Ocean, where these fluxes drive water-mass transformations that are an integral component of the Atlantic Meridional Overturning Circulation (AMOC). Here we use the ECMWF Interim Reanalysis to provide a high-resolution view of the spatial structure of the air-sea turbulent heat fluxes over the sub-polar North Atlantic Ocean. As has been previously recognized, the Labrador and Greenland Seas are areas where these fluxes are large during the winter months. Our particular focus is on the Iceland Sea region where, despite the fact that water-mass transformation occurs, the winter-time air-sea heat fluxes are smaller than anywhere else in the sub-polar domain. We attribute this minimum to a saddle point in the sea-level pressure field, that results in a reduction in mean surface wind speed, as well as colder sea surface temperatures associated with the regional ocean circulation. The magnitude of the heat fluxes in this region are modulated by the relative strength of the Icelandic and Lofoten Lows, and this leads to periods of ocean cooling and even ocean warming when, intriguingly, the sensible and latent heat fluxes are of opposite sign. This suggests that the air-sea forcing in this area has large-scale impacts for climate, and that even modest shifts in the atmospheric circulation could potentially impact the AMOC. **Citation:** Moore, G. W. K., I. A. Renfrew, and R. S. Pickart (2012), Spatial distribution of air-sea heat fluxes over the sub-polar North Atlantic Ocean, *Geophys. Res. Lett.*, *39*, L18806, doi:10.1029/2012GL053097.

1. Introduction

[2] The exchange of heat, freshwater and momentum across the air-sea boundary represents an important coupling between the ocean and atmosphere. The energy transferred by these fluxes plays a crucial role, on a variety of spatial and temporal scales, in the atmospheric and oceanic circulation. Over the sub-polar North Atlantic Ocean, it is through these fluxes that the atmosphere drives water-mass transformations that are an integral component of the AMOC [*Mauritzen*, 1996]. As so elegantly expressed by *Aagaard and Carmack* [1989], the marginal seas of the sub-polar North Atlantic Ocean are '*delicately poised with respect to their availability to sustain convection*' and so it follows that it is important to document the magnitude and the variability in the air-sea fluxes in this region. Please see Figure S1 in the auxiliary material for place names.[1]

[3] Direct measurements of air-sea fluxes have been limited to small spatial domains and/or relatively short periods of time that do not allow for a complete characterization of their temporal and/or spatial variability. Furthermore, over the sub-polar North Atlantic Ocean, studies presenting direct observations are relatively rare [*Bumke et al.*, 2002; *Persson et al.*, 2005; *Petersen and Renfrew*, 2009]. Heat flux climatologies based on the extensive archives of ship observations have been developed but are constrained at higher latitudes by the scarcity of surface observations [*Bunker*, 1976; *Berry and Kent*, 2009]. An alternative is to use reanalyses fields, which are a blend of atmospheric observations and short-term model forecasts, to characterize the temporal and spatial variability in the air-sea heat fluxes [*Moore and Renfrew*, 2002; *Renfrew et al.*, 2002; *Roberts et al.*, 2012]. For the sub-polar North Atlantic Ocean, the quantity and quality of the observational data going into the reanalysis is high and so they provide an excellent characterization of the surface heat fluxes associated with particular synoptic-scale weather patterns.

[4] In this paper we use the Interim Reanalysis (ERA-I) from the European Centre for Medium-Range Weather Forecasts (ECMWF) [*Dee et al.*, 2011] to document the wintertime characteristics of the air-sea fluxes of sensible and latent heat over the sub-polar North Atlantic Ocean. Particular emphasis is placed on the region of the Iceland Sea (Figure S1) where water-mass transformation is known to occur [*Swift and Aagaard*, 1981], yet little is known about the atmospheric forcing. The surface fields and the air-sea heat fluxes from the ERA-I reanalysis, its predecessor the ERA-40, and the operational ECMWF analysis with whom it shares common surface layer and surface exchange parameterizations, have been validated against observations in a number of the sub-polar North Atlantic's regions [*Renfrew et al.*, 2002, 2009; *Harden et al.*, 2011].

2. Methods

[5] For this study, we used the 6-hourly sea-level pressure, 10 m wind, 2 m air temperature, surface temperature, and sea ice concentration fields as well as the turbulent surface fluxes of sensible and latent heat from the ERA-I. The fluxes in the ERA-I are forecast fields and we have chosen to use

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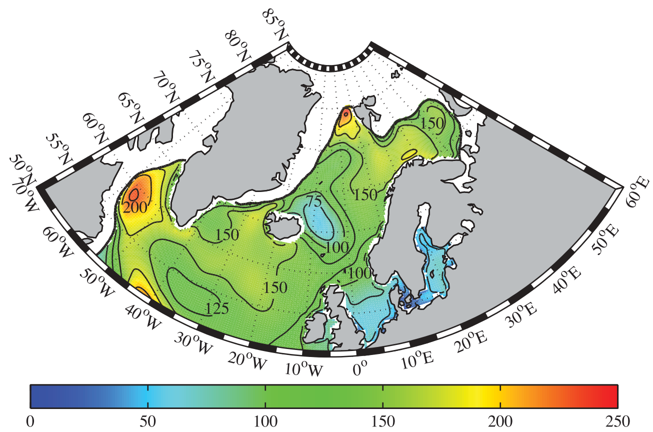

Figure 1. Winter mean (DJFM) climatology of the total turbulent heat flux (W/m^2- contours and shading) from the ERAI 1979–2012. The thick black line represents the 25% winter mean ice concentration isocontour.

6-hourly averages to represent them [*Harden et al.*, 2011]. We use the convention that a positive heat flux is directed from the ocean into the atmosphere. The data are available at a horizontal resolution of 0.75°. For this work, monthly mean averages were computed from the 6-hourly data for the winter months, defined as December, January, February and March for the period from 1979–2012.

3. Results

[6] Figure 1 shows the winter mean total turbulent heat flux, defined as the sum of the sensible and latent heat fluxes, over the sub-polar North Atlantic Ocean. The field is only shown over ice-free regions, i.e., where the sea ice concentration is less than 25%. The entire region can be seen to have a positive total turbulent heat flux indicating that during the winter there is a net transfer of heat from the ocean into the atmosphere. Offshore of the ice-edges in the Labrador and northern Greenland Seas are local maxima in excess of 200 W/m^2. There are also local maxima in the Barents Sea and off the North Cape of Norway. Equally striking are two regions where there are local minima. The most pronounced of these is located in the vicinity of the Iceland Sea where the winter mean total turbulent heat flux is less than 75 W/m^2. There is second minimum near 55°N, 35°W where it is less than 125 W/m^2.

[7] The winter mean structure of the sea-level pressure, 10 m wind field, and 2 m air temperature field (Figure 2) shed light on the heat flux distribution. The Icelandic and Lofoten Lows as well the trough that connects them are evident in the pressure field. The cyclonic circulation associated with the Icelandic Low advects cold air over the Labrador Sea and warm air northwards towards Scandinavia. The cyclonic circulation associated with the Lofoten Low advects cold air over the Greenland Sea that is associated with barrier flow along the northeast coast of Greenland [*Harden et al.*, 2011]. The sea-surface temperature also plays an important role in determining the magnitude of the air-sea fluxes, and this field is also shown in Figure S1. The intrusion of warm, subtropical-origin water northwards along the west coast of Scandinavia is evident as are the colder sea-surface temperatures associated with the East Greenland and Labrador Currents. The Iceland Sea is also a region of relatively cold sea surface temperatures associated with water that has spread eastwards from the East Greenland Current [*Jonsson*, 2007].

[8] The minimum in winter mean total turbulent heat flux in the Iceland Sea region is co-located with the saddle point in sea-level pressure between the Icelandic and Lofoten Lows, as well as being in the vicinity of the cold surface waters originating from the East Greenland Current. The saddle point is also a region where the mean wind is small in magnitude. The dominance of the Icelandic Low over the Lofoten Low in the long-term mean results in surface air temperatures over the Iceland Sea that are significantly higher than in other regions such as the Labrador and Greenland Seas.

[9] *Jahnke-Bornemann and Brümmer* [2009] document a see-saw in the strength of the Icelandic and Lofoten Lows that should impact the sense of the atmospheric flow over the Iceland Sea region, thereby acting to modulate the magnitude of the air-sea heat fluxes in the region. To test this hypothesis, we identified all winter months (DJFM) during the period 1979–2012 in which the monthly mean total heat flux in the Iceland Sea minimum identified in Figure 1 was either less than the 10th percentile value (~10 W/m^2) or greater than the 90th percentile value (~100 W/m^2). The 10th percentile composite included the 11 months that are indicated in Table S1; while the 90th percentile composite included the 15 months that are indicated in Table S2. Composites of the total turbulent heat flux for these two populations are shown in Figure 3.

[10] The 10th percentile composite (Figure 3a) shows a region of low total turbulent heat flux that extends across the Iceland and southern Greenland Seas. The minimum in the region of the Iceland Sea is negative indicating that there is a transfer of heat from the atmosphere to the ocean. Table 1 indicates that this is the result of a negative sensible heat flux and this leads to a negative Bowen Ratio in the region (Figure S2). In addition, the total turbulent heat flux across the northern Greenland and Barents Seas is reduced from the climatological mean, while it is above the climatological

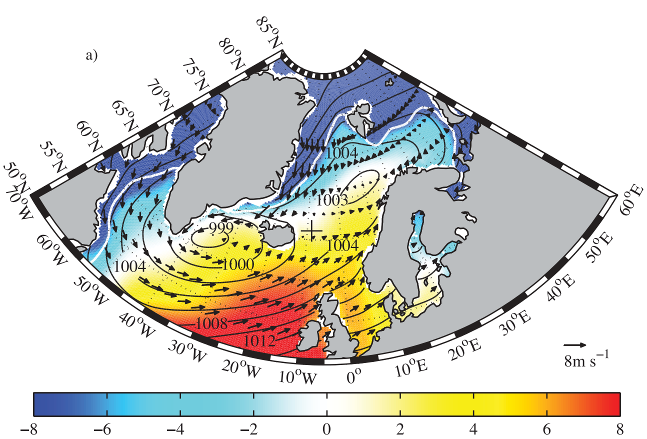

Figure 2. Winter mean (DJFM) climatology of the sea-level pressure (mb-contours); the 10 m wind (m/s-vectors) and the 2 m air temperature (°C-shading). The thick white line represents the 25% winter mean ice concentration isocontour. The '+' denotes the location in the Iceland Sea where there is a relative minimum in the total turbulent heat flux.

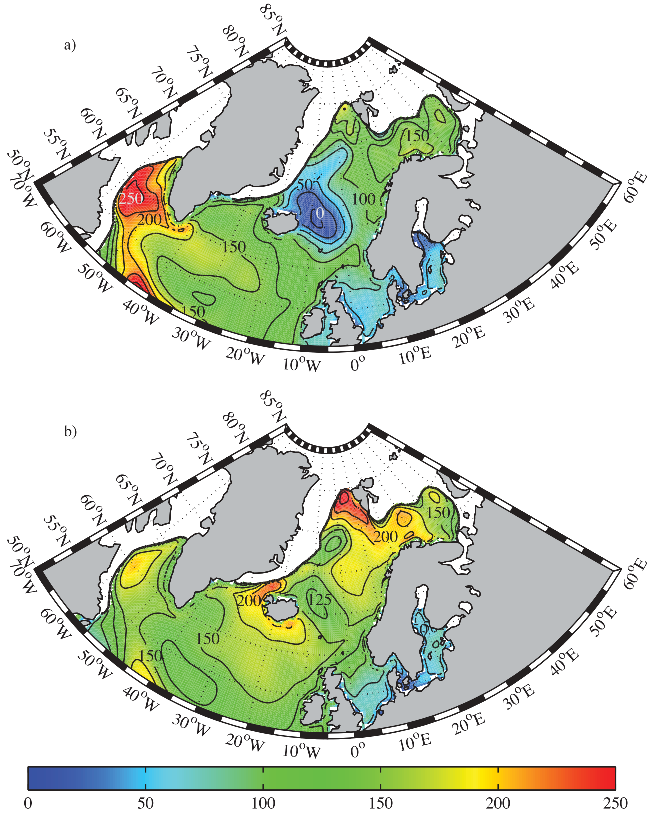

Figure 3. Composite monthly mean total turbulent heat flux (W/m^2- contours and shading) for winter months (DJFM) during which the total turbulent heat flux at the Iceland Sea site is in the: (a) 10th or (b) 90th percentile. The thick black line represents the 25% winter mean ice concentration isocontour.

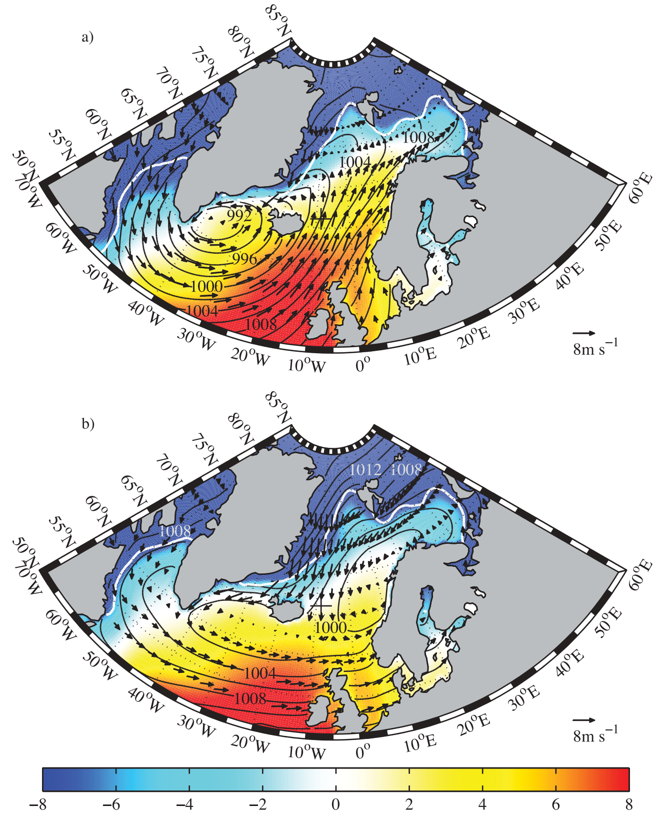

Figure 4. Composite monthly mean sea-level pressure (mb-contours); 10 m wind (m/s-vectors) and 2 m air temperature (°C-shading) for winter months (DJFM) during which the total turbulent heat flux at the Iceland Sea site '+' is in the: (a) 10th or (b) 90th percentile. The '+' denotes the location in the Iceland Sea where there is a relative minimum in the total turbulent heat flux. The thick white line represents the 25% winter mean ice concentration isocontour.

mean across the Labrador Sea is. There is also evidence of an elevated total turbulent heat flux in the Cape Farewell region.

[11] The 90th percentile composite (Figure 3b) shows a general reversal in the magnitude of the total turbulent heat fluxes across the sub-polar North Atlantic Ocean: the Greenland, Barents and Norwegian Sea fluxes are above the mean, whereas the Labrador Sea flux is below the wintertime mean. Over the Iceland Sea the total heat flux is in excess of 100 W/m^2 and both the sensible and latent heat fluxes are positive as is the Bowen Ratio (Table 1 and Figure S2). There is also a local maximum in the Denmark Strait as well as the North Cape region of Norway.

[12] The corresponding composites of the sea-level pressure, 10 m wind and 2 m temperature fields for these two populations are shown in Figure 4 with values at the Iceland Sea site provided in Table 1. A low monthly mean total turbulent heat flux over the Iceland Sea is seen to be associated with a deeper than usual Icelandic Low and more intense cyclonic circulation (Figure 4a). This results in enhanced northwesterly flow over the Labrador Sea and pronounced southerly flow over the Nordic Seas resulting in warmer surface air temperatures over the Iceland Sea (Table 1). In contrast, a high monthly mean total turbulent

Table 1. Values of Pertinent Surface Layer and Air-Sea Flux Parameters for the Iceland Sea Location[a]

	Climatological Mean	Low Heat Flux Composite	High Heat Flux Composite
Sea-level pressure Icelandic Low	998 mb	991 mb	1000.5 mb
Sea-level pressure Lofoten Low	1002 mb	1007mb	998.5 mb
Meridional component of 10 m wind	0.2 m/s	4.8 m/s	−3.2 m/s
Zonal component of 10 m wind	0.4 m/s	0.4 m/s	−0.3 m/s
2 m Air Temperature	1.3°C	2.9°C	0.4°C
Sea Surface Temperature	2.3°C	2.1°C	3.0°C
Air-Sea Temperature Difference	−1.0°C	0.9°C	−2.6°C
Sensible Heat Flux	16 W/m^2	−16 W/m^2	46 W/m^2
Latent Heat Flux	41 W/m^2	10 W/m^2	70 W/m^2
Total Turbulent Heat Flux	57 W/m^2	−6 W/m^2	116 W/m^2

[a]Winter mean values are shown as well as values for the low and high heat flux composite cases.

heat flux over the Iceland Sea is associated with a weaker than usual Icelandic Low and an anomalously deep Lofoten Low (Figure 4b). The weaker cyclonic circulation associated with the Icelandic Low when coupled with the stronger cyclonic circulation associated with the Lofoten Low results in enhanced northerly flow over the Greenland, Barents and Iceland Seas that advects colder air into these regions (Table 1), as well as weaker northwesterly flow over the Labrador Sea.

4. Discussion

[13] Modern meteorological reanalyses are now able to provide climatological fields of air-sea turbulent heat fluxes that are at high enough resolution to provide detailed information for the individual seas of the subpolar North Atlantic Ocean. These fields have been verified through comparisons against observations and, given their similarity to the operational forecast model (in terms of parameterizations), can also be considered to be reliable, robust and regularly subject to comprehensive verification. On the whole, the presented air-sea flux fields confirm results from earlier studies [*Moore and Renfrew*, 2002; *Yu and Weller*, 2007; *Berry and Kent*, 2009]. In this region the ocean generally loses heat to the atmosphere with prominent local maxima offshore of ice-edges in the Labrador and Greenland Seas. However, for the first time we have elucidated the nature of the local minimum in the winter mean total turbulent heat flux situated in the Iceland Sea. While this feature was present in previous climatologies [*Moore and Renfrew*, 2002; *Yu and Weller*, 2007], it was not commented upon nor examined.

[14] We have shown that the Iceland Sea minimum in total turbulent heat flux is the result of several factors: the saddle point in the sea-level pressure field in the region that results in low mean wind speeds (Figure 2), the relatively warm mean surface air temperatures (Figure 2), and the relatively cold mean sea surface temperatures emanating from the East Greenland Current (Figure S1). All of these combine to produce the reduced magnitude of the mean total turbulent heat flux.

[15] However, by considering winter months in which the monthly mean total turbulent heat flux at the Iceland Sea site was either anomalously low or high, we have identified two distinct circulation regimes that result in low or high heat fluxes at this site (Figure 3). In the low heat flux regime, the Icelandic Low is stronger than usual while the Lofoten Low is weaker than usual (Figure 4a). This leads to enhanced cyclonic circulation and strong southerly flow across the Iceland Sea resulting in warm air advection. Indeed, the sensible heat flux is negative in this region (i.e., the atmosphere is warmer than the ocean) contributing to the low total heat flux (Figure 4b). In the high heat flux regime, the relative strengths of the Icelandic and Lofoten Lows are reversed, leading to northerly flow over the Iceland Sea and resulting in cold air advection (Table 1). The identified minimum in mean total turbulent heat flux is therefore the result of the juxtaposition of these two markedly different states.

[16] It is interesting to note that the high heat flux regime occurs more often in the early part of the ERA-I record, while the low heat flux regime occurs more often in the later part of the record (Tables S1 and S2). This suggests that there may be a trend towards lower total turbulent heat fluxes; an investigation of this will be the subject of future work.

[17] A see-saw in the relative strengths of the Icelandic and Lofoten Lows has been documented previously [*Jahnke-Bornemann and Brümmer*, 2009] but its impact on air-sea interaction in the sub-polar North Atlantic Ocean is a new result that suggests that modes of low-frequency variability other than the North Atlantic Oscillation [*Dickson et al.*, 1996] may play a role in modulating the air-sea interaction in the region. Indeed, low-frequency variability in the structure the sea-level pressure field that mimics this see-saw has been noted in studies that focus on the interaction between the North Atlantic Oscillation and other teleconnections such as the East Atlantic and Scandinavian patterns [*Moore et al.*, 2011; *Moore and Renfrew*, 2012].

[18] The results of this study indicate that air-sea interaction over the sub-polar North Atlantic Ocean is more nuanced that previously thought. While water-mass transformation is known to occur in the Iceland Sea, typical winter mixed-layer depths there are only on the order of 200 m, far less than has been measured in the Labrador and Greenland Seas [*Swift and Aagaard*, 1981]. This is consistent with the moderate air-sea forcing northeast of Iceland described here. However, the doming of isopycnals associated with the cyclonic flow of the Iceland Sea Gyre means that dense water resides at relatively shallow depths, and implies that even moderate air-sea forcing in winter can form water as dense as North Atlantic Deep Water. *Våge et al.* [2011] have argued that the Iceland Sea is the source region for the densest component of the Denmark Strait Overflow Water which feeds the Deep Western Boundary Current. This suggests that the air-sea forcing in this area has large-scale impacts for climate, and that even modest shifts in the atmospheric circulation could potentially impact the lower limb of the AMOC.

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