GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L06601, doi:10.1029/2007GL032971, 2008

Atmospheric conditions associated with oceanic convection in the south-east Labrador Sea

David A. J. Sproson,[1] Ian A. Renfrew,[1] and Karen J. Heywood[1]

Received 11 December 2007; revised 5 February 2008; accepted 13 February 2008; published 18 March 2008.

[1] It has been speculated that low-level reverse tip-jets, caused by the interaction of synoptic-scale atmospheric flow and Greenland, are an important mechanism for forcing open ocean convection in the south-east Labrador Sea. Here float data and meteorological reanalysis fields from the winter of 1996/1997, in combination with a simple mixed-layer ocean model, are used to show that, although relatively deep ocean convection did occur during this winter, the primary forcing mechanism was cold-air outbreaks from the Labrador coast rather than the smaller scale reverse tip-jets. During this winter, the North Atlantic Oscillation (NAO) was in a weak positive phase. Similar treatments of the winters of 1994/1995 (strong, positive NAO) and 1995/1996 (strong, negative NAO) suggest that the result is robust regardless of the state of the NAO.

Citation: Sproson, D. A. J., I. A. Renfrew, and K. J. Heywood (2008), Atmospheric conditions associated with oceanic convection in the south-east Labrador Sea, *Geophys. Res. Lett.*, *35*, L06601, doi:10.1029/2007GL032971.

1. Introduction

[2] The interaction of the steep, high topography of Greenland and synoptic and smaller scale cyclones causes a number of intense, small scale wind phenomena around the coast of Greenland. The first of these, so-called ‘tip-jets’ [*Doyle and Shapiro*, 1999], are low-level westerly jets emanating from Cape Farewell characterized by a small meridional extent of around 200 km, a zonal extent of up to 1000 km and surface wind speeds generally exceeding 25 m s^{-1} [*Moore and Renfrew*, 2005]. In addition, an easterly ‘reverse tip-jet’ was later suggested by NCEP reanalysis [*Moore*, 2003]. A climatology of high wind speed events using QuikSCAT-derived surface winds [*Moore and Renfrew*, 2005] showed that both tip-jets and reverse tip-jets were common wintertime features. *Doyle and Shapiro* [1999] noted that there were often extremely high ocean to atmosphere heat fluxes associated with these events, up to around 800 W m^{-2}, possibly with significant effects on the ocean below.

[3] Ocean observations [*Lavender et al.*, 2000] revealed recirculations and relatively deep mixed-layers indicative of open ocean convection in the Irminger and south-east Labrador Seas. Such circulations are important in preconditioning the ocean for convection [*Marshall and Schott*, 1999], doming up isopycnals, so exposing more weakly stratified water to the atmospheric forcing, as well as isolating the water column, thus allowing repeated modification by the atmosphere. This, together with the enhanced heat fluxes associated with the Greenland tip-jet, rekindled interest in the Irminger Sea as a possible convection site, with potentially important implications for the meridional overturning circulation [*Pickart et al.*, 2003a, 2003b; *Bacon et al.*, 2003; *Centurioni and Gould*, 2004].

[4] In an idealized modeling study, *Pickart et al.* [2003a] used a climatological representation of the tip-jet and a simple representation of Greenland to show that the tip-jet was important both in the preconditioning of the model ocean through the provision of cyclonic wind stress curl and in the triggering of deep convection up to 1800 m, supporting theories that deep water formation does take place in the Irminger Sea [*Pickart et al.*, 2003b].

[5] Wintertime observations of mixed-layer depth in the Irminger Sea are relatively scarce, due largely to the inhospitable winter conditions in the area. However, direct measurements in the winters of 2002/2003 and 2003/2004 [*Våge et al.*, 2008] showed mixed-layers deepening to around 400 m before the onset of restratification during the spring. During these winters, the North Atlantic Oscillation (NAO) index was not strongly positive, reducing the number of robust tip jets [*Moore*, 2003]. A one dimensional mixed-layer model [*Price et al.*, 1989] was able to reproduce the deepening of the mixed-layer. However if the signature of the tip-jets was removed from the forcing fields, the mixed-layer only deepened to around 300 m [*Våge et al.*, 2008]. Application of the same model to the high NAO winter of 1994/1995 showed a deepening of the mixed-layer exceeding 1600 m with the tip-jet signature present, and only around 1200 m once the signature had been removed [*Våge et al.*, 2008]. Thus it is clear that tip-jets have a strong influence on ocean processes in the Irminger Sea.

[6] An important question, first raised by *Moore and Renfrew* [2005], which currently remains unanswered is whether reverse tip-jets have a similar such effect on the south-east Labrador Sea. A simulation of one of the strongest reverse tip-jets identified by *Moore and Renfrew* [2005], using a high resolution atmosphere only model, showed fairly strong heat fluxes, up to 250 W m^{-2} in the core of the jet, in the vicinity of the south-east Labrador recirculation [*Martin and Moore*, 2007]. An examination of buoyancy flux through the surface of the ocean led *Martin and Moore* [2007] to speculate that reverse tip-jets could indeed be important in the deepening of the mixed-layer. *Pickart et al.* [2008] also speculate on the possibility that reverse tip-jets have an impact on deep water formation, though they note that the air in the jets may be too modified to strongly affect the ocean. In this study we present an analysis of heat fluxes in the ECMWF ERA-40 dataset over

---

[1] School of Environmental Sciences, University of East Anglia, Norwich, UK.

0094-8276/08/2007GL032971$05.00

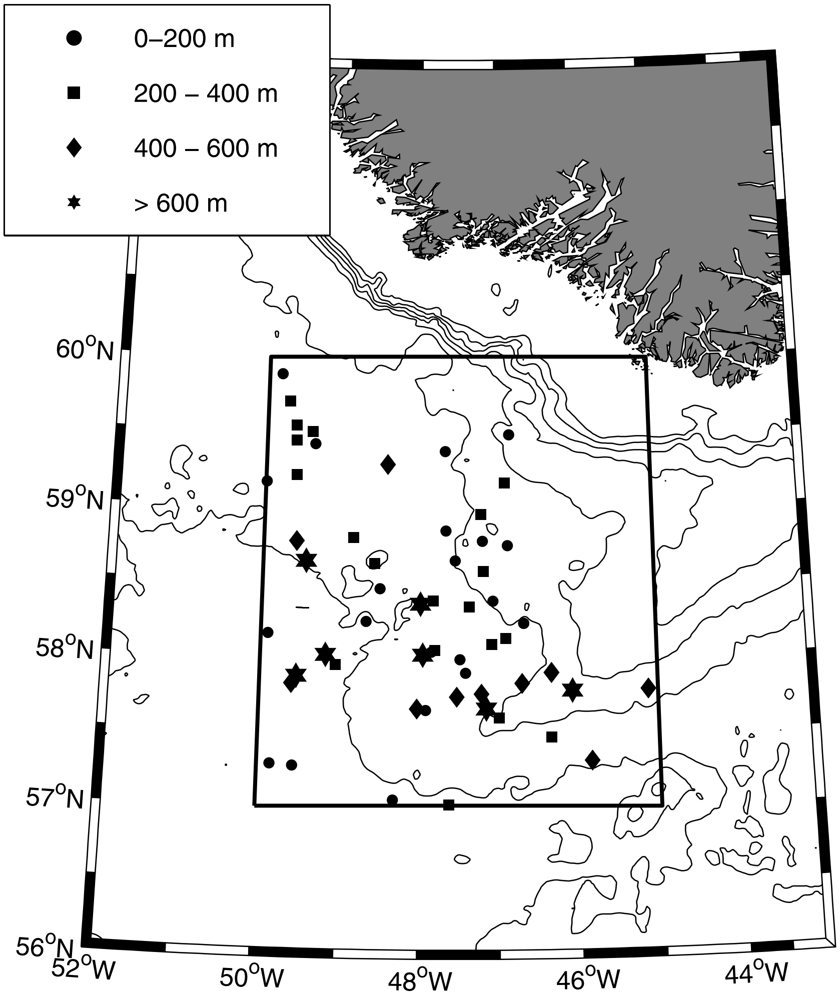

Figure 1. Locations of float profiles and calculated mixed-layer depths (m) in the area 50–45°W, 57–60°N between November 1996 and March 1997 inclusive.

the convective site in the south-east Labrador Sea. Ocean float data are used to establish the extent of oceanic convection and a one-dimensional mixed-layer model is then employed to highlight the meteorological conditions that control the onset and extent of open-ocean convection in the area.

2. Atmospheric Forcing of Deep Convection

[7] We focus on the winter of 1996/1997, as a relatively large number of temperature and salinity profiles from ocean floats released during the Labrador Sea Experiment [*Lab Sea Group*, 1998] were available at this time. Float data from November 1996 through March 1997 in the area 57 – 60°N, 50 – 45°W, which encompasses the recirculation in the south-east Labrador Sea identified by *Lavender et al.* [2000], were used to calculate mixed-layer depths using the method of *Pickart et al.* [2002]. These were found to be broadly consistent with those described previously [*Lavender et al.*, 2002], with the deepest mixed-layers lying between 500 and 800 m (Figure 1). It was assumed that within the South-East Labrador Gyre the evolution of the mixed-layer in the discrete float data was consistent with the evolution of the mixed-layer at a point within the recirculation, as was the case when we compared similar profiling float data with the moored profiler data of *Våge et al.* [2008]. The float data show a significant deepening in the mixed-layer towards the end of the winter, penetrating to over 800 m (Figure 2a).

[8] A one-dimensional model [*Price et al.*, 1989] forced with timeseries of daily longwave, shortwave, sensible and latent heat fluxes, as well as evaporation, convective and large scale precipitation and zonal and meridional surface wind stress was employed to study the processes important in mixed-layer deepening. The forcing timeseries were constructed from the ECMWF ERA-40 [*Uppala et al.*, 2005] fields by averaging over the area of interest (Figure 3), other than wind speed, for which the peak value in the area was used to avoid smoothing out the reverse tip-jet signature. *Renfrew et al.* [2002] showed that the ECMWF operational analyses capture the surface-layer meteorology and fluxes for this region reasonably well, and as the ERA-40 dataset is based on this model and uses the same surface-layer parametrizations we would expect these to also be well represented in ERA-40. Figure 2a shows the observed and modeled deepening of the mixed-layer, initialized on the 14th November 1996, as this was the first day during November when sufficient float data be-

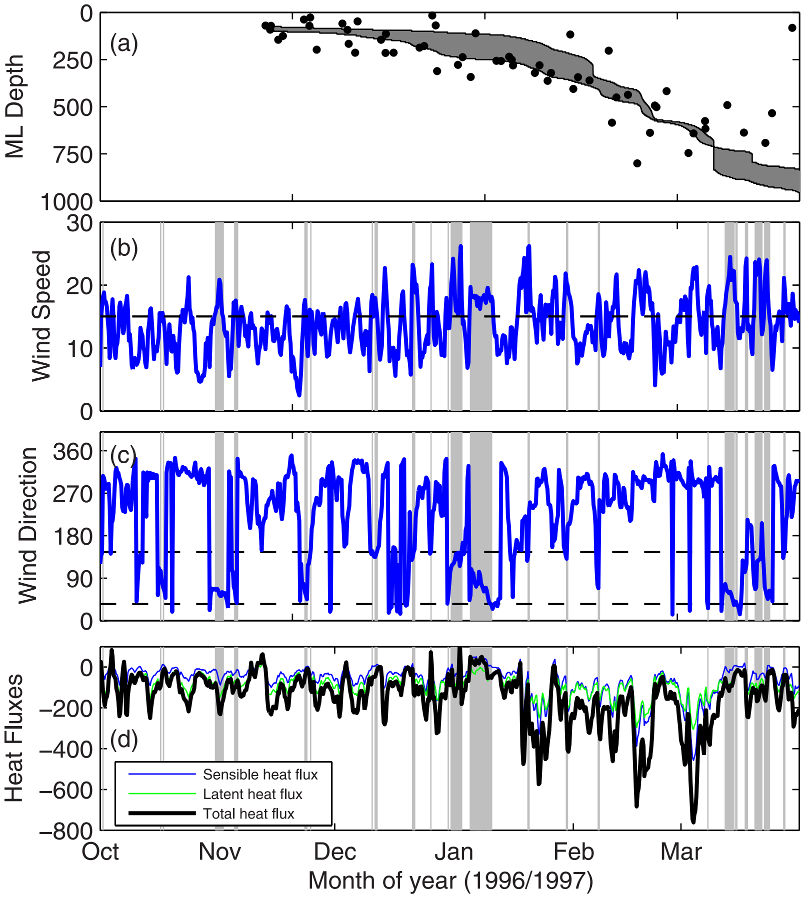

Figure 2. Timeseries for October–March 1996/1997 showing (a) modeled (shaded, showing uncertainty from two initializations) and observed (dots) mixed-layer depths (m), (b) 10 meter wind speed (m s^{-1}), showing the 15 m s^{-1} threshold for a reverse tip-jet, (c) 10 meter wind direction, the 45 and 135° thresholds for a reverse tip-jet, (d) latent, sensible and total turbulent heat fluxes (W m^{-2}) over the area of interest from ECMWF ERA-40. Vertical lines show the objectively identified tip-jets. Note that large heat flux events do not coincide with the reverse tip-jets.

came available. The model was initialized using temperature and salinity profiles obtained from two floats near initialization time. The initial profiles have been stabilized by recursively calling a static instability mixing routine [*Price et al.*, 1989]. The gray envelope shows the upper and lower depth limits of the modeled mixed-layer for the two profiles. While the model did not capture the higher frequency restratification events (which may be partly due to the spatially discrete nature of the float data), the onset and extent of model mixed-layer deepening is broadly consistent with the observations.

[9] Having ascertained from the float data that moderately deep convection occurred in the South-East Labrador Sea in the winter of 1996/1997, we now evaluate the importance of reverse tip-jets in triggering these events. Reverse tip-jets are objectively identified in the ERA-40 re-analysis as times when the peak wind speed in the box bounded by 57–60°N, 45–50°W is at least 15 m s^{-1} and the average wind direction is between 45 and 135 degrees from north, Figure 2c. During this winter, the majority of the reverse tip-jets occurred in two clusters, the first occurring in early January and the second in late March. All of the high heat flux events (greater in magnitude than 400 W m^{-2}) lie in between these two clusters of reverse tip-jet activity. Indeed it can be seen in Figure 2d that the reverse tip-jets identified in the reanalysis are associated with lower than average heat fluxes in the area, with atmosphere to ocean fluxes (i.e. a warming of the ocean) at times.

[10] *Moore* [2003] showed a negative correlation between the incidence of reverse tip-jets and the NAO index, and the converse for forward tip-jets. Given that during the winter of 1996/1997 the NAO was in a weakly positive phase, we would expect there to be fewer than average reverse tip-jets during this time. It is possible, therefore, that if we only consider this winter we may underestimate the role that reverse tip-jets play in forcing oceanic convection. To address this issue, we have considered two further winters: 1994/1995, when the NAO was in a strongly positive phase, and 1995/1996 when the NAO was strongly negative. Significantly more reverse tip-jets were observed in the winter of 1995/1996, consistent with *Moore* [2003]. During both of these winters reverse tip-jets were associated with weaker than average air-sea heat fluxes, as was the case in the winter of 1996/1997 (not shown).

[11] Figure 2 shows that the vast majority of events in 1996/1997 when ocean to atmosphere heat fluxes were large, between 400 and 800 W m^{-2}, were associated with flow from the north or north west. Composites of the 20 analysis times with the largest heat flux out of the ocean (in

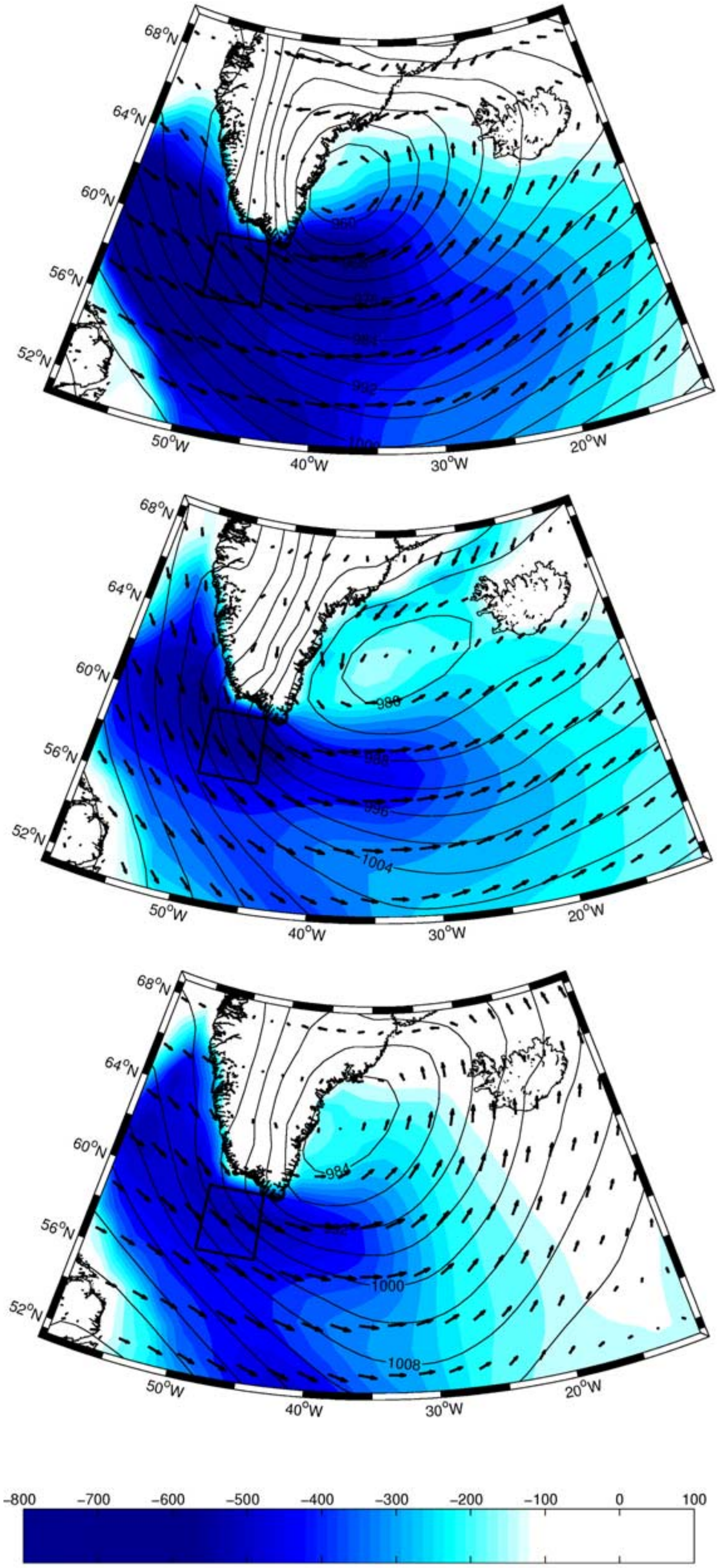

Figure 3. Composite of combined latent and sensible heat flux (W m^{-2}, shaded), 10 m wind vectors every 2.25° and mean sea level pressure (contours, every 4 hPa) for the 20 highest heat flux events in (top) 1996/1997, (middle) 1994/1995, and (bottom) 1995/1996. The box to the south-west of Cape Farewell shows the area over which float data were collected and meteorological variables were averaged.

ERA-40, 1.125° gridded 6 hourly data) are shown in Figure 3 for the winters of 1996/1997 (weakly positive NAO, top), 1994/1995 (strongly positive NAO, middle) and 1995/1996 (strongly negative NAO, bottom). The composite synoptic situation for all of these cases shows a low pressure center off the south-east coast of Greenland, with a generally north-westerly flow over the bulk of the Labrador Sea, including the secondary convection site in the south east of the basin. The strongest heat fluxes are generally seen in the central Labrador Sea, around 60°N, 55°W, near the primary convection site, however the fluxes in the secondary convection site exceed 600 W m^{-2} during the positive NAO winters, which could be strong enough to trigger deep convection if the ocean is suitably preconditioned. Note also that the heat fluxes and wind field show the signature of a westerly tip-jet to the east of Cape Farewell, indicating that this synoptic situation is also providing enhanced atmospheric forcing of the Irminger Sea convection site. A previous study of this area [*Lavender et al.*, 2002] showed a January–April mean of heat fluxes, constructed using a bias-corrected version of the NCEP reanalysis. This displayed no maximum in the South-East Labrador Sea. This is not inconsistent with the results presented in Figure 3 which shows a maximum in this area; when the ERA-40 heat fluxes used in this study are averaged over the same January–April period, broadly the same spatial features are seen (not shown). Equally, when the NCEP reanalysis is composited by high heat flux events in the South-East Labrador Sea, a picture similar to Figure 3 emerges.

3. Discussion and Conclusions

[12] Through the study of ocean temperature and salinity profiles during the winter of 1996/1997 we have confirmed that deep convection occurred at the secondary convection site in the south east Labrador Sea. It has been speculated [*Martin and Moore*, 2007; *Moore and Renfrew*, 2005] that reverse tip-jets may be important in causing convection in this area, in a similar manner to the way that westerly tip-jets have been shown to trigger convection in the Irminger gyre [*Pickart et al.*, 2003a; *Våge et al.*, 2008]. *Martin and Moore* [2007] showed through a high resolution numerical study of a particularly robust jet that heat fluxes are relatively high during reverse tip-jets, with latent fluxes of up to 150 W m^{-2} and sensible heat fluxes of between 50 and 100 W m^{-2}. These enhanced fluxes are not well resolved in the ECMWF ERA-40 dataset, but there is a representation of the jet in the reanalysis, albeit a somewhat coarse representation with a core wind speed some 10–15 m s^{-1} too low. The instantaneous latent and sensible heat fluxes based on ECMWF winds, temperature and humidity for 0000 UTC on December 21, 2000 (the case simulated by *Martin and Moore* [2007]) are around -10 W m^{-2} and -40 W m^{-2} respectively. We suggest that these small negative fluxes are due to an excessive advection of warm air from the south by the parent cyclone and a lack of advection of cold air from the north east of Cape Farewell, resulting in an overestimation of surface air temperature in the south-east Labrador Sea at this time. Despite this drawback, it is worth emphasizing that the 250 W m^{-2} heat fluxes associated with this strong reverse tip-jet in the mesoscale model [*Martin and Moore*, 2007] are significantly smaller than the largest heat fluxes seen in this area (Figure 2d). Recall that the average of the 20 largest heat flux events is 600 W m^{-2}, with peak values around 750 W m^{-2}. Despite the weak representation of the fluxes associated with reverse tip-jets in ERA-40, the deepening of the mixed-layer is well captured (in fact overestimated) in the model when forced by this dataset. This suggests that despite the crude representation of reverse tip-jets in ERA-40, the heat flux fields are well represented on the scale of the Labrador recirculation.

[13] Although ERA-40 does not show enhanced heat fluxes during reverse tip-jets, periods of strong heat fluxes over the secondary Labrador Sea convection site are observed in the dataset, with peak values of around 750 W m^{-2}. These strong fluxes coincide with the onset of the deepening of the mixed-layer, and are associated with cold-air outbreaks from the Labrador coast. During these periods the atmosphere over the Labrador Sea is in a westerly regime and elevated ocean-atmosphere fluxes of over 600 W m^{-2} have been observed [*Renfrew and Moore*, 1999; *Renfrew et al.*, 2002]. Hence we conclude that open ocean convection in the south-east Labrador Sea is being forced primarily by westerly cold-air outbreaks off the Labrador Coast and not reverse tip-jets. Thus, in terms of atmospheric forcing, the south-east Labrador Sea convection site is part of the central Labrador Sea and Irminger Sea convection regime, i.e. open ocean convection at these three sites may be triggered by broadly the same synoptic-scale meteorological situation. We note, however, that a definitive conclusion on the role that reverse tip-jets play in this area requires a much longer climatology using a high resolution dataset which correctly represents the detail of the structure of, and fluxes associated with, reverse tip-jets.

[14] **Acknowledgments.** We would like to thank two anonymous reviewers for their helpful comments which have greatly improved this study. Data have been provided by ECMWF, World Ocean Circulation Experiment (http://woce.nodc.noaa.gov), Coriolis Data Centre (http://www.coriolis.eu.org/cdc) and British Atmospheric Data Centre. DS is funded through NERC Ph.D. studentship NER/S/A/2006/14110.

References

Bacon, S., W. J. Gould, and Y. Jia (2003), Open-ocean convection in the Irminger Sea, *Geophys. Res. Lett.*, *30*(5), 1246, doi:10.1029/2002GL016271.

Centurioni, L., and W. Gould (2004), Winter conditions in the Irminger Sea observed with profiling floats, *J. Mar. Sci.*, *62*, 313–336.

Doyle, J. D., and M. A. Shapiro (1999), Flow response to large-scale topography: The Greenland tip jet, *Tellus, Ser. A*, *51*, 728–748.

Lab Sea Group (1998), The Labrador Sea Deep Convection Experiment, *Bull. Am. Meteorol. Soc.*, *79*, 2033–2058.

Lavender, K. L., R. E. Davis, and W. B. Owens (2000), Mid-depth recirculation observed in the interior Labrador and Irminger seas by direct velocity measurements, *Nature*, *407*, 66–69.

Lavender, K. L., R. E. Davis, and W. B. Owens (2002), Observations of open-ocean deep convection in the Labrador Sea from subsurface floats, *J. Phys. Oceanogr.*, *32*, 511–526.

Marshall, J., and F. Schott (1999), Open ocean convection: Observations, theory, and models, *Rev. Geophys.*, *37*, 1–64.

Martin, R., and G. W. K. Moore (2007), Air-sea interaction associated with a Greenland reverse tip jet, *Geophys. Res. Lett.*, *34*, L24802, doi:10.1029/2007GL031093.

Moore, G. W. K. (2003), Gale force winds over the Irminger Sea to the east of Cape Farewell, Greenland, *Geophys. Res. Lett.*, *30*(17), 1894, doi:10.1029/2003GL018012.

Moore, G. W. K., and I. A. Renfrew (2005), Tip jets and barrier winds: A QuikSCAT climatology of high wind speed events around Greenland, *J. Clim.*, *18*, 3713–3725.

Pickart, R. S., D. J. Torres, and R. A. Clarke (2002), Hydrography of the Labrador Sea during active convection, *J. Phys. Oceanogr.*, *32*, 428–457.

Pickart, R. S., M. A. Spall, M. H. Ribergaard, G. W. K. Moore, and R. F. Milliff (2003a), Deep convection in the Irminger Sea forced by the Greenland tip jet, *Nature*, *424*, 152–156.

Pickart, R. S., F. Straneo, and G. W. K. Moore (2003b), Is Labrador Sea Water formed in the Irminger Basin?, *Deep Sea Res., Part I*, *50*, 23–52.

Pickart, R. S., K. Våge, G. W. K. Moore, I. A. Renfrew, M. H. Ribergaard, and H. C. Davies (2008), Convection in the western North Atlantic subpolar gyre: Do small-scale wind events matter?, in *Arctic-Subarctic Ocean Fluxes: Defining the Role of the Northern Seas in Climate*, edited by R. Dickson, J. Meincke, and P. Rhines, Springer, New York, in press.

Price, J. F., R. A. Weller, and R. Pinkel (1989), Diurnal cycling: Observations and models of the upper ocean response to diurnal heating, cooling, and wind mixing, *J. Geophys. Res.*, *91*, 8411–8427.

Renfrew, I. A., and G. W. K. Moore (1999), An extreme cold air outbreak over the Labrador Sea: Roll vortices and air-sea interaction, *Mon. Weather Rev.*, *127*, 2379–2394.

Renfrew, I. A., G. W. K. Moore, P. S. Guest, and K. A. Bumke (2002), Comparison of surface layer and surface turbulent flux observations over the Labrador Sea with ECMWF analyses and NCEP reanalyses, *J. Phys. Oceanogr.*, *32*, 383–400.

Uppala, S. M., et al. (2005), The ERA-40 re-analysis, *Q. J. R. Meteorol. Soc.*, *131*, 2961–3012.

Våge, K., R. S. Pickart, G. W. K. Moore, and M. H. Ribergaard (2008), Winter mixed-layer development in the central Irminger Sea: The effect of strong, intermittent wind events, *J. Phys. Oceanogr*, in press.

K. J. Heywood, I. A. Renfrew, and D. A. J. Sproson, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK. (d.sproson@uea.ac.uk)