Mesoscale Structure of Cape Farewell Tip Jets

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ABSTRACT

Cape Farewell, Greenland’s southernmost point, is characterized by a number of low-level jets that are the result of topographic flow distortion associated with passing extratropical cyclones. The heavy seas associated with these wind events are a hazard to maritime traffic in the region. In addition, the air-sea heat flux associated with these weather systems plays an important role in the climate system by contributing to the forcing of the lower limb of the Atlantic meridional overturning circulation. In this paper, the North American Regional Reanalysis will be used to generate a higher-resolution climatology of these mesoscale jets as compared to previous studies. Through the use of a diagnostic that partitions the occurrence frequency of high-speed wind events by wind direction, the author shows that there are four different types of Cape Farewell tip jets that are characterized as having either northwesterly, southwesterly, northeasterly, or southeasterly wind direction. All four types have distinct regions in the vicinity of Cape Farewell where their respective occurrence frequencies and air-sea heat fluxes are at a maximum. The southwesterly and northeasterly jets closely resemble the wind systems previously identified as being westerly and easterly tip jets. There are also instances where one type evolves into another and so it is possible to view westerly tip jets as a continuum with the northwesterly and southwesterly events identified in this paper representing end members with a similar picture for easterly tip jets. The position of a particular event along these continua will determine its impact on local weather and the coupled climate system.

1. Introduction

Although the seas in the vicinity of Cape Farewell, Greenland’s southernmost point, have been known to be a hazard to maritime traffic as a result of the strong winds that occur in the region, including the sinking of the M/S Hans Hedtoft with the loss of 95 lives in a northeasterly gale during January 1959 (Hocking 1969), Doyle and Shapiro (1999) were the first to describe a high-speed low-level jet near Cape Farewell. Using an idealized model of flow past Greenland as well as case studies of two events, they identified an orographic weather system or tip jet that was characterized by westerly surface winds in excess of 30 m s⁻¹. Moore (2003) used the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (hereafter NCEP reanalysis) to show that the surface wind field in the vicinity of Cape Farewell was bimodal in nature with the possibility of both high-speed westerly and easterly tip jets. In addition, Moore (2003) showed that both classes of tip jets were associated with the interaction of extratropical cyclones with the high topography of southern Greenland. Subsequently a global climatology of QuikSCAT winds indicated that the Cape Farewell region was the windiest location on the ocean’s surface (Sampe and Xie 2007).

These weather systems play an important role in the regional and downstream weather (Renfrew et al. 2008; Harden et al. 2011). The elevated air–sea heat fluxes associated with westerly Cape Farewell tip jets have been proposed to contribute to oceanic convection that results in the formation of Labrador Seawater in the Irminger Sea (Pickart et al. 2003a,b; Våge et al. 2009). Case studies of easterly tip jets indicate that they result in elevated heat fluxes in the southeastern Labrador Sea (Martin and Moore 2007; Ohigashi and Moore 2009) where they may contribute to the oceanic convection that occurs in this region (Lavender et al. 2002).

Tip jets that form as the result of the flow distortion associated with the interaction of background flow with high topography have subsequently been identified in
2. Data and methods

The NARR is a regional reanalysis that covers the North American continent as well as the adjoining oceanic regions including southeast Greenland and the Irminger Sea as far east as Iceland with lateral boundary conditions provided by the NCEP-2 global reanalysis (Mesinger et al. 2006). It has a horizontal resolution of approximately 32 km. For this paper we use the full 3-hourly dataset for the months of January, February, and March 1979–2014. A comparison of the NARR surface fields with both buoy and aircraft observations from the Cape Farewell region show good agreement (Moore et al. 2008; Renfrew et al. 2009b). As the NARR is a regional product, there is a concern that there may be edge effects near its boundary. The Cape Farewell region is well within the NARR domain being situated approximately 20° of longitude west of its eastern boundary (Mesinger et al. 2006). In addition, the winter mean 10-m wind field along the southeast coast of Greenland in the NARR was shown to have a similar structure to that in the ERA-I (Våge et al. 2013). However the higher spatial resolution of the NARR resulted in a meso-β-scale structure in the wind field that was absent in the ERA-I.

Although the surface meteorological fields in reanalyses are typically well constrained by observations, the same is not necessarily true for the air–sea fluxes because of their strong dependence on the underlying numerical model’s surface and boundary layer parameterizations (Smith et al. 2001; Renfrew et al. 2002). Indeed, the NARR surface heat fluxes in the coastal waters off Greenland have been shown to be biased high as compared to other analyses/reanalyses from the ECMWF and observations (Renfrew et al. 2009b). Accordingly, we have chosen to use a well-established bulk algorithm for the heat flux (Smith 1988; DeCosmo et al. 2011), with horizontal resolutions larger then this threshold may be missing details in terms of their structure, evolution, or impact on the ocean.

As a result, there is a clear need to develop climatologies of these jets that have sufficient horizontal resolution to capture their mesoscale structure and that of their air–sea flux fields. The North American Regional Reanalysis (NARR) will be used to accomplish this task (Mesinger et al. 2006). Its horizontal resolution of 32 km suggests that it is able to resolve the topographically forced flow in the vicinity of Cape Farewell (DuVivier and Cassano 2013).

In this paper, the NARR will be used to show that there are four different types of Cape Farewell tips jets that are characterized as having either northwesterly, southwesterly, northeasterly, or southeasterly wind direction. All four types have distinct regions in the vicinity of Cape Farewell where their respective occurrence frequencies and air–sea heat fluxes are a maximum that are related to the specific nature of the interaction of the parent extratropical cyclone with the high topography of Greenland.

3. Results

Figure 1 shows the power spectrum of the 10-m wind speed in the vicinity of Cape Farewell for the months of January, February, and March as represented in the NARR, the ERA-I with a horizontal resolution of 0.75° (Dee et al. 2011), the 40-yr ECMWF Re-Analysis (ERA-40) with a native resolution of horizontal resolution of 1.125° but archived at 2.5° (Uppala et al. 2005), and the NCEP reanalysis with a Gaussian horizontal resolution of 1.875° (Kalnay et al. 1996). The NARR, ERA-I, and NCEP spectra are for the years 1979–2014, while that for the ERA-40 is for the period 1979–2002. Also shown are spectra characteristic of 3D turbulence, $k^{-5/3}$ (Skamarock 2004), and scatterometer winds, $k^{-2.2}$, (Patoux and Brown 2001). As discussed by previous authors (Condron and Renfrew 2013; Laffineur et al. 2014), the global reanalyses, all have reduced power at length scales below ~400 km. As compared to the global...
reanalyses, the NARR has significantly more power at length scales between 100 and 400 km. In addition, the slope of its spectrum in this wavelength regime approximates that of the scatterometer winds suggesting that it is able to better assimilate these data that have a horizontal resolution of approximately 25 km.

Figure 2 shows two diagnostics that have been used to identify high-speed winds associated with topographic flow distortion: the 95th percentile 10-m wind speed and the occurrence frequency of 10-m wind speeds in excess of a given threshold. Both diagnostics are based on the NARR 3-hourly 10-m wind field during the months January, February, and March 1979–2014. The particular wind speed cutoff used in Fig. 2 is 15 m s$^{-1}$; other cutoffs yielded similar results.

In agreement with previous work, these diagnostics indicate that the area to the east of Cape Farewell is the windiest location in the region with 95th percentile 10-m wind speeds in excess of 20 m s$^{-1}$ and 10-m wind speeds in excess of 15 m s$^{-1}$ occurring over 25% of the time. Apart from these individual maxima, which are offset from each other, both fields indicate that there is a tendency for extreme 10-m wind speeds to increase in magnitude as one moves eastward from the Labrador Sea’s ice edge toward Cape Farewell before reducing again as one moves northeastward along the southeast coast of Greenland.

More details on the characteristics of Cape Farewell topographic jets can be found when one partitions the occurrence frequency at each grid point by wind direction. In this instance, four wind directions were chosen: northwesterly, northeasterly, southeasterly, and southeasterly. Other partitions result in similar results but for the particular case at hand, this partition leads to insight into the complexity of topographic flow distortion by southern Greenland. Figure 3 shows this partition and compared to Fig. 2b, one can see the added information that is obtained through this technique. In particular, it is evident that there are four distinct locations in the vicinity of Cape Farewell where a maximum occurs for each of these wind directions. The region of elevated occurrence frequency for southeasterly flow (Fig. 3a) occurs to the east of Cape Farewell in the same region as that identified by Doyle and Shapiro (1999) for the original westerly tip jet. The region for northeasterly flow (Fig. 3b) also occurs to the east of Cape Farewell but in closer proximity to Greenland. In addition, it can be seen to be an extension of the tendency for high-speed
northeasterly flow along the southeast coast of Greenland that is associated with barrier flow. All of these characteristics are similar to that of the original easterly tip jet described by Moore and Renfrew (2005). The region of elevated occurrence frequency for northeasterly flow (Fig. 3c) has a northwest–southeast orientation to the west of Cape Farewell and represents a new class of westerly tip jets that, as will be argued, is distinct from that identified by Doyle and Shapiro (1999). The region of elevated occurrence frequency for southeasterly flow (Fig. 3d) occurs to the northwest of Cape Farewell and represents an orographic jet identified by Moore (2012).

High-speed wind events at the four locations where the occurrence frequency is elevated were defined to occur at times when the 10-m wind speed at that location with the appropriate directionality exceeded the corresponding 95th percentile 10-m wind speed (Fig. 2a). If this condition was met for more than 3 h (i.e., one time step), the time of the maximum in the 10-m wind speed was selected for that event. Using this approach, ~200 southeasterly, ~200 northeasterly, ~150 northerly, and ~40 southeasterly events were identified during January, February, and March 1979–2014. Typically, all of these events lasted on average for 1 day.

The composite sea level pressure, 10-m wind, and 10-m wind speed fields associated with the high-speed wind events at these four locations are shown in Fig. 4. The southeasterly events (Fig. 4a) can be seen to be associated with a deep low pressure system to the northeast of Cape Farewell with evidence of onshore flow to the north of the low center as well as a zonal pressure gradient across southern Greenland to the east of 45°W. The region of highest wind speeds extends zonally eastward from Cape Farewell. There also exists outflow across the Labrador Sea. The northeasterly events (Fig. 4b) are associated with a deep low pressure system to the south of Cape Farewell. The region of high

![Fig. 3. Occurrence frequency (%) of 10-m wind speeds in excess 15 m s⁻¹ for (a) southwesterly, (b) northeasterly, (c) northwesterly, and (d) southeasterly flow. The thick black lines represent the winter mean 50% sea ice concentration contour. The +, *, □, and Δ denote the locations of the maxima in the respective occurrence frequencies. Results are based on the NARR during January, February, and March 1979–2014.]
wind speed is tied to the coastline in the vicinity of Cape Farewell as well as to the north along the southeast coast of Greenland and subsequently extends offshore to the south of the cape. The northwesterly events (Fig. 4c) are also associated with a deep low pressure system to the northeast of Cape Farewell and outflow over the Labrador Sea, as was the case for the southwesterly events (Fig. 4a). However, in this case the region of low pressure has a more elliptical shape with the enhanced zonal pressure gradient extending across all of southern Greenland. The orientation and extent of the region of highest wind speeds is also different from that for the southwesterly events and extends along the southwest coast of Greenland to the west of Cape Farewell. Finally, the southeasterly events (Fig. 4d) are seen to be associated with a low pressure system to the southwest of Cape Farewell with the region of high wind speeds extending westward over the Labrador Sea. There is again evidence of an enhanced zonal pressure gradient, of the opposite sign to that in the above cases, across southern Greenland.

The composite total turbulent heat flux, defined to be the sum of the sensible and latent heat flux with the convention that positive fluxes are out of the ocean, for the four classes of high-speed wind events are shown in Fig. 5. In all cases, the structure of the region of elevated total turbulent heat flux mirrors the respective region of high wind speed. As a result, the region where each of these types of events has its greatest impact on the buoyancy of the surface waters is distinct. The maximum heat flux for southwesterly events (Fig. 5a) exceeds 600 W m$^{-2}$ and extends eastward from Cape Farewell.
For these events, there is also a region of elevated heat flux in the western Labrador Sea. The maximum heat flux for northeasterly events (Fig. 5b) at 450 W m$^{-2}$ is smaller than that for southwesterly events (Fig. 5a). The maximum is also more tightly focused in the region just to east of Cape Farewell. The maximum heat flux for northwesterly events (Fig. 5c) also exceeds 600 W m$^{-2}$. However, the region of highest heat fluxes is shifted westward and has a different orientation as compared to that for the southwesterly events (Fig. 5a). As was the case for the southwesterly flow, there are also elevated fluxes across the Labrador Sea. The largest heat fluxes for southeasterly flow are also situated over the eastern Labrador Sea (Fig. 5d). However, its maximum value, 350 W m$^{-2}$, is smaller than that for the other classes of events.

4. Discussion

In this paper, a new climatology of topographic flow distortion by southern Greenland has been presented that is based on the use of the NARR with its high spatial resolution along with a diagnostic that partitions the occurrence frequency of high-speed winds by direction. This climatology indicates that there are four distinct types of Cape Farewell topographic jets. The original westerly and easterly tip jets identified by Doyle and Shapiro (1999) and Moore (2003) are represented by the southwesterly (Fig. 3a) and northeasterly (Fig. 3b) occurrence frequency maxima, respectively. The southeasterly occurrence frequency maximum (Fig. 3d) is similar to that identified by Moore (2012). The northwesterly occurrence frequency maximum
In all cases, the tip jets were the result of the interaction of the high topography with extratropical cyclones. The flow fields including the location of the parent low associated with the composite southwesterly (Fig. 4a) and northeasterly (Fig. 4b) tip jets are similar to those previously reported (Moore 2003; Moore and Renfrew 2005; Martin and Moore 2007; Ohigashi and Moore 2009; Våge et al. 2009). Although the existence of the southeasterly occurrence frequency maximum was previously identified, the associated atmospheric circulation presented in this paper (Fig. 4d) is a new result and clearly shows evidence of an upwind distortion of the parent extratropical cyclone by Greenland’s high topography. This distortion is characterized by an enhanced pressure gradient across southern Greenland as well as a mesoscale ridge along the southeast coast of Greenland. This sort of upwind distortion of an extratropical cyclone over the Labrador Sea by Greenland has been noted in previous case studies (Moore and Vachon 2002; Martin and Moore 2006).

The occurrence frequency of the southeasterly tip jets is much smaller than that for the other classes. This class of events was associated with an extratropical cyclone that was transiting the Labrador Sea (Fig. 4d). Such a storm track is relatively rare during the winter accounting for its reduced occurrence frequency (Våge et al. 2009). In contrast, the other three classes are all associated with cyclones that transit along the main North Atlantic storm track. Nevertheless, previous work has pointed out that the nature of the large-scale background flow, including the phase of the NAO and the location of the climatological Icelandic low, does impact the position of this storm track resulting in differences in occurrence frequency for easterly and westerly tip jets (Moore 2003; Bakalian et al. 2007; Moore et al. 2011). The impact that such variability has on the four classes of events described in this paper will be discussed in a subsequent work.

The air–sea fluxes of heat and moisture for the four classes of tip jet events have also been presented. The total turbulent heat flux associated with the southwesterly tip jets (Fig. 5a) has a maximum to the east of Cape Farewell in the region where Labrador Seawater forms in the Irminger Sea (Pickart et al. 2003a,b; Våge et al. 2009). For this class of tip jet, elevated heat fluxes are also present over the western Labrador Sea in the vicinity of the primary region where Labrador Seawater forms (Pickart et al. 2002; Moore et al. 2014). This spatial pattern suggests that there may be some concurrency in the high heat flux events that are responsible for oceanic convection at these two sites.

The turbulent heat flux associated with the north-easterly tip jets (Fig. 5b) is largest directly to the east of Cape Farewell although there is a trailing region over the southeastern Labrador Sea where the heat flux is elevated. Two cases of northeasterly tip jets that have been previously investigated (Martin and Moore 2007; Ohigashi and Moore 2009) had total turbulent heat fluxes on the same order as that of the composite; however, the region of elevated fluxes was more zonal in orientation extending west of Cape Farewell. This suggests that further study is needed to identify the characteristics of northeasterly tip jets that give rise to elevated heat fluxes to the west of Cape Farewell (Sproson et al. 2010).

This region is of importance as it is a secondary site, compared to that in the western Labrador Sea, where deep oceanic mixed layers are also observed to develop (Lavender et al. 2002). The turbulent heat flux associated with the northwesterly tip jets (Fig. 5c) is also elevated in this region and can exceed 500 W m\(^{-2}\). As was the case for southwesterly tip jets (Fig. 5a), the heat fluxes are also elevated over the western Labrador Sea suggesting that these northwesterly tip jets are also associated with cold air outbreaks over the Labrador Sea. Previous work had suggested that the oceanic convection that occurs in the southeast Labrador Sea was associated with such cold air outbreaks (Sproson et al. 2008). The results of this study are consistent with this previous study with the caveat that the largest heat fluxes do not occur over the western Labrador Sea, as is typical for cold air outbreaks in this region (Moore et al. 2014), but rather occur over the eastern Labrador Sea as a result of the flow distortion along the southwest coast of Greenland.

The turbulent heat flux associated with southwesterly tip jets (Fig. 5d) also has a maximum over the southeast Labrador Sea, although its magnitude is smaller than that associated with northwesterly tip jets (Fig. 5c). This suggests that this class of tip jet may also contribute to the atmospheric forcing of oceanic convection in the southeast Labrador Sea.

A comparison of the composite southwesterly (Fig. 4a) and northwesterly (Fig. 4c) tip jets and the associated air–sea heat flux (Figs. 5a,c) indicates that they represent a distinct phenomenon. Among the differences are the location and orientation of the region of highest wind speeds as well as the structure and orientation of the parent low pressure system. In particular, the low is closer to Greenland and has evidence of a tightening of the zonal pressure gradient across southern Greenland for the southwesterly tip jet as compared to that for the northwesterly tip jet. In addition, the region of elevated heat fluxes associated with
the southwesterly tip jets has a more zonal orientation as compared to that for northwesterly tip jets. The heat fluxes over the southeastern Labrador Sea are also higher for northwesterly tip jets. These differences may be related to the formation mechanism for these jets.

It has been proposed that conservation of the Bernoulli function, that results in acceleration down the lee slope, as well as flow distortion around Cape Farewell are responsible for westerly tip jets (Doyle and Shapiro 1999; Moore and Renfrew 2005; Våge et al. 2009). The circulation associated with the southwesterly tip jet suggests that lee acceleration may be the primary formation mechanism for this type of jet, while flow distortion around Cape Farewell may be cause for the northwesterly tip jets.

To confirm these differences, the divergence of the composite 10-m wind field was calculated for the southwesterly and northwesterly high wind events. With respect to the southwesterly events (Fig. 6a), there exists a region of enhanced divergence extending across southern Greenland that intersects Cape Farewell with a northwest–southeast orientation. Such a region is consistent with descending motion over southern Greenland. There is also a region of convergence along the southeast coast of Greenland to the north of Cape Farewell that is suggestive of ascending motion. Indeed the sea level pressure composite for this event (Fig. 3a) is consistent with onshore flow in this region that would result in forced ascent over the coastal topography. As a result, there is evidence of a recirculation in this region with some of the air parcels that descend downward toward Cape Farewell originating over the Irminger Sea. Such a recirculation has not been noted in previous studies (Doyle and Shapiro 1999; Våge et al. 2009).

In contrast, the northwesterly events have a region of divergence, weaker than that associated with the southwesterly events, which is offshore of the southwest coast of Greenland (Fig. 6b). As a result, there is only weak divergence over Greenland and in addition, the region of convergence along the southeast coast of Greenland is also weaker than that for southwesterly flow. The latter is consistent with the sea level pressure composite (Fig. 3c) that shows the flow in this region is more aligned with the coast than was the case for southwesterly flow. The convergence signature associated with northwesterly flow is consistent with the results of Våge et al. (2009) who noted that descending motion was present in this region, albeit weaker than that over southern Greenland, during westerly tip jet events. In both situations, there is also evidence of a dipole in the convergence field along the southeast coast of Greenland near 67°N, 35°W. Katabatic flow occurs in this region (Oltmanns et al. 2014) and this dipole may be associated with that phenomenon.

The composite northeasterly and southeasterly tip jets are much more tightly confined to the topography (Figs. 4b,d) as compared to the southwesterly and northwesterly jets (Figs. 4a,c). This is the result of a difference in formation mechanism. As has been discussed by previous authors (Ohigashi and Moore 2009; Renfrew et al. 2009a), the northeasterly and southeasterly jets are the examples of so-called corner jets that in the Northern Hemisphere result in an acceleration of the wind on the left-hand side of the barrier (Barstad and Grønas 2005).

The results presented by Våge et al. (2009) suggest that there may be instances where a northwesterly tip jet transitions into a southwesterly tip jet as the parent low continues its evolution. This was considered in the present study by calculating the overlap between the
events at the two locations. Overlaps within 1 day occurred approximately 30% of the time suggesting that such transitions do indeed occur. As a result, it is probably more correct to view westerly tip jets as a continuum with the northwesterly and southwesterly events identified in this paper representing end members with a similar picture for easterly tip jets. The position of a particular event along these continua will modulate its impact on local weather as well as the coupled climate system in ways that require further study.

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