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Buoy observations from the windiest location in the world ocean, Cape Farewell, Greenland

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[1] Cape Farewell, Greenland's southernmost point, is a region of significant interest in the meteorological and oceanographic communities in that atmospheric flow distortion associated with the high topography of the region leads to a number of high wind speed jets. The resulting large air-sea fluxes of momentum and buoyancy have a dramatic impact on the region's weather and ocean circulation. Here the first in-situ observations of the surface meteorology in the region, collected from an instrumented buoy, are presented. The buoy wind speeds are compared to 10 m wind speeds from the QuikSCAT satellite and the North American Regional Reanalysis (NARR). We show that the QuikSCAT retrievals have a high wind speed bias that is absent from the NARR winds. The spatial characteristics of the high wind speed events are also presented. **Citation:** Moore, G. W. K., R. S. Pickart, and I. A. Renfrew (2008), Buoy observations from the windiest location in the world ocean, Cape Farewell, Greenland, *Geophys. Res. Lett.*, *35*, L18802, doi:10.1029/2008GL034845.

1. Introduction

[2] The high topography of southern Greenland results in significant atmospheric flow distortion in the region near Cape Farewell, its southernmost point, leading to the common occurrence of high surface wind speeds in its vicinity. Indeed, a recent global climatology of surface marine wind speed indicates that Cape Farewell is the windiest location on the ocean's surface [*Sampe and Xie*, 2007]. Forecasters have been aware of the unique nature of this region for some time, and there is even evidence that these winds may have assisted in the Viking colonization of Greenland and Vinland [*Renfrew et al.*, 2008]. However, the first description in the scientific literature was only recently provided by *Doyle and Shapiro* [1999], who reported on the existence of a narrow region of westerly high surface wind speed that extended eastward from Cape Farewell, which they dubbed a "tip jet".

[3] *Moore* [2003] used the NCEP reanalysis to develop a climatology of high wind speed events near Cape Farewell. He found that the zonal wind in this region was bimodal with an increased probability of observing both westerly and easterly high wind speed events. Through a composite analysis, the westerly high wind speed events were found to be associated with tip jets of the type identified by *Doyle and Shapiro* [1999], while the easterly wind events represented a new phenomenon referred to as "reverse tip jets". *Moore and Renfrew* [2005] extended this analysis through the use of the higher resolution 10 m winds retrieved from the QuikSCAT scatterometer that allowed for a much more detailed view of the surface winds around Cape Farewell.

[4] The intense air-sea interaction that is associated with these jets is important for both the surface and deep ocean circulation in the region. For example, the surface wind stress plays a role in the forcing of the East Greenland Current [*Spall and Price*, 1998] as well as in the cyclonic recirculation gyres in the Irminger and Labrador Seas [*Lavender et al.*, 2000; *Spall and Pickart*, 2003]. In this regard, *Doyle and Shapiro* [1999] showed that there were large momentum fluxes associated with a tip jet event, while *Martin and Moore* [2007] showed that this was also true for reverse tip jets. *Doyle and Shapiro* [1999] also noted that there were high fluxes of heat and moisture associated with a tip jet. It has been argued that these elevated heat fluxes, integrated over an entire winter, are responsible for deep oceanic convection in the Irminger Sea to the east of Cape Farewell [*Pickart et al.*, 2003; *Vage et al.*, 2008]. In the Labrador Sea, to the west of Cape Farewell, there are two sites of deep ocean convection: in the western Labrador Sea in a region where intense air-sea interaction is known to take place via cold-air outbreaks off the continent [*Clarke and Gascard*, 1983; *Renfrew and Moore*, 1999; *Pickart et al.*, 2002]; and immediately southwest of Cape Farewell within a closed recirculation gyre [*Lavender et al.*, 2002]. *Martin and Moore* [2007] proposed that easterly reverse tip jets may provide the atmospheric forcing for convection at this site. However this interpretation has been questioned by *Sproson et al.* [2008] who argue that convection at the secondary site is also the result of cold-air outbreaks.

[5] Thus far, the investigation of both types of tip jets has relied exclusively on global numerical weather prediction (NWP) reanalyses, regional NWP simulations of particular case studies, or QuikSCAT winds. The lack of in-situ data with which to validate these datasets and simulations has hampered our understanding of the structure and dynamics of these jets as well as their impact on the ocean. For example, there is evidence that retrievals of the 10 m wind speed from the QuickSCAT satellite using both the NASA and Remote Sensing Systems (RSS) geophysical models result in an overestimation of the surface wind speeds in high wind conditions [*Ebuchi et al.*, 2002]. On the hand, *Chelton and Freilich* [2005] showed that the 10 m winds retrieved from QuikSCAT, with the NASA geophysical model, were in good agreement with a number of deep ocean buoys for wind speeds in the range from 10 to 22 m s^{-1}. The recent availability of the 32 km NCEP North American

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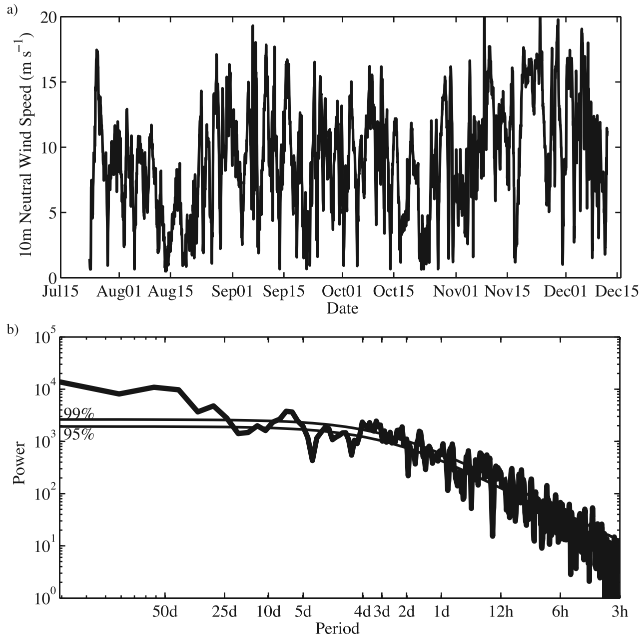

Figure 1. (a) Time series and (b) power spectrum of the neutral 10m wind speed from the Cape Farewell buoy July 24 to December 6 2004. In Figure 1b, the 95% and 99% significance estimates are also shown.

Regional Reanalysis (NARR) [*Mesinger et al.*, 2006] offers the possibility of a higher resolution representation of the surface wind and other meteorological fields in the Cape Farewell region. However validation is needed before the NARR is used in this context.

[6] In 2004, a surface buoy was deployed to the east of Cape Farewell with the goal of collecting meteorological data that could be used to study the high wind speed jets in the region. Here, we use this buoy data to characterize the wind field near Cape Farewell. In addition, the observations are compared to co-located 10 m wind speed retrievals, with both the NASA and RSS geophysical models from the QuikSCAT satellite, as well as surface fields from the NARR. Finally, NARR-based composites of the tip jet and reverse tip jet events observed by the buoy are presented, revealing several features that have not been previously identified.

2. Data

[7] On July 24 2004, a 3 meter discus meteorological buoy was moored in 2,977 m of water approximately 300 km east of Cape Farewell, at 59.6°N 38.6°W. It remained operational until December 7 2004 when it broke loose from its mooring. The buoy included a fin to help align the buoy with the wind so as to minimize flow distortion around the anemometer [*Hosom et al.*, 1995]. Air temperature, relative humidity and sea surface temperature data were also measured. Total errors for wind speed and direction are on the order of 0.1 m s^{-1} and 6°, while that for air temperature, relative humidity and sea surface temperature are on the order of 0.2°C, 1% and are 0.1°C respectively (K. Colbo and R. A. Weller, The accuracy of the IMET sensor package, submitted to *Journal of Atmospheric and Oceanic Technology*, 2008). For this paper, we have used hourly-mean meteorological observations adjusted, using standard surface-layer theory, to the appropriate heights for a comparison. To facilitate the comparison with the QuikSCAT data, an equivalent neutral 10 m wind speed was calculated for both the buoy and NARR data [e.g.,

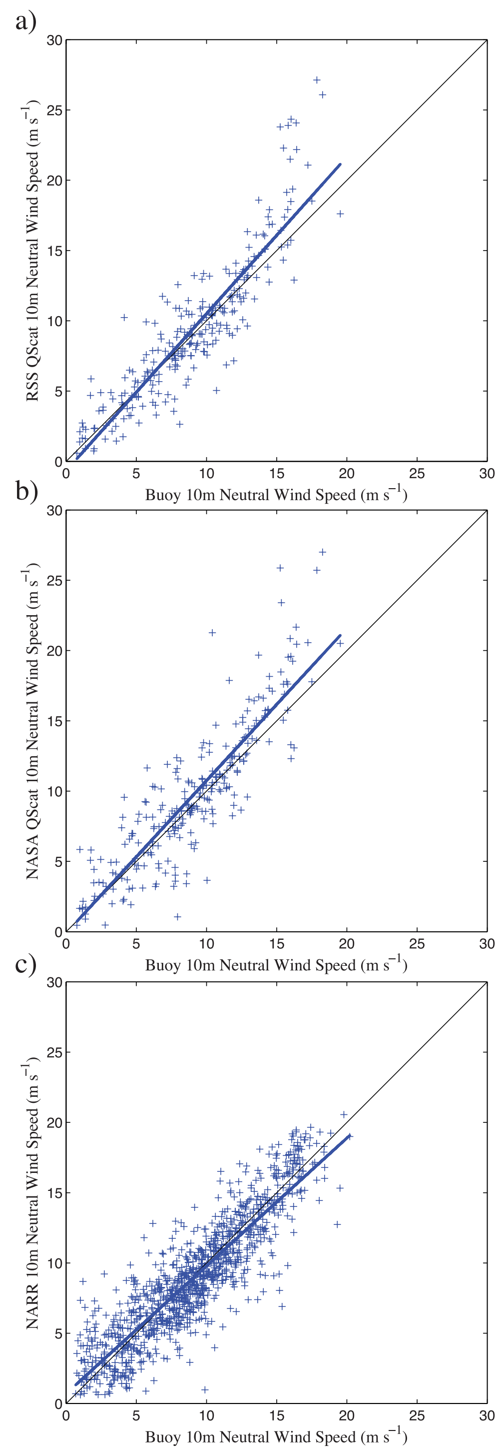

Figure 2. Scatterplots of the neutral 10m wind speed observed at the Cape Farewell buoy with co-located: (a) RSS QuikScat retrievals, (b) NASA QuikScat retrievals, and (c) NARR data.

Table 1. Statistical Comparison Between the Buoy Observations and the QuikSCAT and NARR Data[a]

	NARR	NASA QuikSCAT	RSS QuikSCAT
Buoy 10 m wind speed	r = 0.88;m = 0.90; RMS error = 2 m s^{-1}	r = 0.87;m = 1.08; RMS error = 2.6 m s^{-1}	r = 0.89;m = 1.1 RMS error = 2.3 m s^{-1}
Buoy 10 m wind direction	r = 0.92;m = 0.89; RMS error = 31°	r = 0.90;m = 0.90; RMS error = 33°	r = 0.90;m = 0.90; RMS error = 36°
Buoy 2 m temperature	r = 0.93;m = 0.84; RMS error = 0.84°C		
Buoy 2 m specific humidity	r = 0.94;m = 0.77; RMS error = 0.54 g kg^{-1}		
Buoy sea surface temperature	r = 0.95;m = 0.91; RMS error = 0.42°C		

[a]The correlation coefficient (r), the slope of least squares linear fit (m) and root mean square error are shown.

Chelton and Freilich, 2005]. The comparison with the QuikSCAT data was carried out at 06Z and 18Z each day, the nominal crossing points for the satellite over the buoy location, while the comparison with the NARR data was carried out 8 times daily. Subsampling the NARR data to twice daily did not change the results significantly.

3. Results

[8] Figure 1 shows the time series of hourly mean neutral 10 m wind speed from the buoy as well as the associated power spectrum calculated by a multi-taper method with the statistics based on an AR(1) noise model [*Ghil et al.*, 2002]. The time series reveals a highly variable wind field with a mean value of 8.9 m s^{-1} and standard deviation of 4.1 m s^{-1}. There was a tendency for higher wind speeds later in the year. For example, there was only one event during August in which the wind speed exceeded 16 m s^{-1}, while in November there were eleven events. There is evidence of variability on a number of different time scales, as is more apparent in the power spectrum (Figure 1b). At the lowest frequencies, there is statistically significant power associated with the seasonal trend towards higher wind speeds. There is also statistically significant power around 30 days that may be associated with changes in the North Atlantic storm track [*Marshall et al.*, 1998; *Sathiyamoorthy and Moore*, 2002]. There is also an isolated peak near 7 days that may be due to the passage of individual cyclones. At periods less than 4 days, there is a near continuum of statistically significant power presumably associated with variability in the structure of individual cyclones. Finally, there is an isolated statistically significant peak at 1 day that is a reflection of variability in the wind field associated with the diurnal cycle.

[9] Figure 2 compares the neutral 10 m wind speed measured by the buoy with the co-located QuikSCAT and NARR winds. The comparison with the QuikSCAT RSS retrieval (Figure 2a and Table 1) indicates good overall agreement. However, there is an overestimation of the retrieved wind speed at high wind speeds. For example, there were 10 events in which the RSS QuikSCAT winds exceeded 20 m s^{-1} but for all of these the buoy winds were less than 20 m s^{-1}. The good agreement at lower wind speeds tends to constrain this disagreement, resulting in a least squares slope that exceeds 1 by approximately 10% (Table 1). The comparison with the NASA retrieval (Figure 2b and Table 1) is similar, with the exception that the disagreement at high wind speeds is slightly reduced: there were only 5 events when the QuikSCAT winds exceeded 20 m s^{-1}. There is a corresponding reduction in the slope of the least squares linear fit (Table 1). Both QuikSCAT wind speed and wind direction retrievals have least squares errors (with respect to the buoy data) of approximately 2.5 m s^{-1} and 30° respectively (Table 1).

[10] In contrast, the comparison with the NARR neutral 10 m wind speed shows no evidence of a disagreement at high wind speeds and had a comparable correlation coefficient (Figure 2c and Table 1). Indeed, it appears that there is a slight underestimation in the magnitude of the neutral 10 m wind speed field in the NARR dataset, with the least squares line having a slope that is less than 1 by approximately 10% (Table 1). The NARR neutral 10 m wind speed and direction have a least squares error of approximately 2 m s^{-1} and 30° with respect to the buoy data (Table 1).

[11] Figure 3 shows composites of the NARR 10 m wind field associated with the buoy-observed tip jets (13 events) and reverse tip jets (12 events). A cut-off of 16 m s^{-1} was used to identify the high wind speed events with the sign of the zonal component used to partition the events as westerly or easterly. The composites and their statistical significance were generated using a technique similar to that used by *Moore and Renfrew* [2005].

[12] The tip jet composite (Figure 3a) shows clear evidence of a cyclonic circulation with a center to the northeast of Cape Farewell, similar to that found in previous composites. There is evidence of small scale structure along the southeast coast of Greenland that is absent from the earlier composites. In particular, note the coastal jet near 66°N 35°W. Just inland of this coastal jet is a region of high topography known as the Schweizerland Alps and the jet may be the result of flow distortion around this topographic barrier. There is also evidence of outflow from Greenland to the south of this coastal jet. There are a number of large fiords in this region and this outflow may be associated with katabatic flow known locally as a piteraq [*Klein and Heinemann*, 2002]. The reverse tip jet composite (Figure 3b) also shows evidence of a cyclonic circulation with a center to the southeast of Cape Farewell. The convergence and concomitant acceleration of the easterly flow as it impinges on and is deflected southwards by the high topography of Greenland is evident.

4. Discussion

[13] We have presented the first in-situ observations of the surface winds in the vicinity of Cape Farewell Greenland.

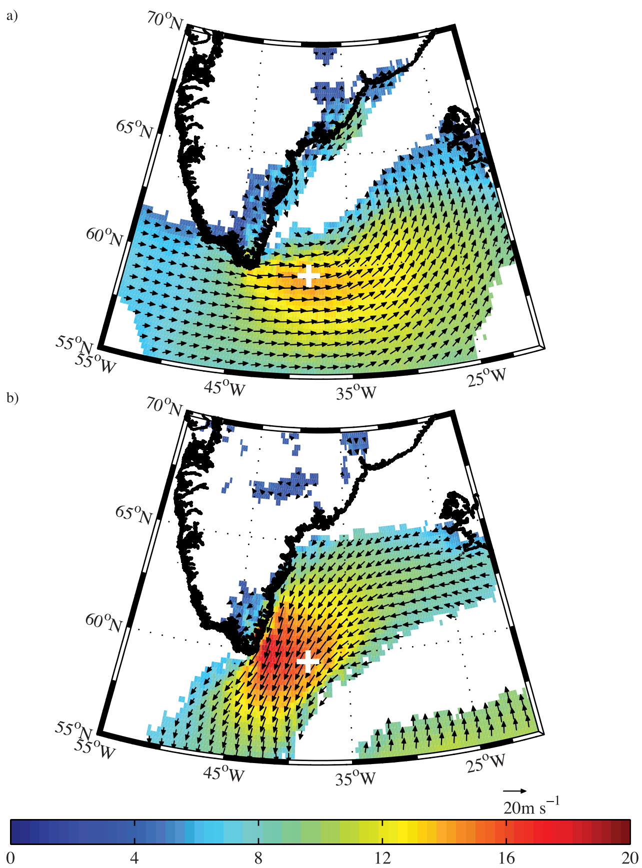

Figure 3. Composite of the 10m wind speed field (m s^{-1}) from the NARR for (a) tip jets and (b) reverse tip jets observed at the Cape Farewell buoy. The composites are shown at locations where they are statistically significant at the 95% level. The location of the buoy is indicated by the plus.

Unfortunately the period of the buoy's operation (July to early December) did not coincide with the windiest time of the year (December through February) [*Moore*, 2003; *Sampe and Xie*, 2007] and so there is an under-representation of high wind events in the dataset. Nevertheless, the data show clear evidence of variability on a number of different time scales associated with seasonality, changes in the location of the North Atlantic storm track, the passage of individual cyclones and the diurnal cycle. Comparisons with retrieved 10 m wind speed from the QuikSCAT instrument (using both the NASA and RSS geophysical models) shows evidence of a high wind speed bias. This implies that QuikSCAT climatologies of high wind speed events in the vicinity of Greenland [*Moore and Renfrew*, 2005] and perhaps elsewhere [*Sampe and Xie*, 2007] may overestimate the magnitude of these events. In addition, the magnitude of the least squares error for both retrievals, approximately 2.5 m s^{-1}, exceeds the design constraints of the instrument and previous error estimates [*Ebuchi et al.*, 2002; *Chelton and Freilich*, 2005].

[14] The reason for this discrepancy is unclear. *Large et al.* [1995] discuss the possibility that the surface wave field may lead to distortions in the marine wind profile that results in an underestimation of the wind speed by buoys and indeed research aircraft observations in the region indicate that wave heights in excess of 4 m occurred during a reverse tip jet event [*Renfrew et al.*, 2008]. However a similar high wind speed bias is present in a comparison of QuikSCAT and low-level aircraft observations, which should be independent of the surface wave field, in this region (I. A. Renfrew et al., A comparison of aircraft-based surface-layer observations over Denmark Strait and the Irminger Sea with meteorological analyses and QuikSCAT winds, manuscript in preparation, 2008). Furthermore, the NARR 10 m wind field did not suffer from the same bias suggesting that the problem may lie with the scatterometer's geophysical models that are known to suffer from reduced sensitivity at high wind speeds [*Quilfen et al.*, 2007]. Being a region where high wind speeds are common, suggests that Cape Farewell is an ideal location for further scatterometer calibration and validation efforts.

[15] As shown in Table 1, the NARR 2 m air temperature, 2 m specific humidity and sea surface temperature fields were generally in good agreement with the buoy observations. This is consistent with a comparison between the NARR fields and low-level aircraft observations made during the Greenland Flow Distortion experiment [*Renfrew et al.*, 2008, submitted manuscript, 2008]. These comparisons suggest that the NARR fields may be useful in studying the surface meteorology of the Cape Farewell region. The NARR tip jet composites include information not present in previous climatologies, including the presence of a coastal jet along the southeast coast of Greenland, in the vicinity of the Schweizerland Alps, and katabatic flow between this coastal jet and Cape Farewell. There are also differences with previous composites. For example, the reverse tip composite doesn't show any evidence of the anti-cyclonic curvature in the flow to the west of Cape Farewell. The reason for these differences may be related to the buoy location, in that the high winds at this site occur during a different phase of the tip-jet life-cycles compared to previous climatologies, i.e. these composites illustrate a different phase of the life-cycle. Alternatively, the limited period of buoy operation and reduced number of events may also contribute to the composite differences.

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