**The Characteristics and Temporal Variability of Föhn Winds at King Edward Point, South Georgia**

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**Abstract**

The mountainous subantarctic island of South Georgia lies within the belt of strong westerly winds that blow around the Southern Ocean. Interaction of the prevailing circumpolar westerly winds with the island’s central mountain chain, which rises to nearly 3000 m, generates warm, dry föhn winds on the downwind side of the island, which are a significant feature of the local climate. We make use of ten years of automatic weather station observations from King Edward Point (KEP), on the northeastern (climatologically downwind) coast of South Georgia, to develop a climatology of the occurrence and properties of föhn winds in this region. Using objective criteria to identify the onset and cessation of föhn, we find that KEP experiences föhn conditions for around 30% of the time. Föhn events last for about 30 hours on average and are associated with significant increases in temperature and wind speed, and decreases in relative humidity. On average, a föhn event is observed every four days, with little seasonal variation seen in the frequency of occurrence. However, föhn events observed during the austral summer season are, on average, both longer and more intense (as measured by changes in temperature, relative humidity and wind speed) than those occurring in other seasons. The fraction of the time for which föhn conditions are observed at KEP increases (decreases) during months when the prevailing westerlies are strengthened (weakened). Monthly mean temperatures at KEP are positively correlated with the föhn fraction but variations in the latter only explain 16% of the variance of monthly mean temperature. We conclude that, while föhn plays an important role in shaping the local climate of South Georgia, other processes may be of greater importance in controlling regional climate variability and change.

(286 words)

**Keywords:** Föhn, South Georgia, Subantarctic, Southern Ocean, orography, climate change

**1. Introduction**

The island of South Georgia is situated just to the south of the main oceanic polar front in the South Atlantic sector of the Southern Ocean (Figure 1(a)) and, consequently, experiences a climate that is typical of the cool and wet conditions that prevail in the maritime subantarctic. The combined influence of this regional climate with South Georgia’s steep and complex orography results in the island being heavily glaciated.

The continental shelf waters around South Georgia support one of the most diverse and productive marine ecosystems on Earth (Atkinson *et al*., 2001; Young *et al*., 2011; Hogg *et al*., 2011). Large populations of higher predators (whales, seals, and seabirds) and an important commercial fishery depend, directly or indirectly, on the high biomass of zooplankton (particularly Antarctic krill) that is sustained by the large phytoplankton blooms that form in these waters. These blooms result from the high availability of nutrients derived from the island, particularly from glacial runoff. Discharge of glacial meltwater also provides a significant flux of fresh water onto the continental shelf. This buoyancy flux is an important driver of the local ocean circulation (Young *et al*., 2011) and is, consequently, a further control on the regional marine ecosystem. An investigation of the drivers of glacial melt on the island is thus an important first step towards understanding how this unique ecosystem may respond to climate change.

One process that could be an important driver of melt on South Georgia’s glaciers is the föhn effect. The World Meteorological Organization (1992) defines föhn as a warm, dry, downslope wind, descending on the leeside of a mountain range as a result of synoptic-scale, cross-barrier flow. South Georgia’s central mountain chain lies across the track of prevailing westerly winds, making the island’s northeast coastal region susceptible to föhn (Bannister, 2015). Föhn has been identified as an important driver of extreme high temperatures and enhanced glacial melt at several Antarctic and subantarctic locations, including the McMurdo Dry Valleys (Speirs *et al*., 2013), the Antarctic Peninsula (Cape *et al*., 2015), and the South Orkney Islands (King *et al*., 2017). A common feature of all these locations, shared with South Georgia, is a mountain barrier oriented across a prevailing wind.

The earliest observation of a föhn event on South Georgia was made at Royal Bay (see Figure 2) on 1 May 1883, by a German expedition to the island during the First International Polar Year (von Danckelman, 1884). Since then, it has been recognised that the island’s central mountain range greatly influences regional precipitation and weather patterns (Mansfield and Glassey, 1957), but, until now, there has never been a systematic investigation of föhn winds in the lee of South Georgia and their impact on the island’s climate. In this paper we develop the first climatology of the occurrence and characteristics of föhn winds on the northeastern side of South Georgia using observations from a single automatic weather station, which we place into a wider context using data from a high-resolution simulation with a regional atmospheric model. We then use our föhn climatology to explore the relationships between large-scale atmospheric circulation variability, the occurrence of föhn, and climate variability on South Georgia. This paper is organised as follows: in section 2 we describe the topography, physical environment and climatic setting of South Georgia. In section 3 we describe the observational data, the atmospheric model and the method that we use to detect the occurrence of föhn. In section 4 we use a model study of a föhn event to validate our technique for detecting föhn from observations. Having done this, we then develop an observational climatology of föhn winds at a station on the northeast (climatologically downwind) coast of South Georgia. We use this climatology to investigate the impact of large-scale circulation variations on the occurrence of föhn. Finally, in section 5, we discuss the potential importance of föhn winds in shaping the regional climate of South Georgia and controlling its variability.

**2. Physical Setting**

South Georgia is a small (3528 km2 in area) and mountainous (maximum elevation of 2934 m) subantarctic island situated south of the main oceanic polar front in the South Atlantic sector of the Southern Ocean (Figure 1(a)). The climate of South Georgia is typical of the maritime subantarctic, with an annual mean temperature of 2.0oC and annual mean precipitation of 1590 mm recorded at King Edward Point (hereafter KEP, see Figure 2 for this and other locations mentioned in the text) on the northeast coast over the period 1951-1980. Approximately 56% of the total land surface of the island is covered by permanent snow and ice. However, the regional climate of South Georgia is spatially heterogeneous (Bannister, 2015). Although the island is typically less than 30 km wide along its approximately 150 km length, its mountainous spine (Figure 2) forms an effective physical barrier to the prevailing westerly winds of the lower troposphere (Figure 1(b)). The mountain barrier reaches a maximum elevation of 2934 m at Mount Paget and has a typical elevation of around 2000 m along the Allardyce and Salvesen ranges. The western and southwestern coastlines are particularly exposed to eastward-moving low pressure systems, and thus experience low cloud and strong winds throughout the year. In contrast, the northeastern side of the island is sheltered by the mountain barrier (Hosking *et al*., 2015) and often experiences clearer and calmer weather. Despite this sheltering, wind speeds in excess of 30 ms-1 have been recorded at KEP.

The only long-term climate record for South Georgia comes from two nearby stations in King Edward Cove, on the island’s northeast coast. Manual surface observations were taken at Grytviken whaling station between 1905 and 1907, after which manual observations continued at nearby KEP until 1982. After a break in the record, measurements at KEP resumed in 2001 using an automatic weather station (AWS) and continue to the present (Shanklin *et al*., 2009). Based on analysis of this discontinuous record, Thomas *et al*. (2018) have shown that the annual average surface temperature on northeast South Georgia has risen by 1.42oC (0.13oC decade-1) between 1907 and 2016. There is a strong seasonal component to this warming trend, with austral summer months experiencing a greater annual trend (0.23oC decade-1 during the period 1951 – 2016) than any other season. While a number of short climate records are available from other former whaling stations on the central part of the island’s northeast coast, and from Bird Island off the north-west tip of South Georgia, there are no instrumental records available from the relatively inaccessible southwest coast.

Along with the observed increase in air temperatures at KEP, geomorphological evidence generally indicates that the majority of the island’s glaciers are currently at their minimum extent since the beginning of the Holocene (Clapperton and Sugden, 1988; Clapperton *et al*., 1989a; 1989b). Investigations using aerial photography and satellite imagery obtained since the 1950s indicate that the largest 20th century retreats have all taken place along the north-eastern (climatologically downwind) coast where retreat rates have accelerated to an average 60 m per year, but glaciers on the south-western (climatologically upwind) coast have been retreating more slowly (Gordon and Timmis, 1992; Gordon *et al*., 2008; Cook *et al*., 2010). This pattern of recent island-wide glacier retreat is consistent with regional atmospheric warming, but the asymmetry of the observed changes suggests that there may be interactions between regional climate change and the island’s complex orography.

Given South Georgia’s potential susceptibility to föhn, changes in the strength of the westerlies, associated with large-scale climate variability, will affect the frequency and intensity of föhn events on the northeast side of the island. Hence, the local response to broad-scale climate variability and change could be very different on the two sides of the island. During the 20th century, the strength of the circumpolar westerlies above South Georgia increased by around 3 ms-1 while the frequency of occurrence of warm days at KEP (potentially linked to föhn activity) also increased (Thomas *et al*., 2018). The observed rapid retreat of glaciers on the northeast side of the island is thus, at least qualitatively, consistent with enhanced glacial melt and ablation associated with increased föhn activity driven by the strengthening westerlies. A similar mechanism has been shown to be a driver of warming and cryospheric change on the eastern side of the Antarctic Peninsula (Marshall *et al*., 2006; Luckman *et al*., 2014; Cape *et al*, 2015).

**3. Method**

**3.1 Meteorological observations**

Meteorological data presented here were obtained from an AWS operated from 2001 by the British Antarctic Survey at KEP (WMO station number 88903; 54o17′S, 36o29′W, approximately 4 masl elevation), which measured pressure, temperature and (from March 2006) relative humidity at 2 m, and wind speed and direction at 10 m (see Shanklin *et al*., 2009 and Table 1 for further details). Data were recorded at hourly intervals from 2001 to March 2006 and at one-minute intervals thereafter, and have been visually inspected to remove suspect observations. We selected the period January 2003 – December 2012 for our study of föhn events since near-continuous data are available for this period and the temporal resolution of the AWS measurements is much better than that of the earlier manual observations, which were made at six-hourly intervals or less frequently. While the majority of years had less than 2% missing data, the years 2006, 2007, and 2008 had 4.8%, 19.2%, and 6.1% missing data, respectively. Local time on South Georgia is two hours behind Greenwich Mean Time (GMT -2:00) but all times in this paper are expressed as Coordinated Universal Time (UTC).

**3.2 Föhn identification scheme**

Using the AWS observations at 1-hour (January 2003 – March 2006) and 1-minute (March 2006 – December 2012) frequency, a set of criteria based on changes in air temperature, relative humidity, and wind speed and wind direction were developed to identify the start and end of föhn events at KEP. Identifying and detecting near-surface föhn signatures through timeseries analysis has been similarly adopted in other studies of föhn (see e.g. Gaffin, 2007; Speirs *et al*., 2013). Our primary criterion for the onset of föhn conditions is:

(1) An increase of air temperature, greater than 2oC within one hour

This threshold is set to remove detections of any gradual changes in temperature, which may be associated with diurnal changes, solar and cloud effects, or other downslope wind effects (see e.g. Mansfield and Glassey, 1957). If an event meets this criterion, then we required that it must also meet *each* of the following secondary criteria:

(2) A marked decrease in relative humidity, during the specified event, and;

(3) A marked increase in wind speed, during the specified event, and;

(4) Wind from the direction of the barrier

Considering the orientation of the island’s main mountain chain, winds with a direction 150o – 330o were deemed to be indicative of cross-barrier flow-over conditions that have potential for generating leeside föhn at KEP. Unlike criterion (1), we did not set specific thresholds for criteria (2) and (3) because the signals in near-surface wind speed and relative humidity were often more muted, variable or inconsistent compared to the temperature signal. Wind speed was not given a specific threshold because it is strongly controlled by the local complex topography of King Edward Cove and can easily obscure föhn onset and cessation, while relative humidity was similarly not given a specific threshold because it was found that the warming conditions often remained established despite an increase in relative humidity compared to its pre-föhn value (see Bannister, 2015, for examples and further details). Additional limitations in data availability and missing data (e.g. relative humidity data was only available from March 2006 onwards, Table 1) also restricted thresholding. Despite the lack of fixed thresholds, all detected events showed a relative humidity decrease of at least 3% and a wind speed increase of at least 1.8 ms-1.

We identified the cessation of föhn conditions by a sudden drop in temperature (taken to be the greatest change in temperature over the shortest period of time), which may or may not have coincided with concurrent changes in wind speed, wind direction, and/or relative humidity. If there was no discernible drop in temperature, and the observed wind direction was still within the 150o – 330o range, then any sudden decrease in wind speed or sudden increase in relative humidity (whichever change occurred first over the shortest period of time) defined the end of föhn conditions. If there was no discernible end to an event (i.e. no sudden changes in any of the variables) despite having apparently started, then the event was not recorded as föhn. Since the föhn effect on South Georgia has never before been quantified in any great detail, and given the various limitations of the dataset previously outlined, the method for föhn detection described here strives to be the most objective it can be for the type and amount of data and observations available. In section 4 below, we present a simulation of föhn conditions over South Georgia using a high-resolution atmospheric model that confirms that our observationally-based criteria for the onset and cessation of föhn conditions have a sound basis. In what follows, the term ‘föhn event’ refers to an individual episode of föhn conditions with its start and end defined as described above. We define a ‘föhn day’ as a day that experiences 6 or more hours of föhn conditions.

**3.3 The WRF model**

We have carried out high-resolution atmospheric simulations for the South Georgia region using the Weather Research and Forecasting (WRF) model in order to investigate the atmospheric flows associated with föhn conditions and to set the observations from KEP into a wider regional context. WRF is a fully-compressible, non-hydrostatic regional atmospheric model that uses a terrain-following pressure coordinate in the vertical (Skamarock *et al.*, 2008), making it a suitable tool for studying atmospheric flow over complex terrain at high resolution. For the case study presented here, we use WRF version 3.8.1 along with the model configuration as described in detail in Bannister (2015). Table 2 provides a summary of the WRF model setup and the parametrisations used.

The case study simulation presented here was run on a series of three nested domains. The outermost domain covered a large area of the Southern Ocean around South Georgia, with 94 $×$ 54 grid cells at a horizontal resolution of 8.1 km. The second nested domain covered the whole of South Georgia, with 85 $×$ 73 grid cells at a horizontal resolution of 2.7 km and the innermost domain covered the highest part of the axial mountain chain, with 52 $×$ 52 grid cells at a horizontal resolution of 0.9 km. All three domains had 70 vertical levels between the surface and the model top at 50 hPa, with the lowest model level about 6 m above the surface. Given the high spatial and temporal resolutions necessary for capturing flow regimes on South Georgia, we imposed small model domains and a short model integration timestep in order to prevent numerical instability while ensuring sufficient accuracy. Extensive preliminary simulations testing the sensitivity of föhn to grid resolution showed greater biases in comparison to tests involving variations in the downscaling technique and in the size and positioning of the model domains (Bannister, 2015). A large grid-spacing ratio (between the forcing data and WRF) was also employed since these sensitivity simulations also highlighted that large-scale föhn flow and dynamics were captured regardless of model nesting setup (not shown). Despite the relatively small size of the innermost domain, visual inspection of the model output showed that spurious effects in temperature and wind (caused by the boundary edges) did not propagate towards KEP. .

The initial and lateral boundary conditions were derived from the European Centre for Medium-Range Weather Forecasts Interim Reanalysis (ERA-Interim, Dee *et al*., 2011), with the lateral boundary conditions (along with sea surface temperature and sea ice fields) updated every six hours. Model topography for South Georgia was taken from a digital terrain model with 4 arc second (approximately 0.1 km) resolution, based on Shuttle Radar Topography Mission 90 m resolution data, while land surface types were derived using a 90 m resolution dataset (available at <http://www.sggis.gov.gs>) derived from Landsat Normalised Difference Vegetation Index data. Model parameter values were optimised following a series of sensitivity tests described in Bannister (2015). In contrast to Bannister (2015), horizontal diffusion was computed in physical space rather than along model levels (whereby diffusion acts on horizontal gradients computed using a vertical correction term rather than on gradients in coordinate surfaces). Collier *et al*. (2015) have previously shown that this approach leads to more accurate flow simulations in topographically-complex environments where the model level surfaces are significantly sloped. To allow for the stabilisation of soil temperature and moisture and ground heat fluxes, we also included a 2-day spin-up period for the case study. Only model output from the 2.7 km and 0.9 km domains are presented here.

**4. Results**

**4.1 Föhn event case study: 9 – 10 August 2012**

In order to confirm that our detection scheme is correctly identifying the onset and cessation of föhn conditions, and that the structure of the detected events is compatible with föhn theory, we have examined the atmospheric flows associated with a föhn event using the WRF model configuration described in section 3.3. This case study was selected for being a typical example (within the context of the föhn climatology presented later) of a föhn event, which gave rise to temperatures exceeding 0oC at KEP during winter and was characterised by rapid changes in wind speed and relative humidity.

Figure 3(a) – (d) shows the evolution of this event in observations from KEP during 9 – 10 August 2012. At 1749 UTC on 9 August, there was a distinct föhn signature detected in the observations (grey shading, Figure 3 (a) – (d)), with a rapid increase in temperature and wind speed, along with a simultaneous decrease in relative humidity. Within one hour of föhn onset, the temperature at KEP had increased by 7.9oC. The maximum temperature and wind speed recorded were 11.0oC and 11.4 ms-1 respectively (the highest measurements of the day), while relative humidity reached a minimum of 41%. The average wind direction during the event was 316o. The föhn event lasted 10 hours and 35 minutes in total, when the end of the event was marked by a drop in temperature of 4.9oC within one hour at 0424 UTC on 10 August. This föhn event was induced by the eastward movement of a low pressure system across the Scotia Sea (Figure 3(e)), which generated strong westerly airflow as the system passed south of the island.

The corresponding timeseries of modelled variables from the high-resolution (0.9 km) domain (at the grid cell closest to KEP) are shown in Figure 3 (a) – (d). Despite not reaching the extrema of the observations, the WRF model does replicate the observed sustained warming and drying during the event. Consistent with the observed start of the event, föhn onset is accompanied by a 2.0oC increase in modelled temperature (and concurrent changes in the other model variables) at 1900 UTC on 9 August. Although the model underestimates temperature changes compared to the observations, Figures 4(b) and (f) show that the warmest modelled temperatures during the event (at 0000 UTC on 10 August) were not at KEP but occurred along the low-lying coastal regions directly in the lee of the mountains. In agreement with the observations, the temperature exceeds 10oC approximately 5km south of KEP in the model. Figure 4 further illustrates the asymmetry of the influence of föhn across South Georgia, with a clear cross-barrier temperature gradient between the southwest and northeast coastlines, and a rain shadow over KEP which is consistent with the rain gauge observations (not shown) for this period. The structure of the leeside near-surface wind fields and the downslope wind maxima (Figures 4(c) and (g)) clearly indicate the influence of orographic forcing on the flow over South Georgia. Cross-sections of potential temperature during the event (Figure 5(b) and (e)) suggest that the flow is nonlinear, as evidenced by the large wave amplitudes and strong leeside acceleration (Elvidge *et al*., 2016) which are not present directly before (Figure 5(a) and (d)) or after the event (Figure 5(c) and (f)). The WRF model simulation therefore confirms that the rapid warming and drying observed at KEP was due to a dynamic föhn, where strong downslope winds develop in the presence of strong westerly cross-barrier flow and the associated isentropic drawdown causes surface warming and drying in the immediate lee of the mountains of South Georgia. Isentropic drawdown downwind of the mountain crest was evidenced in all three of the WRF model domains.

The case study presented above, along with others presented in Bannister (2015), confirm that the modelled atmospheric flows associated with these events are broadly consistent with both föhn theory and with the observations from KEP. This gives us some confidence that our scheme does indeed detect the onset and cessation of föhn. Having confirmed this, we now use our observation-based scheme to develop a climatology of föhn at KEP.

**4.2 Frequency of occurrence and characteristics of föhn at King Edward Point**

**4.2.1 Mean characteristics**

Over the period January 2003 to December 2012, our scheme detected a total of 874 föhn events. This translates into a frequency of 7.3 events per month, or one event approximately every four days. With such a high frequency of föhn events, KEP experiences föhn conditions for approximately 30% of the total time. The mean, maximum, and minimum conditions of the 874 föhn events are presented in Table 3. On average, föhn events last for 29 hours and 49 minutes, and are characterised by a mean change (extreme value observed during föhn minus the value observed at the time of föhn onset) in temperature, wind speed, and relative humidity of 7.3oC, 10.3 ms-1, and 41%, respectively. The highest maximum temperature reached during a föhn event was 23.5oC (9 February 2004), equating to a total temperature rise of 19.3oC during the event (also the greatest temperature change observed). The driest event was recorded on 16 December 2011, when the relative humidity dropped to 7% (a total drop of 85%, the greatest drop in relative humidity observed), while the windiest föhn occurred on 30 August 2006, when the wind speed peaked at 21.8 ms-1.

**4.2.2 Interannual variability**

Figure 6(a) shows the total number of föhn events which were recorded each year between 2003 and 2012. The frequency of föhn events shows considerable interannual variability. The highest number of events was recorded in 2006 (103 in total), compared to 2007 which had the fewest (54 in total). However, 2007 also had the highest amount of missing data (approximately 19.2%, the equivalent of ~70.1 days) compared to any other year in the record examined here. Based on the assumption that one föhn event occurred for every four days of missing data, we would expect an additional 18 föhn events to have occurred, which would raise the total for 2007 to 72 events. On average, there are 87.4 föhn events per year. The number of föhn events detected in 2003-2005 may be biased low relative to 2006-2012 as a result of the change from hourly to one-minute sampling. Re-running the föhn detection algorithm on hourly-sampled data for 2006-2012 reduced the number of events detected by 17%.Of all the months between 2003 and 2012, January 2004 is found to have the highest total duration of föhn conditions, with 70.2% (≈ 522 hours) of the month identified as föhn. It is interesting to note that January 2004 is the equal warmest month (along with January 2009) between 2003 and 2012, as well as being the equal fourth warmest month since 1905, with a mean temperature of 7.7oC.

**4.2.3 Seasonal variability**

The total number of föhn events in each month at King Edward Point for the period 2003 – 2012 is given in Figure 6(b). Föhn events occur throughout the year, and they exhibit little to no seasonality. March has the greatest total number of events (95 events in total), despite the greatest number of missing observations in 2007 occurring during March of that year. By contrast, April has the fewest recorded number of events (58 events in total). The mean frequency of occurrence of föhn in any particular month is not significantly different to the annual mean frequency of 72.8 events (p > 0.05 for all months).

Figure 7 presents the fraction of föhn events where the duration, temperature change, relative humidity change, and wind speed change deviate from their respective annual mean values during föhn conditions (see Table 3) by more than one standard deviation. Although Figure 6(b) shows that there is no observable seasonality in the total number of föhn events, Figure 7 shows that there is a statistically significant seasonal cycle in the duration of events and the changes in temperature, relative humidity, and wind speed associated with them. On average, föhn events tend to be longer during the austral summer, with larger temperature and wind speed increases, and drops in relative humidity compared to austral winter föhn events. Föhn events are, on average, just over 8 hours longer during the summer months than in the winter months. This also corresponds to a greater fraction of events with a change in temperature greater than or equal to 10.34oC in summer (34.1%) than winter (20.3%) (Figure 7(b)). Similarly, 29.7% of föhn events which occur in summer have a change in relative humidity greater than or equal to 57%, compared to 16.8% events in winter (Figure 7(c)). There are also a greater fraction of events with a change in wind speed greater than or equal to 13.45 ms-1 in summer (27.2%) than winter (22.1%) (Figure 7(d)). Therefore, although föhn events do not appear to be more common during the summer (Figure 6(b)) they are certainly longer and more intense than they are in the winter (Figure 7).

**4.3 Relation of föhn to large-scale atmospheric circulation**

Föhn occurs when the broad-scale atmospheric circulation forces air across a mountain barrier. In order to investigate how the regional atmospheric circulation controls the occurrence of föhn at KEP, we make use of 6-hourly data from the ERA-Interim reanalysis. For this analysis we restrict our attention to the 5-year period 2008-2012 in order to remove potential biases associated with the change from hourly to one-minute AWS data in 2006 and the large percentage of missing data in 2007.

Figure 8a shows the distribution of wind direction at the 775 hPa level for föhn and non-föhn days at a point shown on Figure 2, approximately 100 km west of KEP. The 775 hPa pressure level lies at an elevation of around 2 km, which is representative of the mean height of the South Georgia mountain barrier crest in the vicinity of KEP. For both föhn and non-föhn days the modal wind direction lies in the westerly sector, consistent with South Georgia’s location within the circumpolar westerly winds. However, the distribution for föhn days is much narrower than that for non-föhn days. The modal direction for föhn days is almost due westerly, while that for non-föhn days is around 30° south of westerly. Less than 1% of föhn days have a wind direction outside the range 195°-330°. The fraction of days classified as föhn peaks at 57% for winds in the sector 270°-285° and falls to only 23% in the sector 210°-225°.

There is also a clear separation between the distributions of 775 hPa wind speed on föhn and non-föhn days (figure 8b). The mean wind speed for föhn days is 19.4 m s-1, compared to 15.1 m s-1 on non-föhn days (difference of means significant, p < 0.001). A wind speed of less than 10 m s-1 is seen on 27% of non-föhn days but on less than 2% of föhn days. The occurrence of föhn conditions at KEP is thus associated with stronger than average westerly winds blowing across South Georgia.

The strength of the westerlies in the vicinity of South Georgia is controlled by the large-scale gradients of pressure and geopotential height around the island. Figure 9 shows the difference between the average mean sea level pressure (MSLP) field for föhn days and that for non-föhn days. Föhn days are associated with anomalously high MSLP over the South Atlantic to the northeast of South Georgia and anomalously low MSLP over the Scotia Sea to the south of the island. This anomaly pattern locally strengthens the meridional pressure gradient, leading to strengthened westerlies over South Georgia.

In order to examine the relationship between broad-scale circulation and the occurrence of föhn at KEP we have extracted daily (1200 UTC) values of MSLP from the ERA-Interim reanalysis at the locations of the two “centres of action” seen on Figure 9 to produce an index, Δp, defined as the difference in pressure anomalies (with respect to the long-term mean) between the centres. Figure 10 shows monthly values of the föhn day fraction (i.e. the fraction of days in that month that were classified as föhn days) at KEP plotted against the monthly average Δp value. Föhn day fraction is moderately well correlated with Δp (r=0.46, p<0.001) and the regression line shown on Figure 10 indicates that a 10 hPa increase in Δp leads to an increase in föhn day fraction of around 0.08.

**4.4 Impact of föhn on the climate of King Edward Point**

Since föhn events are associated with significant changes in temperature, humidity and wind speed, and as föhn conditions are observed at King Edward Point for approximately 30% of the total time, they are likely to be a major influence on the local climate. Table 4 shows mean values of temperature, relative humidity and wind speed at KEP on föhn and non-föhn days, for the year as a whole and for each season individually. On average, föhn days are 3.2°C warmer than non-föhn days, with very little seasonal variation. Föhn events are responsible for the majority of the warmest days at KEP, accounting for 82% of days with a mean temperature greater than 10.0oC. The majority of föhn events result in air temperatures rising above 0°C at KEP, with only 20 out of a total of 874 events failing to meet this threshold. During the winter months (JJA), 76% of föhn days had a mean temperature of 0°C or higher, compared to only 25% of non-föhn days.

As noted in section 4.2, the onset of föhn conditions is associated with a significant drop in relative humidity. Over the year as a whole, the average relative humidity on föhn days is 8.6% lower than on non-föhn days but, in contrast to temperature, there is a marked annual cycle in the humidity difference, with the winter season difference being around half that seen in summer. This seasonal cycle largely results from seasonal changes in the mean humidity on föhn days, while that on non-föhn days remains relatively constant throughout the year.

Föhn events are also the predominant source of strong winds at King Edward Point. Over the period of record studied here they account for 62% of days with mean wind speed ≥5.0 ms-1, and 62% of days with mean wind speed ≥10.0 ms-1. The 10 m wind speed at KEP on föhn days is, on average, 2.4 m s-1 stronger than that on non-föhn days, with little seasonal variation in the difference.

Figure 11 shows monthly temperature anomalies for 2008-2012 (with respect to the 2008-2012 mean) plotted against the föhn day fraction. The two timeseries are only moderately well correlated (r=0.4) but the correlation is highly significant (p<0.01). While monthly variations in föhn day fraction thus explain only 16% of the variance in monthly temperature anomalies, the regression line shown on Figure 11 indicates that a 10% increase in föhn day fraction will lead, on average, to an increase of monthly mean temperature of about 0.3°C.

**5. Discussion**

Our analysis of AWS observations from KEP, situated on the northeastern (climatologically downwind) coast of South Georgia has demonstrated that föhn winds affect this location for around 30% of the total time. Föhn conditions are observed most frequently during periods when the prevailing westerly winds blowing across the mountains of South Georgia are stronger than average. Simulation of the flow across South Georgia under such conditions using a high-resolution model shows that the warm, dry winds on the lee side of the island result from the subsidence of air with a relatively high potential temperature from levels above the crest of the island’s mountain ridge. Elvidge and Renfrew (2016) show that this “isentropic drawdown” mechanism for föhn warming is typically dominant in a “nonlinear” flow regime (Elvidge *et al*, 2016), where the upwind flow is blocked at some level below the ridge crest. This nonlinear flow regime is characterised by values of the upstream Froude number, *Fr = U/NH,* of less than unity. Here *U* is the wind speed averaged between the height, *H*, of the ridge and the surface, and *N* is the Brunt-Väisäla of the layer between *H* and the surface, both calculated for the undisturbed flow upstream of the ridge. Taking *H* = 2000 m as typical of the elevation of the ridge crest immediately upwind of KEP and calculating *Fr* using ERA-Interim data, we find that *Fr* rarely exceeds unity. On around 60% of föhn days *Fr* lies between 0.4 and 0.7. This range of *Fr* is consistent with a nonlinear flow regime and suggests that the warming that is observed during föhn events at KEP results largely from isentropic drawdown. Additional warming may be taking place due to latent heating associated with precipitation on the upwind side of the island, but this is likely to be a secondary contribution in this nonlinear regime (Elvidge and Renfrew, 2016).

For almost all cases of föhn observed at KEP, the wind direction at ridge crest height was between 200° and 320°. The greatest number of occurrences of föhn were seen for wind directions between 270° and 285° and the fraction of days classed as föhn days also peaks in this sector. For winds in the southwesterly sector, the fraction of days classed as föhn days is considerably lower. This is a somewhat surprising observation since, in this latter sector, the wind is blowing directly across the mountain ridge, a situation that should be optimal for the development of lee-side föhn. However, the topography of South Georgia (Figure 2) is not a simple linear ridge of constant height. Between the main summits along the ridge there are gaps of lower elevation, and the alignment of the divide varies significantly along the length of the island. With winds from the southwest, KEP is directly downwind of the highest section of the ridge while winds from the westerly sector blow over lower topography, leading to a higher effective Froude number which may favour the occurrence of föhn in this sector.

We have found little seasonal variation in the frequency of occurrence of föhn at KEP. This contrasts to other locations, such as the McMurdo Dry Valleys (Speirs *et al*., 2013), the Antarctic Peninsula (Cape *et al*., 2015; Wiesenekker *et al*., 2018), and the European Alps (Weber and Prévôt, 2002), where a strong annual cycle in the occurrence of föhn has been observed and can be related to the annual cycle in the speed of the winds across the mountain barrier. The lack of a seasonal cycle in föhn occurrence at KEP is consistent with the weak seasonal variability seen in the wind speed at 775 hPa over South Georgia, (Figure 12), which we have shown is a strong control on the occurrence of föhn at KEP.

While there is no clear seasonal cycle in the occurrence of föhn we have found that summer föhn events last longer and are stronger (as measured by the associated changes in temperature, humidity and wind speed) than winter events. Data extracted from the ERA-interim reanalysis in the vicinity of South Georgia show that the average difference in potential temperature between the 775 hPa level (approximately 2000 m elevation) and the 950 hPa level (approximately 400 m elevation) is 1.3 K greater during summer (DJF) than during winter (JJA, significant at < 1%). Since föhn warming results from the displacement of near-surface air by adiabatically-warmed air descending from around summit level, this observation may explain why summer föhns are stronger (at least as measured by temperature increase) than those observed during winter. Although the seasonal variability in the 775 hPa wind is small, the wind speed, particularly of the u- (westerly) component is highest during the summer season, which may contribute to the longer duration of föhn events in this season.

During föhn, conditions at KEP are significantly warmer, drier and windier than during periods when föhn is not present. Since föhn occurs for around 30% of the time at KEP it will have a significant influence on the local climate, and variations in frequency of occurrence of föhn might be expected to contribute significantly to local climate variability. While we have demonstrated that there is a statistically significant relationship between monthly variations in föhn day fraction and temperature, föhn variability only explains 16% of the variability in monthly temperature anomalies at KEP. This contrasts to other regions, such as the McMurdo Dry Valleys (Spiers *et al.*, 2013) and the Antarctic Peninsula (Cape *et al.*, 2015; Wiesenekker *et al.*, 2018), where föhn variability, linked to atmospheric circulation variability, has been shown to be a major contributor to local climate variability on seasonal to interannual timescales. On South Georgia, while föhn does contribute to local climate variability, its impact appears to be somewhat masked by other processes, such as variability in large-scale thermal advection.

The analysis presented in this paper is largely based on observations from a single AWS at KEP. However, the high-resolution model simulation that we present in section 4.1 clearly shows that the impacts of föhn are not restricted to the immediate vicinity of KEP but extend across much of the central section of South Georgia to the northeast of the axial ridge. The widespread nature of föhn on South Georgia is confirmed in similar case study simulations carried out by Hosking *et al.* (2015), and Vosper (2015). Bannister (2015) and Bannister and King (2015) present the results of a 21-month model simulation using the WRF configuration used for the case study in section 4.1. This extended model study clearly demonstrates that, owing to the strong prevalence of westerly winds, the warming and drying effects of föhn occur most frequently and are widespread on the northeast side of the island, leading to asymmetry about the central mountain chain in the regional climate. Additional AWS measurements are needed to validate model simulations of this complex, small-scale spatial climate variability. Measurements over the island’s glaciers, which may be sensitive to climate variability associated with föhn, would be of particular interest.

Changes in the frequency of occurrence of föhn on the northeastern side of South Georgia, associated with variations in the strength of the prevailing westerly winds, may have contributed to the climate variability seen in the long-term temperature record from KEP (Thomas *et al.,* 2018). In particular, the warming trend seen between the late 1950s and the break in the record in 1982 corresponds with a period where a positive trend was observed in the Southern Hemisphere Annular Mode (SAM) index, which is a proxy for the strength of the zonally-averaged circumpolar westerlies (Marshall, 2003). Bracegirdle *et al.* (2013) examined future trends in the westerlies across a range of climate model predictions from the Fifth Coupled Models Intercomparison Project (CMIP5) and found a mean increase of around 5% in the strength of the westerly winds in the Atlantic sector over the second half of the 21st century under the RCP8.5 high emissions scenario. Our analysis of the statistical relationships between the strength of the westerlies, occurrence of föhn, and temperature at KEP indicate that a 5% increase in the strength of the westerlies would only result in a warming of around 0.2°C at KEP as a result of increased frequency of föhn.

We conclude that, while föhn strongly shapes the spatial variability of climate on South Georgia, it only explains a relatively small fraction of the observed variability in temperature on monthly to interannual timescales. Local processes, including föhn variations associated with changes in the strength of the westerlies, will contribute to future climate change on South Georgia, but future change may be dominated by regional changes in temperature and large-scale thermal advection.

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Table captions

**Table 1.** Details of the AWS at King Edward Point.

**Table 2.** Details of the WRF model configuration used for the case study presented in section 4.1.

**Table 3.** The mean, maximum, and minimum conditions of the 874 observed föhn events at King Edward Point AWS. Changes shown here are relative to values observed at the time of föhn onset.

**Table 4.** Mean annual and seasonal temperature, relative humidity, and wind speed at KEP during föhn and non-föhn days between 2003 and 2012. The columns labelled Δ show the mean for föhn days minus that for non-föhn days. All Δ values are statistically significant (p<0.05).

Figure captions

**Figure 1.** (a) The location of South Georgia relative to the Antarctic Peninsula and the Falkland Islands. The solid red line highlights the oceanic Polar Front, while the solid white line indicates the median 1981 – 2010 September sea ice extent. (b) Mean (1979 – 2015) 10 m wind speed vectors and sea level pressure contours (hPa), derived from the ERA-Interim reanalysis.

**Figure 2.** A topographic map of South Georgia, showing locations mentioned in the text. The red filled circle indicates the location at which 775 hPa wind data were extracted from the ERA-Interim reanalysis to generate figures 8 and 12.

**Figure 3**. (a)-(f) Observed (solid blue lines) and modelled (black circles) 2-m air temperature (a), 2-m relative humidity (b), 10-m wind speed (c), and 10-m wind direction (d) for the 9 – 10 August 2012 föhn event. The grey shaded regions indicate the duration of föhn conditions. Model data were extracted from the 0.9 km WRF domain, at the grid point closest to King Edward Point AWS. (e) Mean sea level pressure and 750hPa wind speed vectors at 0000 UTC on 10 August 2012 from the ERA-Interim reanalysis.

**Figure 4**. WRF model output from the 2.7 km (top row) and 0.9 km (bottom row) domains during the 9-10 August 2012 föhn event. Panels (a) and (e) show the WRF model orography. King Edward Point is indicated by the red-filled circle and the red lines on panel (a) indicate the orientations of the cross-sections shown in Figure 6. The black box indicates the extent of the WRF 0.9 km domain. 10 m wind vectors at 0000 UTC on 10 August are shown superimposed on 10 m wind speed contours (panels (b) and (f)), and on 2 m air temperature contours (panels (c) and (g)). Panels (d) and (h) show total precipitation accumulation during the föhn event.

**Figure 5**. Cross-sections of potential temperature from the WRF 2.7 km domain along the solid red line (panels (a) to (c)) and along the dotted red line (panels (d) to (f)) shown on Figure 5(a). Panel (a) and (d) - 9 August 1800 UTC, (b) and (e) - 10 August 0000 UTC, and (c) and (f) 10 August 0700 UTC.

**Figure 6**. Panel (a) the total number of föhn events recorded each year at King Edward Point between 2003 and 2012 (grey) and the total duration of all föhn events expressed as a percentage of that year (red). The black dotted line denotes the change from data recorded at hourly to one-minute intervals in 2006. Panel (b) the total number of föhn events each month between 2003 and 2012 (grey) and the total duration of all föhn events expressed as percentage of that month (red).

**Figure 7**. The percentage of föhn events between 2003 and 2012 (broken down by season) which exceed (a) a total duration of 57.49 hours, (b) a change in temperature of 10.34oC, (c) a change in relative humidity of 57%, and (d) a change in wind speed of 13.45 ms-1. These thresholds are 1 standard deviation above their respective mean value (see Table 3).

**Figure 8.** (a) Distribution of 775 hPa 1200 UTC wind direction at 54.25°S, 38.0°W over 2008-2012 from the ERA-Interim reanalysis. The black line shows the distribution for the 1213 non-föhn days, red for the 614 föhn days. (b) As for (a), but for 775 hPa wind speed and for days when the 775 hPa wind direction was between 220° and 320°.

**Figure 9.** Difference between the average mean sea level pressure at 1200 UTC on föhn and non-föhn days during 2008-2012. Pressure data are from the ERA-Interim reanalysis. Stippled regions indicate where the difference is statistically significant (p < 0.01)

**Figure 10.** Monthly values of föhn day fraction for 2008-2012 plotted against corresponding monthly mean values of the pressure difference anomaly between the two “centres of action” visible on Figure 11. The solid line is a least-squares linear fit to the data.

**Figure 11.** Monthly temperature anomalies at KEP for 2008-2012 plotted against the föhn day fraction for that month. The solid line is a least-squares linear fit to the data.

**Figure 12.** Monthly mean wind speed at 775 hPa at South Georgia for 2008-2012 from the ERA-Interim reanalysis. Plus signs – scalar wind speed, asterisks – zonal wind component.