Long-term trends in Gale Days and Storminess for the Falkland Islands

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Abstract

Weather typing, based on surface pressure charts, has been one of the principal means of analysis in synoptic climatology. Here, we use an automated scheme to derive Weather Types (WTs) and also calculate Lamb Weather Types (LWTs) for the Falkland Islands. The WTs are based on sea-level pressure data estimated using two Reanalysis products: one that extends from 1948-2014 and another that just uses station pressure data as input and extends back to 1871. The WTs can be used to derive counts of gale days and these will be compared with storminess estimates based on the rate of change of daily-average pressure measurements at the principal observational site (near the capital, Port Stanley) on the islands. A particular emphasis of the paper is the reliability of the results taking into account that we are using Reanalysis datasets from a very data-sparse region of the world. More gale days are estimated during the period from about 1880 to the mid-1910s and since the 1980s. Fewer gale days are evident during other periods, particularly from the mid-1910s to 1947. As these changes are not evident in the storminess measure derived from the sub-daily pressure series for the Port Stanley region, the results in terms of gale-day counts are very suggestive of being due to differences in the quality of the Reanalysis during the different periods. The Reanalysis appears better the higher the number of gale days estimated. The opening of the Panama Canal in 1914 dramatically reduced the number of ships, and hence observations, rounding Cape Horn. The paper also relates seasonal counts of the LWTs and WTs to recently developed long series of temperature and precipitation for the Port Stanley region.

1. Introduction

Lamb Weather Types (LWTs) have been widely used in climatology studies across the British Isles since their introduction by Lamb (1972). The availability of Atmospheric Reanalyses (e.g. Kalnay et al., 1996 and Compo et al., 2011) producing more consistent daily weather charts, has enabled similar Weather Types (WTs) to be developed for diverse mid- and high-latitude regions of the world and to be extended back to the beginning of Reanalyses in 1871 (see discussion in Jones et al., 2013, 2014). Weather Typing is the cornerstone of synoptic climatology and numerous pattern-typing approaches have been developed since the 1960s (see Yarnal, 1993 for an early review). The only scheme more widely used than LWTs is Die Grosswetterlagen (GWL), which extends back to 1881 for Europe. James (2007) provides a history of the GWL approach and an automated scheme that has been developed using Atmospheric Reanalyses.

The automation of LWT approaches (Jenkinson and Collison, 1977, see Appendix A) has also enabled other objective assessments to be made of the number of gales and of storminess indices, which could potentially be more consistent through time than using measurements made with anemometers (which are affected by improvements in instrumentation and by site changes). A summary of what is available for the British Isles and the North Sea region is given on this web site (http://www.cru.uea.ac.uk/cru/data/lwt/). These measures have been used in some sectors such as the impacts of changing weather on floods across the UK (Rumsby and Mackin, 1994, Pattison and Lane, 2012 and Wilby and Quinn, 2013).

The purpose of this study is to calculate storminess measures and LWTs for the domain that encompasses the Falkland Islands (50-55°S by 55-65°W, see also Figure A1 in Appendix A). The Islands are at a similar latitude (but in the Southern Hemisphere) to the UK where indices and measures have already been developed (Jones et al., 2013, 2014). The analysis will produce daily LWTs for the Islands as well as Gale Indices/Storminess measures, which are both developed from measures of the strength and direction of mean flow and vorticity (collectively referred to as the WTs). The latter three measures, which are the main aim of this paper, have been shown over the UK to be strongly related to average temperatures and precipitation amounts (using regional series such as Central England Temperature and England and Wales Precipitation, see Jones et al., 2014). In this study we will assess the strengths of these relationships using the long monthly temperature and precipitation series that have been developed for the Mount Pleasant Airfield (MPA) site on the Falkland Islands (Lister and Jones, 2015). Complete results of the study are available on this web site (http://www.cru.uea.ac.uk/cru/data/falklands/). The Falkland Islands are in a part of the world where the number of sites reporting data to Reanalysis products is markedly poorer than the UK and the surrounding North Atlantic, so we will also address the issue of the differences in reliability of the series from 1871 to the present. This discussion will also address the concerns of Krueger et al. (2013) about the reliability of storminess measures in Reanalysis products.

The paper is structured as follows: Section 2 will introduce the datasets used and Section 3 relates the WTs to the long temperature and precipitation series for the Islands. Section 4 develops the gale index and storminess series and extensively discusses the reliability of the results, while Section 5 provides a few conclusions.

2. Datasets Used and Preliminary Comparisons

Here we use the National Centers for Environmental Prediction (NCEP) Reanalyses which extend back to 1948. For earlier years from 1871 to 1947 we use the 20th Century Reanalyses (20CR). The NCEP Reanalyses (Kalnay et al., 1996) are available at a spatial resolution of 2.5° by 2.5° latitude/longitude at the four synoptic hours (00, 06, 12 and 18 GMT) for each day from 1948. The latitude/longitude resolution used for the objective WT classification scheme (2.5° latitude by 5° longitude, see Appendix A) can be extracted for the region without the need to perform any grid-point interpolation. This grid-resolution is half that used for the British Isles by Jones et al. (1993, 2013). Experimentation (not shown) for the British Isles at this resolution shows that this approach produces similar results to the 5° latitude by 10° longitude grid, but the results in terms of LWTs and gale-day counts are more relevant to regional scales across the British Isles (e.g. Southern Britain, Northern Britain and Ireland). Some aspects of this are discussed briefly in Jones et al. (2014). Although we have yet to experiment with smaller grids, we feel that the spatial resolution used in this paper is the smallest that can be considered for these types of approaches, both in terms of interpretation but also in terms of the spatial gradients of the pressure differences. The smaller spatial scales means that some of the constants used in Jones et al. (2013) need to be altered and these are discussed in Sections 3 and 4 and in Appendix A.

Using these data, we calculated the WT variables (flow strength, direction and vorticity, which are referred to later as F, D and Z) for each day from 1948 onwards producing four separate analyses for each of the synoptic hours and an additional one based on the average of all four synoptic hours (from 00 to 18) within each calendar day: a total of five analysis sets. LWTs were produced for the 18GMT analysis as this time slot is closest to mid-day time on the Islands. A similar exercise was undertaken with 20CR (Compo et al., 2011) to produce similar series from 1871 to 2012. 20CR has improved resolution compared to NCEP (2° by 2° latitude/longitude compared to 2.5° by 2.5°), but this requires interpolation (using bilinear splines) for most of the latitude/longitude grid points (for calculation of the WTs) as they are not directly available as was the case for NCEP.

For each of the three basic weather type variables (flow strength, vorticity and direction) for the 18GMT analysis, we correlated the daily values within each year between NCEP and 20CR for the period 1948 to 2012. Correlation coefficients are plotted in Figure 1. For F and Z, the agreement between NCEP and 20CR has been calculated using standard Pearson correlation coefficients. For direction (which is calculated as an angle) we used circular correlation coefficients (Jammalamadaka and Sarma, 1988; Jammalamadaka et al., 2001). Correlations are greater than 0.8 for F and Z for years since about 1980 but they drop to values less than 0.4 for years from 1948 to the 1950s. For Direction (D), the correlations are lower, but almost all are greater than 0.6 since the late 1970s, but they fall to lower values of 0.1 to 0.4 between 1948 and the 1950s.

The improvement in the late 1970s is partly related to the availability of satellite information from this time, but also to improvements in surface coverage (Cram et al., 2015). The 20CR Reanalyses are solely based upon station pressure measurements as input data, but these are considerably enhanced after 1948 (see Cram et al. 2015, which discusses Version 2 of the International Surface Pressure Databank, ISPD). Many more station pressure measurements are available for the southern South American region since the 1970s. NCEP, which starts in 1948, makes additional use of Radiosonde data from then and satellite data from the mid-to-late 1970s. Satellite data availability is known to have brought about a significant improvement to operational weather forecasting in the Southern Hemisphere at this time (Dee et al., 2011). The NCEP data, therefore, should be better than 20CR for the period since 1948, but NCEP will likely be less good before the satellite era.

The long WT and Gale Index series used later will be based upon NCEP for 1948 to 2014 and 20CR for 1871 to 1947. In the next section we relate the time series of the three WTs (flow strength, wind direction and vorticity) to the only long temperature and precipitation series, developed for Mount Pleasant Airport (MPA) on the easterly side of the Islands (Lister and Jones, 2015) at the monthly scale.

During the last five years or so, considerable efforts to digitize more of the hard-copy sub-daily weather measurements made around the world. The success of this, with respect to pressure data, has been documented by Cram et al. (2015). Efforts are ongoing and future Reanalysis Products will be able to take advantage of improvements to the digital archive of measured surface pressure data.

For the Falklands, sub-daily pressure data have been digitized for observations in and around Port Stanley. This includes Cape Pembroke Lighthouse (from the 1870s to 1947), Stanley from the 1940s to the early 1980s and MPA from 1986 to the present (these locations are shown in Figure 1 of Lister and Jones, 2015). In this study, we have accessed this long series and produced a series of daily-mean sea level pressure (MSLP) values from the 1870s to the near present. The number of measurements taken each day varies (between two to eight per day generally, but a few days with only a single reading) depending on the period. To compare with the Gale Index count (see later definition and Appendix A) we will develop an index of day-to-day MSLP variability within each month from these data. We expect that these two measures should be related and therefore the long-term variability of the latter can be used to assess the reliability of the Gale Index counts derived from 20CR and NCEP.

3. Relationships of the WTs to seasonal temperature and precipitation series

Long time series of WTs and also LWTs have been shown in the UK to be related to regional average series of temperature and precipitation (see e.g. Jones et al., 2014). The long temperature series for MPA extends back to 1895, but there are a few missing months in 1902 and 1907/8. The precipitation series extends back to 1904, but most of the monthly totals are missing during 1921 to 1923. Here we use the series from 1925 and they are complete until 2011, giving 87 years for the correlations with the WTs and LWTs. To undertake a similar analysis as for the British Isles we have produced LWTs (from the WTs) assigning each day from 1871 into one of 27 categories (see Appendix A for the derivation of the LWTs from the objectively-defined WTs). These are produced in exactly the same way as those for the British Isles, except for the smaller grid size meaning that unclassified days (where the flow is weak or chaotic) are produced when F is less than 3 and $|Z|$ is less than 3. This value is half the value used for the British Isles due to the grid size being half that for the British Isles. 1.62% of days between 1871 and 2013 are given the unclassified label. This compares with 1.05% for the British Isles in the analysis of Jones et al. (2013). The halving of this threshold to 3 is discussed in the context of halving of the Gale Day thresholds in Section 4.

For the British Isles, Lamb (1972) further summarised his LWT results into monthly counts for the four principal cardinal wind directions and the two synoptic categories (cyclonic and anticyclonic). Lamb (1972) refers to these as his ‘pure’ types. He also used an additional wind direction (north westerly) as a pure type, but here we have dispensed with this and just used the basic six. This rationalization dispenses with the hybrid types and just produces monthly totals for the six primary types. In this process Lamb (1972) split hybrid types and counted each part towards their primary components (e.g. AS gives 0.5 to A and S, while CNE would give 0.33 to each of C, N and E). This procedure ends up with monthly, seasonal and annual counts of the number of days of A, C, W, N, E and S whose totals for any month (with the unclassified days) will add to the number of days in that month. In Appendix B we show example plots of days of the six pure types (A, C, N, E, S and W) and provide some brief discussion of each.

Figure 2 shows annual counts of the two synoptic types (A and C) and of westerly (W) days, with Figure 3 giving similar plots for Northerly (N), Easterly (E) and Southerly (S) types. Westerly days are by far the most dominant for this region with about 180 days on average per year falling into this type. The next most dominant types are Northerly and Southerly days which experience about 60 days each per year. Easterly and Anticyclonic and Cyclonic day counts are relatively few with about 10/20/30 days respectively per year. Long-term changes in the number of these six major types per year are more marked for some types than others. W days were reduced during the 1950s to the 1970s and enhanced in the 1870s and since the late 1990s. N days show the greatest variability on the decade timescale with periods of enhanced Northerlies (1920s to 1940s, 1960s/1970s and 2000s) and reduced values in the other decades. The oscillatory nature of Northerlies is partly followed by Southerlies in an opposite sense, but the variability of Southerlies is less, except for their decline since the late 1990s. Anticyclonic day counts show reduced numbers in the 1870s and since the 1990s in an opposite sense to that seen for Westerly and Southerly day counts. Cyclonic day counts show an almost doubling of the annual number of days in the late 1940s. Finally, Easterly day counts are relatively few per year and any long-term changes are relatively small. With the change from 20CR to NCEP occurring in 1948, the dramatic increase in C day counts and the reduction in W days at this time must be related as we know that the totals of the six types and the unclassified days has to add to the number of days in the year.

Table 1 gives seasonal correlation coefficients for the MPA temperature series for the six LWTs (A, C, W, N, E and S) and three WTs (F, Z and D). These correlations are given for the two halves of the period (1925-1968 and 1969-2011) and the overall period (1925-2011). For F and Z, the seasonal averages are the simple average of the values for each day of each season. For D, the seasonal average is the resultant wind direction of all days in each season. Warmer temperatures, as expected, relate to reduced southerly counts and enhanced northerlies. As with the British Isles, the correlations are stronger for the equatorward direction (Southerlies here) compared to the poleward direction (Northerlies). As with the British Isles (Jones et al., 2014) the correlations are stronger in the autumn and winter seasons. Also as with the British Isles, there is a strong positive correlation with westerly winds, but this remains strong for all seasons and not just the winter half year as in the British Isles. As westerlies are the dominant wind direction, the same relationship is evident in the correlation with D. As expected, easterly wind counts and cyclonic vorticity lead to cooler temperatures, but the correlations are not as significant as the relationships with southerlies, northerlies and westerlies.

Table 2 contains the same information for seasonal correlations against the MPA precipitation series. Here, the correlations are again as expected, but there are greater differences between the two periods so emphasis in the discussion is on the overall period. Seasonal precipitation totals for MPA are low, principally due to the location of the islands being in the lee of the Andean mountain chain to the west. Greater westerly wind counts lead to reduced precipitation with enhanced precipitation occurring during the relatively few easterly days experienced at MPA. The strongest precipitation correlations are with vorticity (Z) and these are also weakly manifest in the expected correlations with cyclonic day counts and the inverse correlations with anticyclonic day counts, but as stated these are weak and variable between the two periods. Surprisingly, correlations are stronger and more significant in the early period (1925-1968) compared to the latter (1969-2011). Correlations with MPA precipitation are markedly lower than those found for the British Isles (Jones et al., 2014), but this is principally due to the precipitation series there being a regional average (based on at least 35 gauges) whereas MPA is just a single site.

4. Gale Indices and Storminess

Jenkinson and Collison (1977) defined a Gale day occurring over the British Isles when $G = (F^2 + (0.5Z)^2)^{1/2}$ takes a value greater than 30 (see also Hulme and Jones, 1991). They also defined severe gales where G> 40 and very severe gales where G> 50. . The choice for the Gale Day threshold of 30 for the British Isles was made by Jenkinson and Collison (1977). They state that this number approximately produces the annual count of gale days for locations averaged across the British Isles. In this study, as the latitude and longitude spacing is half that of the UK domain, we have halved the threshold for a Gale to 15, in an analogous way to the halving of the threshold for an unclassified day. Days when G > 15 are referred to as Gales, > 20 as Severe Gales and > 25 as Very Severe Gales. This reduction in thresholds produces about 70 Gale Days per year (see later plots in Figures 4 and 5) while the number of Gale Days measured at MPA is 44 per year (Caughey, pers. comm.) The definition used for a Gale Day at MPA is the standard 17ms^{-1} for 10 minutes duration during the day. It must be remembered that MPA is in a sheltered location in the eastern part of the Islands (Jones et al., 2014). Brooks (1920) looking at the daily observations up to 1915 reports an average of 65 gales per year (for 1905-1915, based on Beaufort wind forces) at the more exposed site of Cape Pembroke Lighthouse (the easternmost point of East Falkland, see Figure 1 of Lister and Jones, 2015).

All Very Severe Gale days are listed in Table 3. The full set of results can be found on the web site. The day with the most severe gale occurs on July 25, 1885 (value of 42.8) and the most recent very severe gales since MPA started in 1986 occurred on August 14, 2012 (32.0) and March 2, 2001 (30.4). Caughey (pers. Comm.) sent values of absolute extreme wind speed gusts for MPA for 1986-2014 together with the values on these two days. The absolute records for the 29-year period for each month give the peak gusts between 64 and 72 knots. The peak value on the day in 2012 was 52 knots and in 2001 the value was 56 knots. On both days average daily wind speeds were in excess of 45 knots.

In Figure 4, we show counts of gales, severe gales and very severe gales for the calendar year for the Falkland Islands and also in Figure 5 for the winter (summer) half year from May to October (November to April). Both at the annual timescale and for the two halves of the year, the time series show an increase in the number of gale days since the 1940s, with a second increase from the 1990s onwards. As expected, there are slightly more gale days in the winter half year than in the summer half year, but the summer reduction is not as significant as occurs in the British Isles (Jones et al., 2013). The 1920s to the 1940s have relatively few gale days, but there was a much greater number between the 1880s and the early 1910s at a level slightly greater than experienced in the 1960s and 1970s. It seems highly likely that the higher gale count in the 1880s to the early 1910s relates to greater numbers of ships in the region. Marine reporting virtually ceased in this region when the Panama Canal opened in 1914 (Launius et al., 2010). The reduction then to the 1940s is therefore likely to be related to this with MSLP fields in 20CR being smoother and less extreme. Correlations between annual and half-year counts of gale days are relatively high between 20CR and NCEP during the period 1948 to 2010 (r= 0.686 for annual counts and r=0.650 for MJJASO and 0.702 for NDJFMA). This reasonable agreement cannot be taken as evidence of 20CR being good before 1948, as the amount of input station pressure clearly influences the number of gales produced.

Recent digitization efforts within the ACRE project (http://www.met-acre.org/) have produced a near complete record of sub-daily pressure measurements for the Cape Pembroke Lighthouse (CPL)/Stanley/Mount Pleasant region on East Falkland (see site map in Lister and Jones, 2015). The CPL part of this series (for years up to 1947) was not digitized until after 20CR was produced, so could not have been used. With these data, a subsequent version of 20CR might produce more gales in the period from 1915 to 1947. For this study, we have combined the sub-daily record to one of daily averages. Using this series we calculated a series of day-to-day differences and then calculated the Standard Deviation (SD) of these values for each month since 1871 that had 80% of contributing values in the month. In Figure 6, we plot the annual and half-yearly averages of the monthly SD calculations only when all months are present. There are periods of incomplete daily records producing gaps in the difference series and we have required 80% of days of daily difference data per month to calculate the monthly SD values plotted in Figure 6. The result is that there is hardly any long-term trend in this series. The correlation of this SD series with monthly averages of the daily Gale Index values is 0.24 (using 1716 months). At the daily time scale the correlation between the day-to-day differences and the Gale Index value is 0.18 (based on 52229 days). Both these correlation values are significant at the 95% level given the high number of observations, but although the series are correlated the two series have relatively little variance in common.

NCEP and 20CR are some of the most-widely used and cited datasets in climatology, but many of these studies pay little heed to the potential changes in the reliability of the datasets through time. Krueger et al. (2013) however did. They compared trends in storminess measures (using pressure triangles) for the well-sampled NE Atlantic using station observations compared to the nearest 2° grid points in 20CR. They found good agreement since the 1940s, but this was much poorer for earlier years. Long-term trends with 20CR suggest changes in the gale-day counts for some periods, while the stations indicate little long-term change (with high values in the 1880s and in the 1990s). As most of the station data Krueger et al. (2013) have used in the NE Atlantic region has likely entered 20CR, they state that 20CR trends should not be considered reliable for long-term trends. Although these NE Atlantic data entered 20CR, the assimilation system checks all sub-daily station data entering and removes values that differ too far from the first guess field of the model (see details in Compo et al., 2011). Wang et al. (2014) commenting on the Krueger et al. (2013) study show that this routine quality control is vital. 20CR removes numerous outliers in Krueger et al's (2013) station dataset (the WASA dataset developed by Schmidt et al., 1997) that clearly should have been flagged and corrected for before many of their analyses. The key conclusion from both studies is that the quality of the input data needs to be adequately assessed.

What deductions can we draw from these studies for our work in such a data-sparse region? Our analysis of gale-day counts for the Falkland Islands indicates large differences between periods, which we show can be clearly related to the changes in the number of contributing station pressure data (particularly the reduction of marine pressure observations after the opening of the Panama

Canal). The series of day-to-day pressure differences (monthly SDs averaged to annual values in Figure 6) is indicative of little long-term change in this measure since the 1870s. The two stormiest periods in our gale-index record are from 1880 to 1910 and from about 1990. We can't determine whether the recent period was greater, but the reduction in gale-index frequency between 1915 and the 1980s is almost certainly artificial when considered in the context of Figure 6. With Reanalyses being more widely used, it is essential to appreciate the issue of changes in the available input data. However, it is beyond the scope of this paper to determine a method to say when there is enough and when there isn't. As more sub-daily pressure data are digitized and newer versions of ISPD are used, there will be improvements, but with any local-scale application it is vital to check whether these improvements are in the study region.

Another issue to address in the context of the changing reliability of 20CR for storminess measures is whether this has influenced the derivation of the WTs and the LWTs? Here we have assessed all days, as opposed to the extreme days with the gale index. Counting of days, as seasonal totals, of the principal six LWTs and the three WTs, indicates consistent correlations with the independent long-term temperature and precipitation series for MPA. Almost all the correlations provide the expected relationships, but the surprising finding is that the correlations are often slightly stronger in the first half of the period (1925-1968) compared to the latter (1969-2011). This finding suggests that the LWTs derived from the two Reanalyses are potentially more reliable than the specific numbers associated with the Gale Index values suggest, but both are based on the same calculations embodied by the WTs.

This study has focused on Reanalyses produced by NCEP and 20CR. Reanalyses have also been produced, for example, by the European Centre for Medium-Range Weather Forecasting (ECMWF) and also the Japanese Meteorological Agency. The latest ECMWF Reanalysis (ERA-20C) was produced more recently (http://www.ecmwf.int/en/research/climate-reanalysis/era-20c) than 20CR, but the input version of ISPD used is also very important. For the study in this part of the world, no additional station pressure data has been added in recent years. The complete sub-daily station pressure data for Stanley/MPA has only recently been added to the ISPD and will be available for future Reanalyses.

5. Conclusions

This paper has developed daily WTs and LWTs for the Falkland Islands based on the NCEP Reanalysis for the period 1948-2014 and extended this with 20CR Reanalysis for the period from 1871 to 1947.

Using the long temperature and precipitation series for MPA, we find the expected relationships with the LWT-based circulation types which are similar to those in the British Isles. Those for the Falkland Islands are slightly weaker and they don't indicate the marked difference in seasonal relationships for temperature that are found in the British Isles. This is related to the location of the islands being more maritime in nature with less of a seasonal contrast in temperature than for the British Isles. Relationships with precipitation are as expected, with periods of higher cyclonic vorticity leading to higher precipitation totals.

The principal aim of the paper has been the development of the records of storminess and the use the three WT measures to derive counts of gale days. The gale day counts reveal different numbers of days in different periods. The highest gale day counts with about 70 days per year occur in the period since the start of the 1990s. Lower numbers of gales (~40) occur between 1948 and the mid-1990s. A slightly greater number of gales are estimated during the period from about 1880 and the mid-1910s. A much lower number of gale days is evident during the period from the mid-1910s and 1947 and during the 1870s. Much of the change during these different periods is not evident in the storminess measure derived from the sub-daily pressure series for the Port Stanley region. The change in gale-day counts, therefore, is highly suggestive of the differences in quality of the Reanalysis during the different periods. The Reanalysis appears better the higher the number of gale days recorded while the analysed surface pressure fields are smoother (producing less gale days) in the period from 1915 to the 1970s, when fewer gale days were estimated. This reduction seems related to the number of input pressure values entering 20CR and also NCEP before the satellite era. This impacts the surface pressure fields, but will also impact other variables such as air temperatures and precipitation totals. Data input is higher in the period from 1880 to the mid-1910s because there were more ships rounding Cape Horn. The opening of the Panama Canal in 1914 significantly reduced this number. The amount of input data entering NCEP increased in the late 1940s as more data at the sub-daily resolution has been digitized from southern South America.
The WTs and the Gale Indices for the Falklands are given on this web site (http://www.cru.uea.ac.uk/cru/data/lwt/LWTs_Falklands.html).

Appendix A

The grid–point pattern used for the Falkland Islands is shown in Figure A1. The following wind-flow characteristics are computed from each daily pressure data grid (the integers in bold refer to the grid point reference numbers in the Figure):

$W = \frac{1}{2}(\mathbf{4}+\mathbf{5}) - \frac{1}{2}(\mathbf{12}+\mathbf{13})$ (westerly flow)

$S = 1.64\left[\frac{1}{4}(\mathbf{4}+2.0\times\mathbf{8}+\mathbf{12}) - \frac{1}{4}(\mathbf{2}+2.0\times\mathbf{9}+\mathbf{13})\right]$ (southerly flow)

$F = (S^2+W^2)^{1/2}$ (resultant flow)

$$ZW = 1.04\left[\frac{1}{2}(\mathbf{1}+\mathbf{2}) - \frac{1}{2}(\mathbf{8}+\mathbf{9})\right] - 0.97\left[\frac{1}{2}(\mathbf{8}+\mathbf{9}) - \frac{1}{2}(\mathbf{15}+\mathbf{16})\right]$$

(westerly shear vorticity)

$$ZS = 1.35\left[\frac{1}{4}(\mathbf{5}+2.0\times\mathbf{9}+\mathbf{13}) - \frac{1}{4}(\mathbf{6}+2.0\times\mathbf{10}+\mathbf{14}) - \frac{1}{4}(\mathbf{3}+2.0\times\mathbf{7}+\mathbf{11}) + \frac{1}{4}(\mathbf{4}+2.0\times\mathbf{8}+\mathbf{12})\right]$$

(southerly shear vorticity)

$Z = ZW + ZS$ (total shear vorticity)

The flow units are geostrophic (each is equivalent to 1.2 knots), expressed as hPa per 5^{o} latitude at 52.5^{o}S. The geostrophic vorticity units are expressed as hPa per 5^{o} latitude also at 52.5^{o}S; 100 units are equivalent to 0.525×10^{-4}=0.45 times the Coriolis parameter at 52.5^{o}S. The constants account for relative differences between the grid-point spacing in the east-west and north-south direction.
The equations in the Appendix use a number of coefficients, calculated by Jenkinson and Collison (1977) to take into account the different relative grid spacing at different latitudes. In order to allow this approach to be applied at different latitudes these four terms are explained here for the latitude 52.5° (referred to as ψ):

S, 1.64 is 1/cos (ψ)

ZW, 0.97 and 1.04 are sin(ψ)/sin(ψ-2.5°) and sin(ψ)/sin(ψ+2.5°)

ZS, 1.35 is 1/2(cos(ψ)^2

Jenkinson and Collison (1977) used the following rules to define the appropriate Lamb (1972) weather type:

(i) The direction of flow (D) is 270° minus $tan^{-1}(S/W)$ if both W and S are positive. Subtract from 90^{o} if both W and S are negative. Subtract from 90° if S is negative and from 90° if W is negative.
(ii) If $|Z|$ is less than *F*, flow is essentially straight and corresponds to a Lamb pure directional type.

(iii) If $|Z|$ is greater than $2F$, then the pattern is strongly cyclonic ($Z > 0$) or anticyclonic ($Z < 0$). This corresponds to Lamb's pure cyclonic and anticyclonic type.

(iv) If $|Z|$ lies between F and $2F$ then the flow is partly (anti-) cyclonic and this corresponds to one of Lamb's synoptic/direction hybrid types, e.g. AE.

(v) If F is less than 3 and $|Z|$ is less than 3, there is light indeterminate flow corresponding to Lamb's unclassified type U. The choice of 3 is dependent on the grid spacing and has been reduced by a half from that used in the UK as the grid spacing is half that used in Jones et al. (2013).

The WTs have been calculated as part of this study, but the emphasis is on the three terms F, Z and D (Direction) which were introduced in Jenkinson and Collison (1977).

Appendix B

Figure B1 gives example weather maps for the Falklands domain for the six pure LWTs (A, C, N, E, S and W). The web address (already given) provides LWT codes for each day from the beginning of 1871. The dates in Figure B1 were selected by looking at charts for the 1990s. For W, N and S, there are numerous possibilities to choose from (see counts of the types in Figures 2 and 3). For the other three pure LWTs (A, C and E) there are very few, as these types occur more regularly as hybrid types. Westerly types are the most frequent LWT for the Falkland Islands occurring on over half the days of the year. As shown by the correlations in Tables 1 and 2, westerly flow is positive correlated with temperature and inversely correlated with precipitation. Northerly and southerly air flow is less frequent than westerly, but they occur about 60 days each per year. The impacts of two types are opposite to each other. Correlations with temperature are much stronger, but inverse as expected with Southerly, compared to Northerly. These two types have very weak correlations with precipitation totals. Easterly airflow is related to cooler temperatures and to enhanced precipitation. Anticyclonic days are infrequent and have little relationship with temperature, but with precipitation they would indicate lower precipitation. Cyclonic days are also infrequent and their links to temperature and precipitation are opposite to anticyclonic days. Easterly, Anticyclonic and Cyclonic days are infrequent and they occur about 10/20/30 days respectively each year.

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References

Brooks, C.E.P., 1920. The climate and weather of the Falkland Islands and South Georgia. Geophysical Memoirs 15, Meteorological Office, London, 97–146.

Compo, G.P., Whitaker, J.S., Sardeshmukh, P.D., Matsui, N., Allan, R.J., Yin, X., Gleason, Jr B.E., Vose, R.S., Rutledge, G., Bessemoulin, P., Brönnimann, S., Brunet, M., Crouthamel, R.I., Grant, A.N., Groisman, P.Y., Jones, P.D., Kruk, M.C., Kruger, A.C., Marshall, G.J., Maugeri, M., Mok, H.Y., Nordli, Ø., Ross, T.F., Trigo, R.M., Wang, X.L., Woodruff, S.D., Worley, S.J., 2011: The Twentieth Century Reanalysis Project. *Q. J. R. Meteorol. Soc.* **137** 1-28. DOI:10.1002/qj.776.

Cram, T. et al., 2015: The International Surface Pressure Databank version 2. *Geoscience Data Journal* (in press).

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N. and Vitart, F. 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Q.J.R. Meteorol. Soc.*, **137**: 553–597. doi: 10.1002/qj.828.

Hulme, M. and Jones P.D., 1991: Temperatures and windiness over the United Kingdom during the winters of 1988/89 and 1989/90 compared with previous years. *Weather,* **46**, 126-136, DOI: 10.1002/j.1477-8696.1991.tb05724.x.

James, P., 2007: An objective classification method for the Hess and Brezowsky Grosswetterlagen over Europe. *Theoretical and Applied Climatology* **88**, 17-42.

Jammalamadaka, S. Rao and SenGupta, A. 2001: *Topics in Circular Statistics,* Section 8.2, World Scientific Press, Singapore.

Jammalamadaka, S. and Sarma, Y. 1988: A correlation coefficient for angular variables. In Matusita, K., editor, *Statistical Theory and DataAnalysis 2,* pages 349-364. North Holland, Amsterdam.

Jenkinson, A.F. and Collison, F.P., 1977: An initial climatology of gales over the North Sea, Synoptic Climatology Branch Memorandum No. 62, Meteorological Office, Bracknell.

Jones, P.D., Hulme, M. and Briffa, K.R., 1993: A comparison of Lamb circulation types with an objective classification scheme. International Journal of Climatology 13, 655-663.

Jones, P.D., Salinger, M.J. and Mullan, A.B., 1999. Extratropical circulation indices in the Southern Hemisphere based on station data. *Int. J. Climatol.* **19**, 1301-1317.

Jones, P.D., Harpham, C and Briffa, K.R., 2013: Lamb weather types derived from Reanalysis products. Int. J. Climatol. 33, 1129-1139, DOI: 10.1002/joc.3498.

Jones, P.D., Osborn, T.J, Harpham, C. and Briffa, K.R., 2014: The development of Lamb weather types: from subjective analysis of weather charts to objective approaches using reanalyses. *Weather*, **69**, 128-132.

Krueger, O., Schenk, F., Feser, F. and Weisse, R., 2013: Inconsistencies between long-term trends in storminess derived from the 20CR Reanalysis and observations. J. Climate 26, 868-874, DOI:10.1175/JCLI-D-12-00309.1 .

Lamb H. H. 1972: British Isles weather types and a register of daily sequence of circulation patterns, 1861-1971, Geophysical Memoir 116, HMSO, London, 85pp.

Launius, R.D., Fleming, J.R. and DeVorkin, D.H. (Eds.), 2010: Globalizing Polar Science: Reconsidering the International Polar and Geophysical Years. Palgrave MacMillan, New York, 400pp.

Lister, D.H. and Jones, P.D., 2015: Long-term temperature and precipitation records from the Falkland Islands. *Int. J. Climatol*. **35**, DOI:10.1002/joc.4049.
Pattison, I. and Lane, S.N., 2012: The relationship between Lamb weather types and long-term changes in flood frequency, River Eden, UK. *Int. J. Climatol*. **32**, 1971-1989.
Rumsby, B.T. and Macklin, M.G., 1994: Channel and floodplain response to recent abrupt climate change: The Tyne Basin, Northern England. Earth Surface Processes and Landforms 19, 499-515.
Schmidt T, Alexandersson H, Iden K, Tuomenvirta H (1997) North Atlantic-European pressure observations 1868–1995 (WASA dataset 1.0; CD-ROM included). Technical report 97–3. Danish Meteorological Institute, Copenhagen, Denmark.
Wang, X.L., Feng, Y., Compo, G.R., Zwiers, F.W., Allan, R.J., Swail, V.R. and Sardesmukh, P.D., 2014: Is the storminess in the Twentieth Century Reanalysis really inconsistent with observations? A reply to the comment by Krueger et al. (2013b). *Climate Dynamics* **42**, 1113-1125.
Wilby, R.L. and N.W. Quinn, 2013: Reconstructing multi-decadal variations in fluvial flood risk using atmospheric circulation patterns. *Journal of Hydrology*, **487**, 109-121.
Yarnal, B., 1993: Synoptic climatology in environmental analysis: a primer, Belhaven Press, 195pp.

Tables

Table 1: Seasonal correlations between the MPA Temperature series and the nine circulation indices covering the Falkland Islands for three periods (1925-1968, 1969-2011 and 1925-2011). Seasons are summer (DJF), autumn (MAM), winter (JJA) and spring (SON). Correlations significant at the 95% level are emboldened.

1925-1968

	DJF	MAM	JJA	SON
A	0.083	0.127	0.069	-0.023
C	-0.14	-0.099	-0.059	0.157
W	0.09	0.22	**0.358**	**0.303**
N	**0.319**	0.259	0.293	0.06
E	**-0.251**	-0.224	-0.184	-0.103
S	-0.276	**-0.439**	**-0.577**	**-0.418**
F	**-0.325**	-0.108	0.168	-0.119
Z	-0.172	**-0.333**	-0.236	0.025
D	**0.339**	**0.471**	**0.547**	**0.375**

1969-2011

	DJF	MAM	JJA	SON
A	0.104	0.005	-0.279	0.126
C	**-0.301**	-0.300	-0.242	**-0.365**
W	**0.427**	**0.330**	0.381	0.231
N	-0.281	0.255	**0.301**	0.209
E	**-0.311**	-0.227	**-0.372**	-0.276
S	**-0.311**	**-0.440**	**-0.394**	**-0.307**
F	0.029	0.186	**0.338**	-0.044
Z	**-0.314**	**-0.428**	0.098	**-0.440**
D	0.132	**0.459**	**0.314**	**0.327**

1925-2011

	DJF	MAM	JJA	SON
A	0.103	0.044	-0.154	0.063
C	-0.204	-0.169	-0.09	-0.045
W	**0.303**	**0.283**	**0.419**	**0.277**
N	0.069	**0.268**	**0.276**	0.113
E	**-0.258**	-0.196	**-0.277**	-0.172
S	**-0.333**	**-0.448**	**-0.532**	**-0.38**
F	0.09	0.101	**0.338**	0.008
Z	**-0.261**	**-0.345**	0.019	**-0.211**
D	**0.263**	**0.469**	**0.473**	**0.356**

Table 2: As Table 1, but seasonal correlations with the MPA Precipitation series.

1925-1968

	DJF	MAM	JJA	SON
A	-0.054	-0.183	0.158	-0.049
C	**0.405**	-0.029	0.247	0.021
W	-0.282	-0.273	**-0.365**	**-0.401**
N	**-0.34**	-0.258	-0.177	-0.154
E	**0.411**	0.238	**0.46**	0.17
S	0.267	**0.658**	0.133	**0.533**
F	-0.037	0.101	-0.029	0.013
Z	0.242	**0.358**	0.187	-0.001
Dir	**-0.469**	**-0.625**	-0.143	**-0.464**

1969-2011

	DJF	MAM	JJA	SON
A	-0.255	0.056	-0.273	**-0.367**
C	0.28	0.217	0.261	**0.46**
W	-0.072	-0.025	0.079	-0.105
N	0.054	-0.158	0.146	-0.218
E	0.28	**0.321**	-0.247	**0.412**
S	-0.039	-0.084	-0.116	0.21
F	0.178	0.19	0.257	-0.032
Z	**0.507**	0.232	**0.438**	**0.507**
Dir	0.056	-0.049	0.099	-0.26

1925-2011

	DJF	MAM	JJA	SON
A	-0.158	-0.12	-0.176	**-0.231**
C	**0.339**	0.16	**0.305**	**0.272**
W	-0.152	-0.094	0.055	**-0.227**
N	-0.204	-0.15	-0.009	-0.204
E	**0.352**	**0.33**	0.018	**0.343**
S	0.098	0.125	-0.149	**0.323**
F	0.122	**0.291**	**0.335**	0.133
Z	**0.34**	**0.327**	**0.415**	**0.262**
Dir	**-0.257**	**-0.234**	0.075	**-0.347**

Table 3: List of days with Very Severe gales for the Falkland Islands

Year	Month	Day	Gale Index
1871	5	21	28.3
1879	6	30	25.8
1879	7	1	28.2
1880	1	9	28.9
1880	1	10	34.3
1883	9	10	26
1883	9	12	26.6
1884	7	27	25.6
1885	5	10	29
1885	7	25	42.8
1886	2	25	25.7
1886	4	16	27.6
1886	9	13	27.1
1887	5	11	34.6
1890	4	13	27.7
1892	6	4	30.6
1895	5	23	26.1
1898	1	25	25.6
1899	10	4	26.5
1900	12	12	26.2
1902	8	4	27.2
1902	9	24	30.6
1903	1	10	27.4
1904	1	2	30.3
1906	3	20	26.1
1909	2	7	28.4
1910	8	13	25.4
1920	8	24	28
1921	7	31	29.8
1923	5	22	26.9
1930	3	3	25.8
1952	4	2	25.1
1960	8	6	25.8
1972	8	2	26.4
1976	6	25	26
1979	3	8	26
1982	8	6	26
1987	3	7	29.2
1992	3	21	26.8
1993	8	9	26.4
1994	6	26	26.3
1998	11	30	26.7
2000	6	2	26.4
2000	9	7	26.2
2001	3	2	30.4
2001	8	20	25.3

2002	4	17	26.2
2003	4	26	25.6
2010	8	30	25.2
2012	8	14	32
2013	10	27	25.8

Figure Captions

Figure 1: Correlations of daily values for each year for F, Z and D between NCEP and 20CR.

Figure 2: Annual counts of days classified as Anticyclonic, Cyclonic and Westerly. These counts are produced from 20CR up to 1947 and from NCEP for 1948 onwards.

Figure 3: Annual counts of days classified as Northerly, Easterly and Southerly. These counts are produced from 20CR up to 1947 and from NCEP for 1948 onwards.

Figure 4: Annual counts of Gale, Severe and Very Severe Gale days for the Falkland Islands, based on 20CR from 1871 to 1947 and NCEP from 1948 to 2013.

Figure 5a: Counts of Gales, Severe Gales and Very Severe Gales for the Falklands (for the winter half year from May to October) based on 20CR for 1871-1947 and NCEP for 1948-2014.

Figure 5b: Counts of Gales, Severe Gales and Very Severe Gales for the Falklands (for the summer half year from November to April) based on 20CR for 1871-1947 and NCEP for 1948-2014.

Figure 6: Annual averages of monthly standard deviations of day-to-day pressure differences (top curve). Averages for NDJFMA and MJJASO are shown in the lower two plots. The smoothing is based on a 30-year Gaussian filter, omitting the missing years.

Figures A1: Locations of the grid points over the Falkland Islands used in the calculation of the Jenkinson flow and vorticity terms. Grid-point numbers are those used in the equations in Appendix 1.

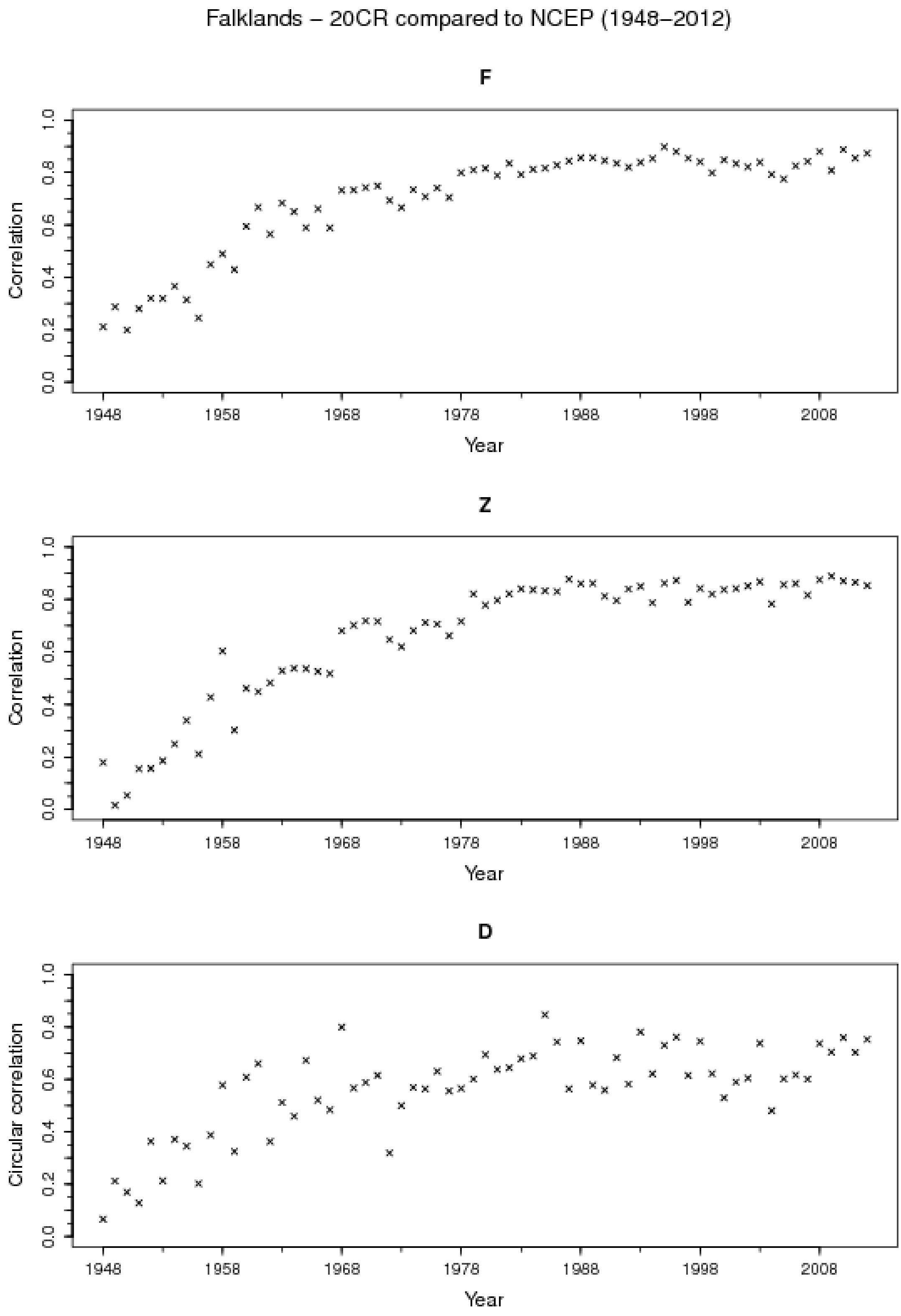

Figure 1: Correlations of daily values for each year for F, Z and D between NCEP and 20CR.

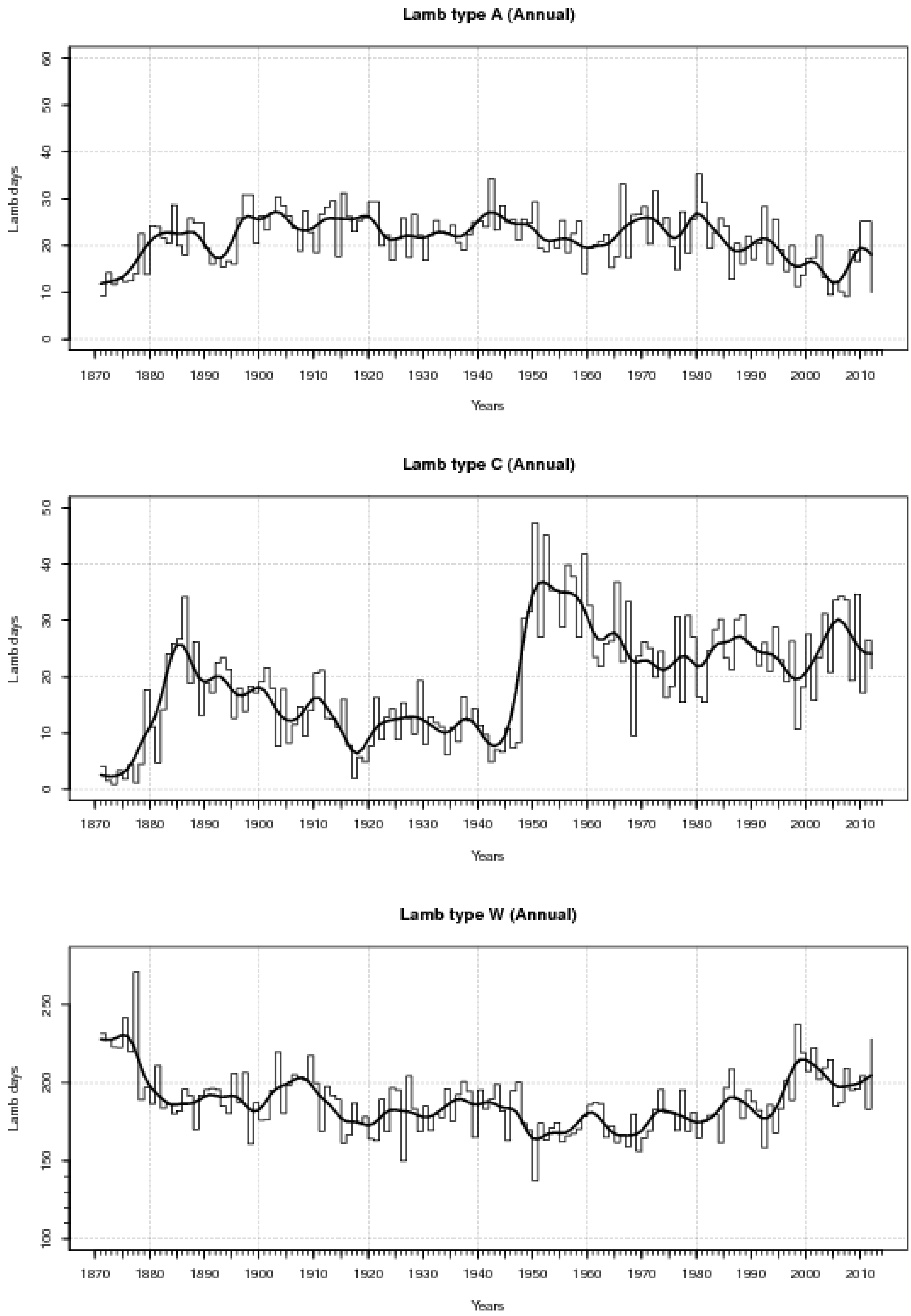

Figure 2: Annual counts of days classified as Anticyclonic, Cyclonic and Westerly. These counts are produced from 20CR up to 1947 and from NCEP for 1948 onwards.

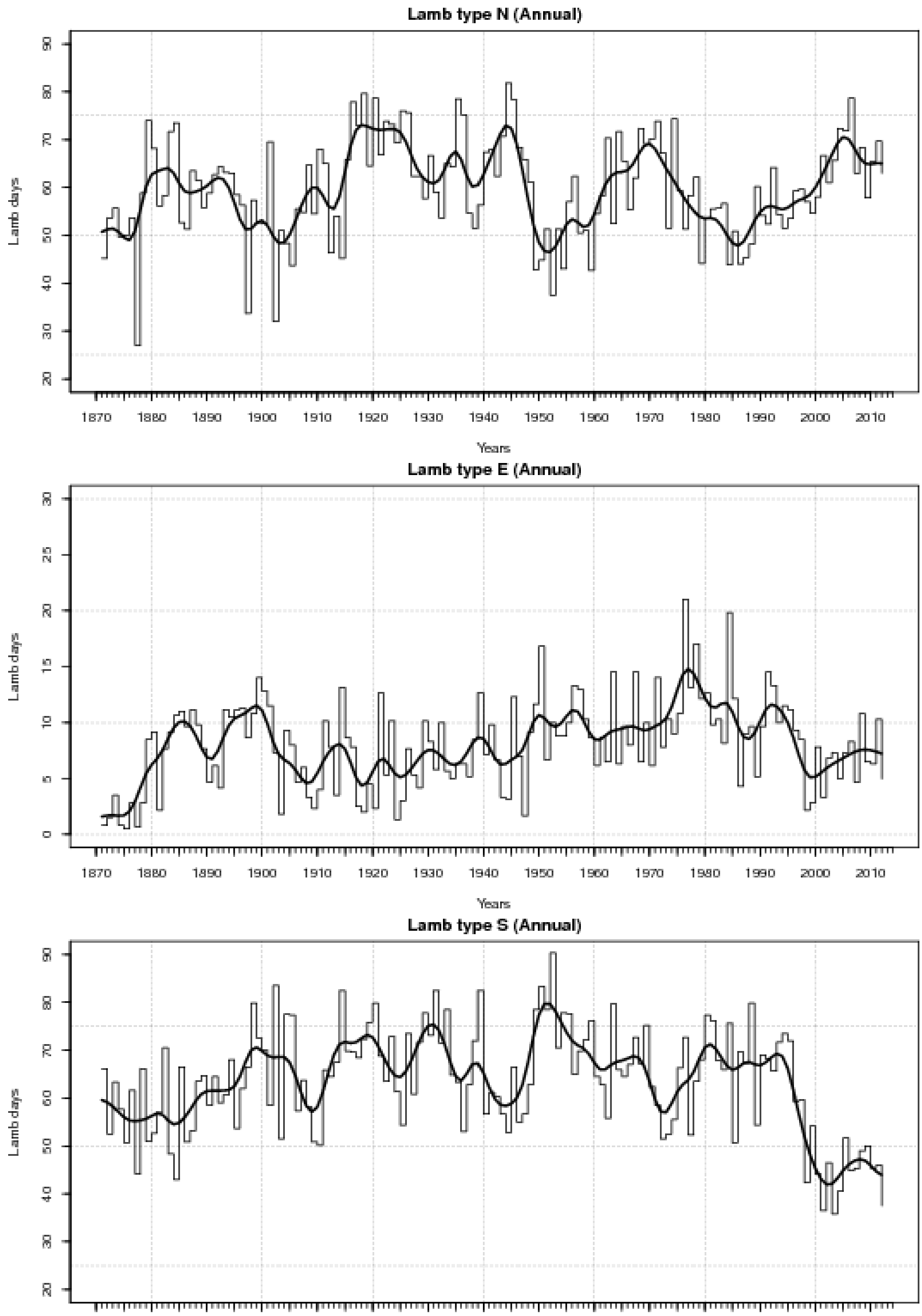

Figure 3: Annual counts of days classified as Northerly, Easterly and Southerly. These counts are produced from 20CR up to 1947 and from NCEP for 1948 onwards.

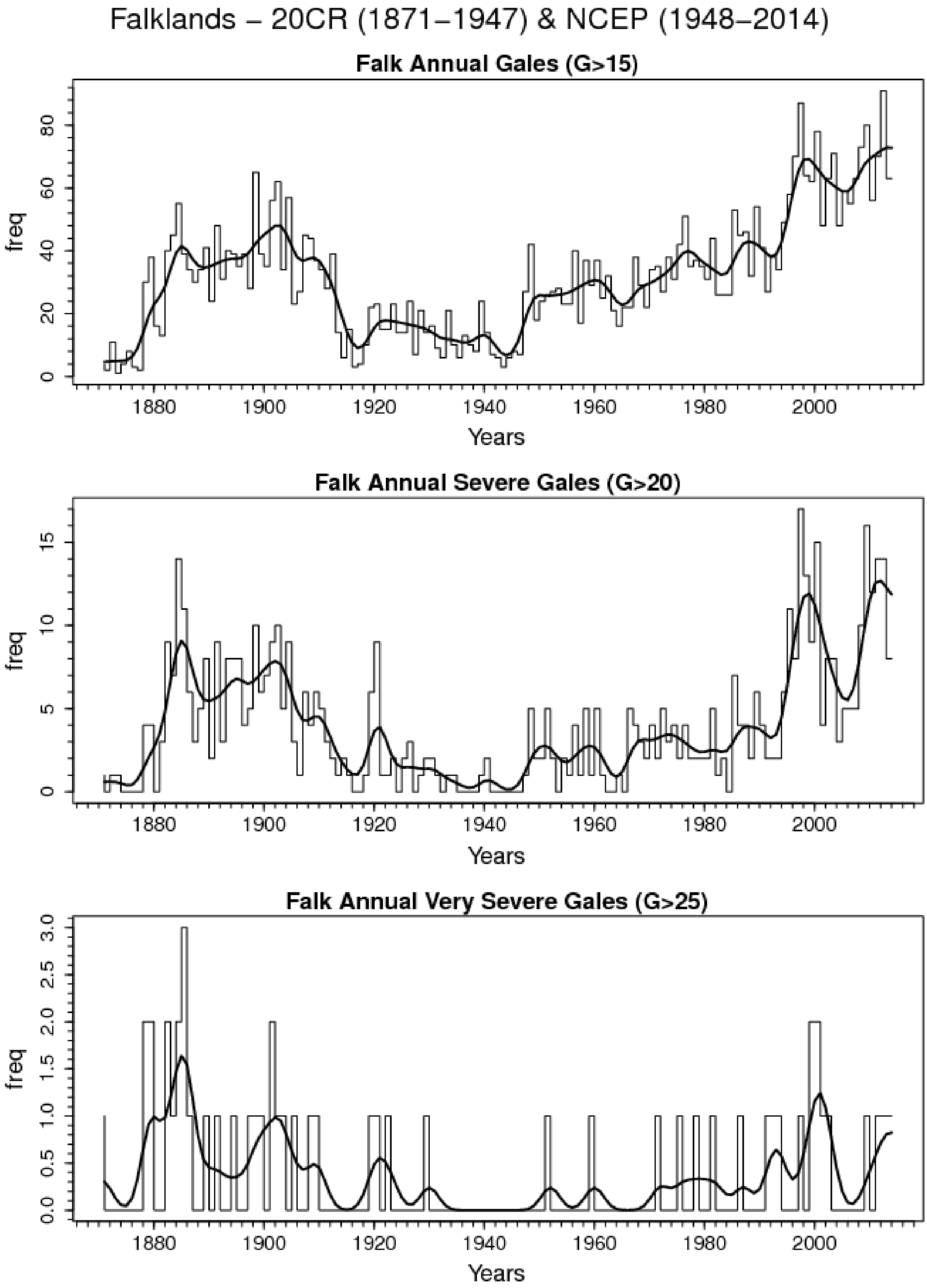

Figure 4: Annual counts of Gale, Severe and Very Severe Gale days for the Falkland Islands, based on 20CR from 1871 to 1947 and NCEP from 1948 to 2013.

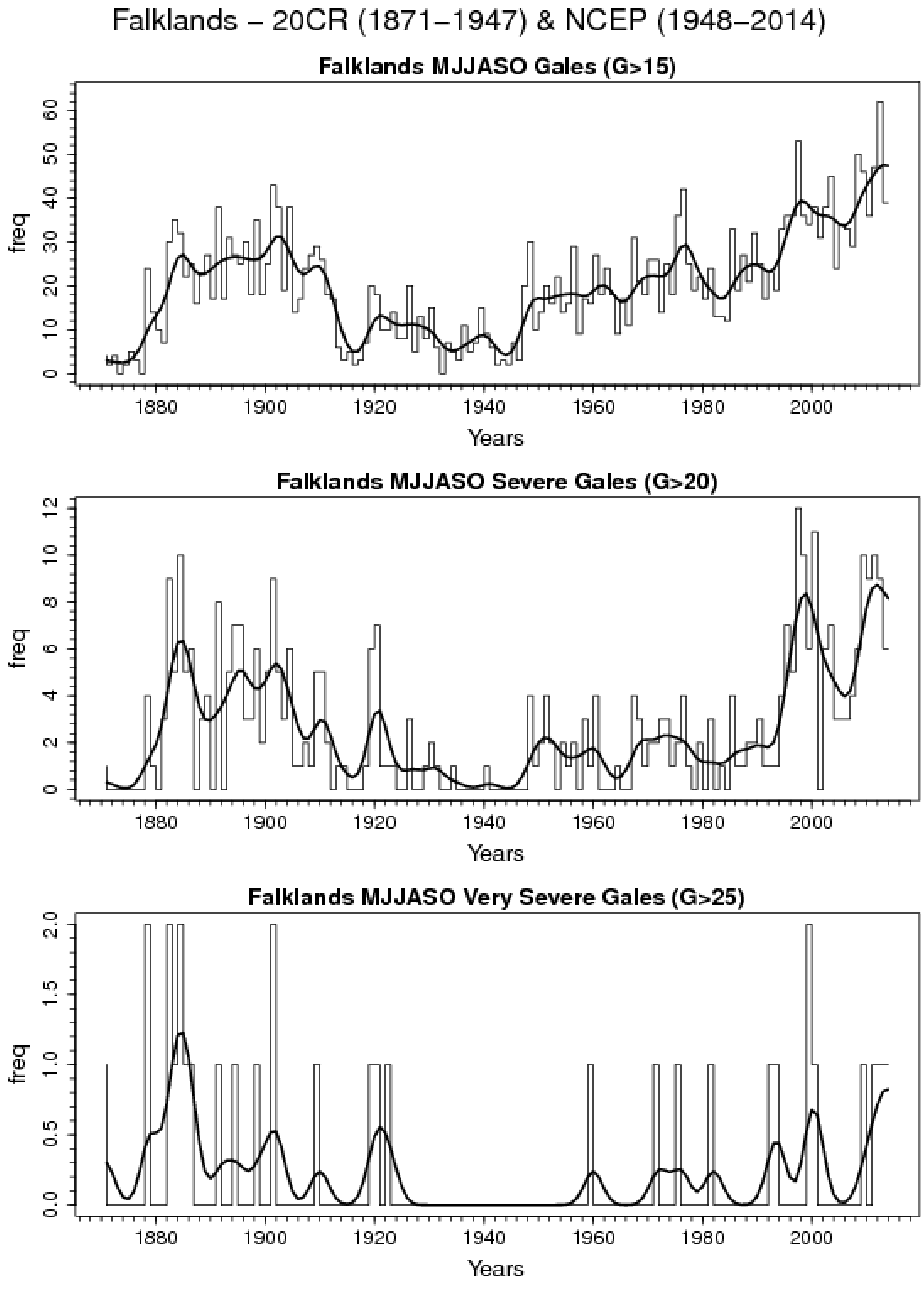

Figure 5a: Counts of Gales, Severe Gales and Very Severe Gales for the Falklands (for the winter half year from May to October) based on 20CR for 1871-1947 and NCEP for 1948-2014.

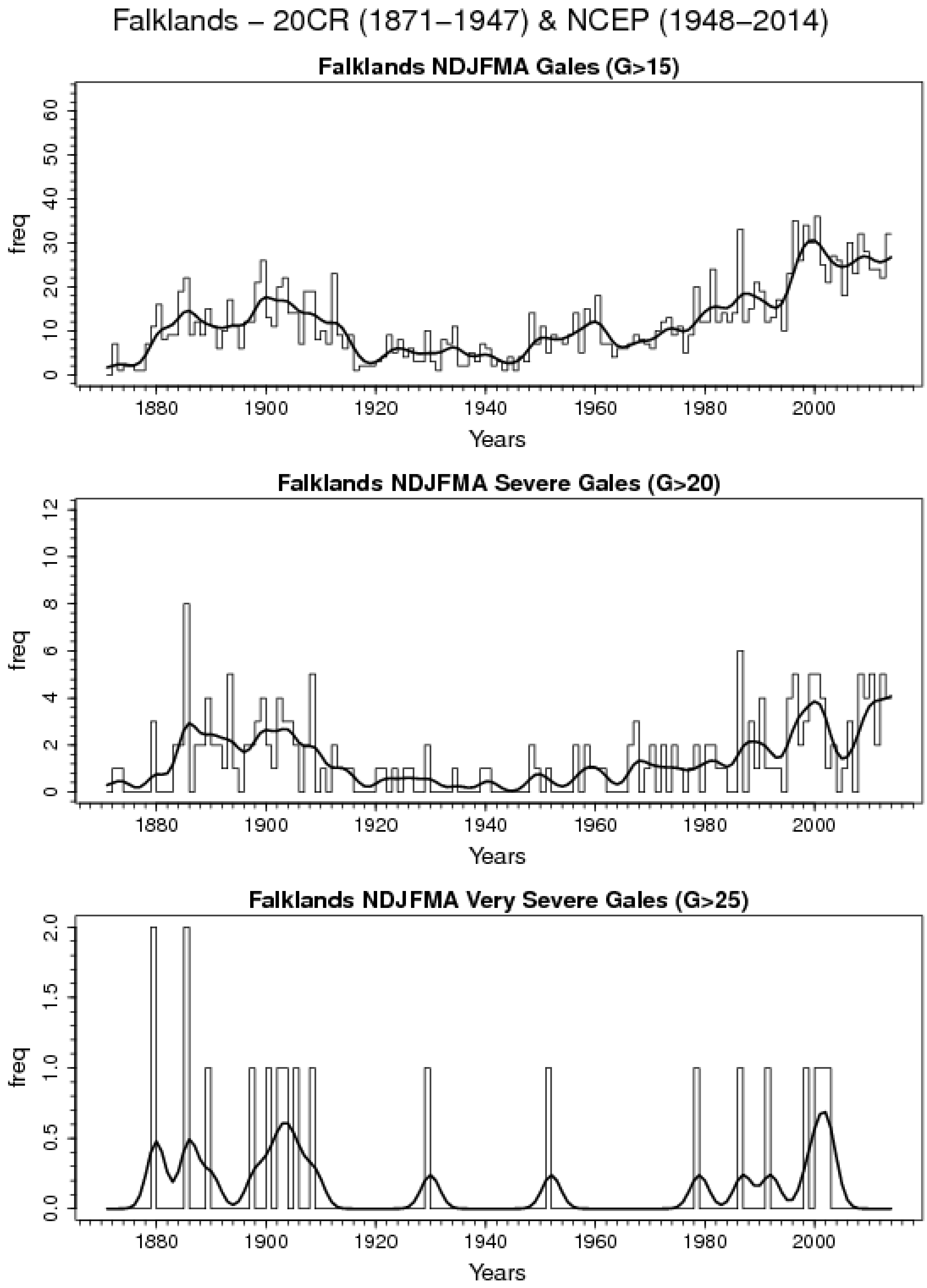

Figure 5b: Counts of Gales, Severe Gales and Very Severe Gales for the Falklands (for the summer half year from November to April) based on 20CR for 1871-1947 and NCEP for 1948-2014.

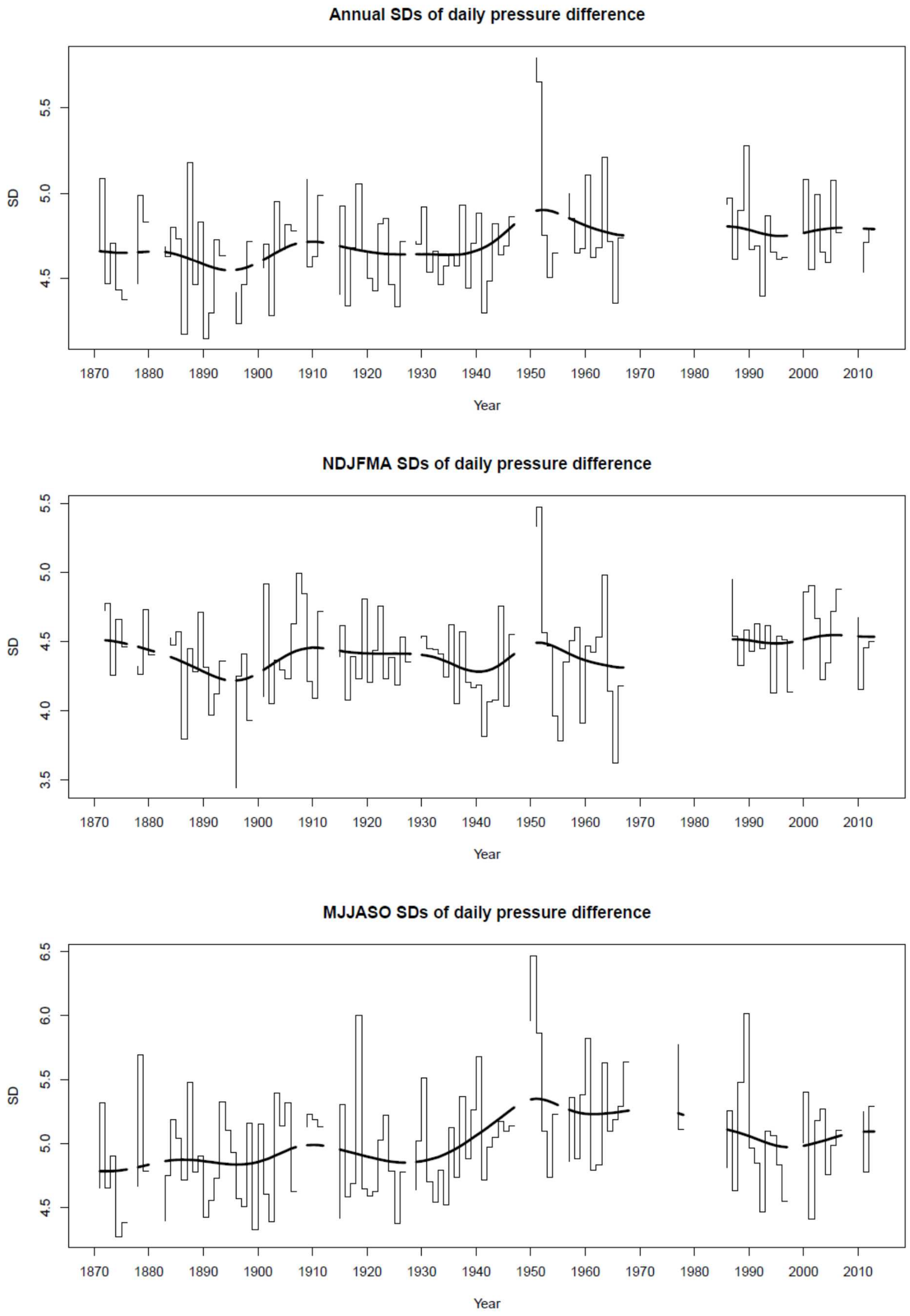

Figure 6: Annual averages of monthly standard deviations of day-to-day pressure differences (top curve). Averages for NDJFMA and MJJASO are shown in the lower two plots. The smoothing is based on a 30-year Gaussian filter, omitting the missing years.

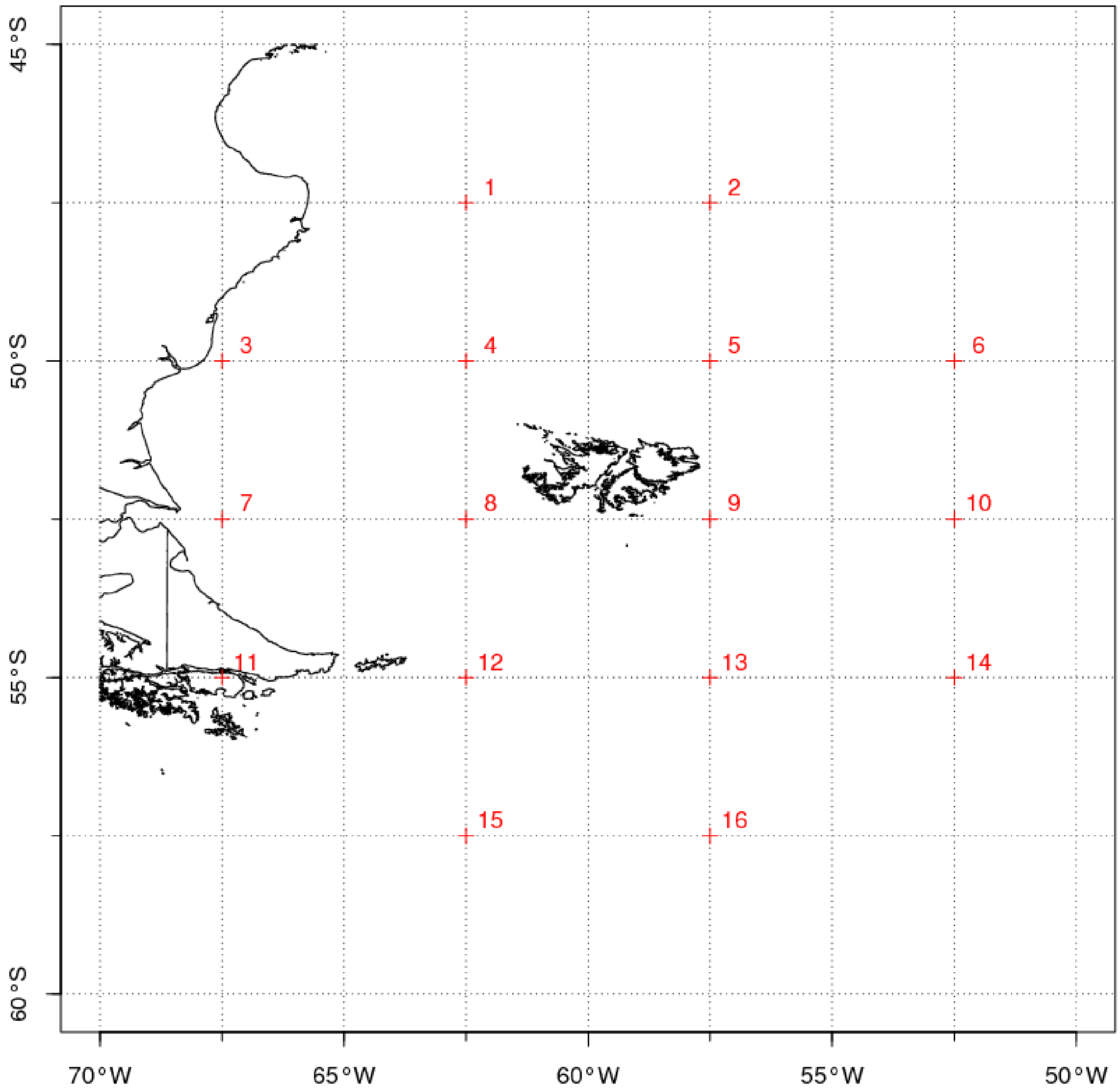

Figure A1: Locations of the grid points over the Falkland Islands used in the calculation of the Jenkinson flow and vorticity terms. Grid-point numbers are those used in the equations in Appendix 1.

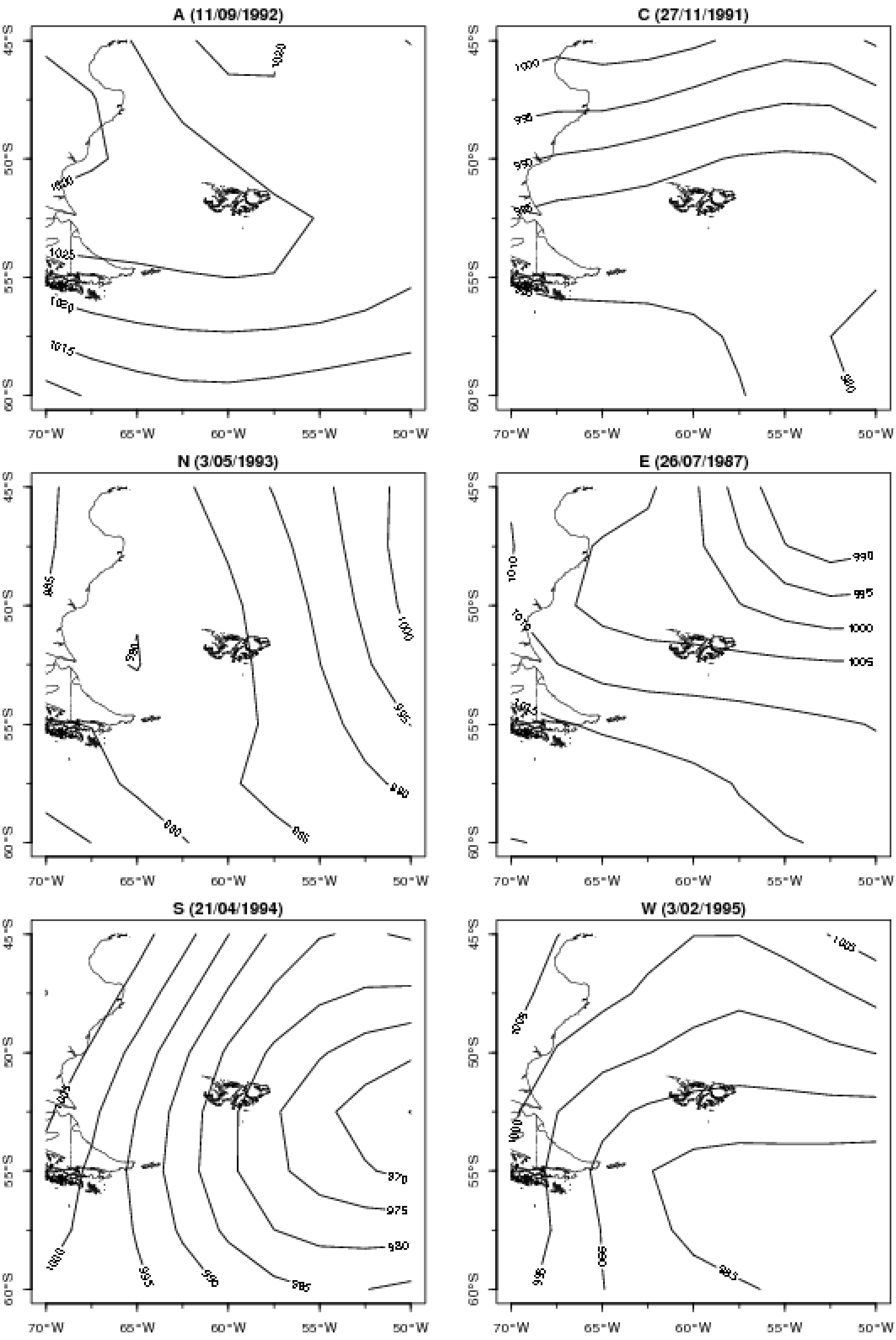

Figure B1: Example plots of the six 'pure' Lamb Weather types for the Falkland Islands. For each the date of the NCEP plot is given with contours for MSLP every 5hPa.