Identification of frequency changes in synoptic circulation types and consequences for glacier mass balance in Norway

Rowan Fealy and John Sweeney

Abstract

The cumulative net mass balances of maritime glaciers in Norway displayed a net surplus over the 1963-2000 period, in contrast to the more continentally located glaciers and that of the global glacier trend, which was one of marked retreat. This period also corresponds to an increase in westerly circulation associated with an intensification of North Atlantic Oscillation (NAO). However, since 2000, all Norwegian glaciers have been decreasing in volume. This paper seeks to establish the causal mechanisms that resulted in the positive net balances occurring on Norwegian maritime glaciers. To achieve this, a Temporal Synoptic Index (TSI) was derived for a 30-year period, commencing in 1968, for a number of synoptic meteorological stations in Norway. This period coincides with the beginning of wide spread glacier mass balance measurements in Norway. The TSI is derived using Principal Components Analysis (PCA) and subsequent clustering of component scores to classify days for both winter and summer seasons. Findings indicate that the occurrence of 'warm' type air masses during the summer months have increased in frequency, particularly since the late 1980s. A general reduction in the frequency of 'cold' cluster types during the winter months is also evident after this period. These reductions in 'cold' cluster frequencies in winter appear to have been largely replaced with increases in the frequency of 'warm' types, with an increased moisture carrying capacity, particularly since the late 1970s. The frequency occurrence of these key air mass types is shown to be significantly related to glacier mass balance during both the accumulation and ablation season. Winter air mass types from maritime source regions act to enhance accumulation and suppress ablation, while summer continental source types suppress accumulation and enhance ablation.

Key words: Norway, circulation changes, Principal Components Analysis (PCA), Temporal Synoptic Index (TSI), glacier mass balance.

ICARUS,
Department of Geography,
NUI Maynooth,
Co. Kildare,
Ireland

e-mail:- rowan.fealy@nuim.ie
Ph: 00 353 1 7084562
Fax: 00 353 1 7083573

INTRODUCTION

In spite of the relatively small contribution of glaciers to the total terrestrial storage of water, their sensitivity to changes in climate means that they are important contributors to decadal and longer timescale variations in sea level (Oerlemans & Fortuin 1992). The current worldwide reduction apparent in the volume of glaciers is estimated to have contributed between 0.2 to 0.4 mm/yr to global sea level rise averaged over the 20th century (IPCC 2001). Globally, there is evidence to suggest that mass balance variability has been increasing, especially since the 1980s, which is likely attributable to climatic variability (Dyurgerov & Meier 1999, Dyurgerov 2002). For example, between 1982 and 1995, Storglaciären in Sweden, recorded eight of its thirteen highest values of winter accumulation, while six of its summertime ablation values were amongst the highest recorded, indicating an increase in the frequency of extremes (Pohjola & Rodgers 1997a). These findings are consistent with those of Hurrell (1995) who suggests that the moisture flux over the North Atlantic has increased since the 1980s. Globally, the rate of volume loss also appears to have increased since the end of the 1980s and predictions of global warming suggest that these trends are likely to continue (Dyurgerov 2003). In contrast to the mass glacier recession evident in nearly all glaciated regions, Scandinavian glaciers, predominantly those in maritime locations, were experiencing net gains over the last three decades of the last century coinciding with an increasing tendency for more positive phases of the North Atlantic Oscillation (NAO) resulting from an intensification of westerlies, particularly since the 1970s (Figure 1).

In the mid-latitudes, the NAO accounts for 37% of the variability of the winter 500 hPa heights over the North Atlantic (Marshall et al. 2001). It is the leading mode of climate variability, particularly in winter when it is most pronounced in amplitude (Marshall et al. 2001). The NAO is also linked to the leading annular mode of climate variability in the Northern Hemisphere, the Arctic Oscillation (AO). Positive phases of the NAO produce a tendency towards higher winter temperatures in Northern Europe due to an intensification of westerlies transporting oceanic heat onto the European continent. As a consequence, recent wintertime temperature trends have been associated with high index phases of the NAO (Marshall et al. 2001). Precipitation during positive phases of the NAO exhibits a strongly north-south gradient, with positive anomalies associated with northern Europe and negative anomalies associated with southern Europe. The recent high index phase has been associated with a number of positive mass balance years on maritime glaciers in western Norway, while in the Alps, mass balance values were among the lowest recorded.

Most climate-glacier studies to date have concentrated on localised interactions at or near the glacier surface (Laumann & Reeh 1993, Vincent & Vallon 1997, Greuell & Böhm 1998). These studies typically involve amassing detailed glaciological measurements over hours, days or seasons, which are then related to on-site, or nearby, meteorological measurements. They are generally conducted on a glacier specific basis and, while they are useful, they suggest little about the large-scale circulation controls that exert an influence on glacier mass balances regionally or at the hemispherical scale.

A number of techniques have been developed in order to classify or categorise circulation patterns that are then assessed in terms of the surface environment. These techniques, based on either manual classification, correlation based, empirical orthogonal functions, PCA, indexing or compositing (Yarnal et al. 2001) broadly fall into two distinct categories, that of manual and automated classification procedures. Manual techniques have also been referred to as subjective techniques while automated techniques are termed objective. However, this distinction is not a constructive one, as automated techniques also require a number of subjective decisions to be made, which questions their implied objectivity.

Manual classification techniques, such as the Lamb classification of daily circulation patterns over the British Isles (Lamb 1972) or *Grosswetterlagen* for central Europe (Hess and Brezowsky 1977) and the Muller classification (1977) for the southern United States have a long and distinguished history in synoptic climatology. However, the subjective nature of these techniques, based on a manual classification of synoptic weather charts according to arbitrary criteria, is difficult to replicate, is labour intensive (Barry and Perry 1973) and is totally dependant on the investigator's level of knowledge and judgement (Yarnal 1993).

Application of manual classifications to diverse problems are often greatly limited due to their being tailored for specific purposes, such as an analysis of regional airflow patterns by Mayes (1991), who assessed daily and monthly airflow types for four specific regions in the British Isles and their effect on local precipitation. Despite some of these limitations, the more generic classifications (Yarnal 1993), such as the Lamb and *Grosswetterlagen* classification have found widespread application in a range of environmental analyses (Yarnal 1993).

The potential for more automated and seemingly objective techniques has become increasingly feasible with the advent of increasing computing power. The Lamb classification for the British Isles, which was discontinued after Hubert Lamb's death in 1997, was replaced by an 'automated' technique, the Jenkinson and Collison daily catalogue of UK weather types, based on an objective scheme developed by Jenkinson and Collison (1977). The Jenkinson and Collison classification derives numerical indices of mean pressure, meridional and zonal flow and vorticity and total vorticity from a regularized 16-point grid of mean sea level pressure data using a domain centred on the

UK. As daily gridded sea level pressure data for the Northern Hemisphere is available from 1880 onwards, is updated daily and due to the ease of applicability of the classification technique, a number of studies have been based on, or application of, the Jenkinson and Collison classification technique.

PCA, an eigenvector based technique, has found widespread application in the study of climatology, where large and potentially noisy data can obscure the signal being sought; it offers the potential to greatly reduce the data size while extracting a maximum of information. Wibig (1999) employed rotated principal components of the 500 hPa heights to classify circulation patterns over the Euro-Atlantic sector which were then related to precipitation distributions over Europe during the winter months. In each month, a number of patterns were distinguished: the North Atlantic Oscillation, Scandinavian, Central European, East European and the East Atlantic pattern.

A number of studies have linked European glacier mass balance with these large scale modes of atmospheric variability (Pohjola & Rodgers 1997a, 1997b, Washington et al. 2000, Nesje & Dahl 2000, Nesje et al. 2000, Six et al. 2001, Fealy & Sweeney 2005). While these studies have predominantly focused on individual or regional glacier mass balances, recent work by Rasmussen and Conway (2004) and Six et al. (2001) attempt to address some of these shortcomings. Six et al. (2001) compared Alpine and Scandinavian annual mass balance variations to the North Atlantic Oscillation. Nesje & Dahl (2000) and Nesje et al. (2000) in a study of Scandinavian glaciers found that the highest correlations occurred with winter balances, for the more maritime glaciers, and a seasonally averaged wintertime NAO. They also found that correlations decreased with increasing continentality and latitude, which may reflect a limiting factor in the effectiveness of advection from westerlies as suggested by Chen & Hellström (1999).

This paper seeks to fill some of the gaps that exist in our understanding of the linkages between synoptic climate and glacier mass balance. To date few systematic analyses have examined the interactions between the various scales at which these linkages occur and operate. This paper presents a synoptic typing methodology, which has previously been applied successfully to a number of circulation-to-environment studies (Kalkstein & Corrigan 1986, Kalkstein et al. 1990, Kalkstein et al. 1996, Cheng & Lam 2000) which explicitly takes account of a range of climate variables, all of which are considered important in determining the effects of climate on glacier mass balance.

The method employed, which is an eigenvector based technique, is concerned with changes in type and frequencies of atmospheric circulation over time (Yarnal 1993), rather than spatial variation, and is a technique that has had many applications over the last decade and a half. As opposed to classifying one variable over a large spatial area, synoptic typing classifies multiple surface elements over time from a specific location. The method employed seeks to group or classify combinations of weather elements, characteristic of air masses, displaying similar properties (Yarnal 1993). The benefit of this is that, while it is synoptic in scale, thermal and moisture variables are directly taken account of in the analysis. These variables are not explicitly included in many other synoptic classification studies. The technique has been extended to incorporate clusters that are spatially coherent and correspond closely to weather map features (Davis and Kalkstein 1990, Kalkstein et al. 1996, Green and Kalkstein 1996, Sheridan 2002).

Scandinavian glaciers and in particular, Norwegian maritime glaciers, were examined further due to their response to climate, over the 1968-1997 period, which was counter to that of glaciers on a global scale, with a few minor exceptions. Positive cumulative net balances resulted in glacier advances of a number of the maritime glaciers between the 1970s-1990s, halting the recession trend that was evident up to this period. The positive net balances being recorded on the maritime glaciers during this period appear to be largely due to increases in winter precipitation, resulting in an accumulation surplus at the end of the balance year. These increases in precipitation, which Hanssen-Bauer & Førland (1998) showed were statistically significant over south-western regions of Norway from 1960-1997, are likely the result of increased zonal airflow (Førland et al. 1996) consistent with an increasing tendency for positive phases of the NAO.

DATA AND METHODOLOGY

The methodology presented in this paper, entitled ‘Temporal Synoptic Index’ (TSI) (Kalkstein et al. 1990), is an automated and objective synoptic classification procedure, which classifies individual days into homogenous air mass categories based on the similarity of weather elements indicative of regional-scale climate. The procedure is used to classify daily data for a 30-year period, between 1968-1997, for both the winter and summer months, from five Norwegian synoptic weather stations (Figure 2). The stations are on a north-south transect and were selected based on data availability and their proximity relative to a number of long-term monitored Norwegian glaciers.

Due to the inclusion of local weather elements, this methodology also facilitates an assessment of possible within airmass type changes, such as temperature or humidity changes, which may occur as a consequence of climate change but may be too subtle to be detected in mean annual or monthly temperature series, which take no account of the synoptic situation (Kalkstein et al. 1990). Crucially, this approach directly facilitates an analysis of frequency changes of the different air mass types, which in the absence of any internal changes of the air mass properties, may also result from changes in the climate system.

Meteorological Data

Data from five synoptic weather stations, Skåbu, Flesland, Ørlandet, Bodø and Nordstraum (Figure 3) were obtained from the Norwegian Meteorological Institute (DNMI). Daily data, measured at 0hr, 6hr, 12hr and 18hr UTC, were acquired for all stations except Skåbu and Nordstraum which only recorded data three times daily. Stations, covering the period 1968-1997, were selected primarily based on the availability of the four times daily resolution data at the time this study commenced. The beginning of this time period also coincides with the commencement of long-term monitoring of a substantial number of glaciers began in Norway, which continues up to present.

The data for each station consisted of a number of meteorological elements:

- mean sea-level pressure (hPa),
- mean temperature (^{o}C),
- relative humidity (%),
- wind direction (degrees),
- wind speed (ms^{-1}),
- cloud amount (oktas) and
- visibility (km)

These meteorological elements were selected, due to their availability and because these elements represent the key properties that can be used to distinguish between different air mass types. Combinations of these meteorological elements have also been successfully used for synoptic typing in a number of previous studies (Kalkstein & Corrigan 1986, Kalkstein et al. 1990, Davis & Kalkstein, 1990, Kalkstein et al. 1996, Green & Kalkstein 1996, Cheng & Lam 2000, Sheridan 2002, Bejarán & Camilloni 2003). As mean sea level pressure for Skåbu was not available for the period of interest, averaged data from three surrounding stations, approximately equidistant from Skåbu, was used as surrogate data for this variable. The effects of using this averaged data are considered to be minimal as sea level pressure is largely homogeneous over large areas.

Some prior processing was required to be performed on the data before any analysis could be conducted. Specific humidity was calculated based on observations of relative humidity, temperature and pressure. The wind variables, wind direction and wind speed, were converted to a south scalar (*v*) and a west scalar (*u*). Finally, visibility, recorded as a coded value, was converted to distance in kilometres. Cloud amount, despite being recorded as a categorical value, oktas, was not recoded.

This resulted in a dataset with each day being defined by a total of seven elements measured four times daily. The data were then filtered to produce two subsets for each station, the first consisted of the winter months of December, January and February, while the second consisted of data for the summer months of June, July and August. Both these seasons were chosen as it likely that any climate change signal would be most apparent and therefore detectable during these seasons.

Glacier mass balance measurements and data

In Norway, mass balance data is calculated using the so-called traditional stratigraphic method (Østrem & Brugman 1991). The accuracy of measurements is dependent on a number of factors, such as, the number of sample points and the degree of precision in identifying the previous summer surface (Kjøllmoen 2003; See Dyurgerov (2002) for a fuller discussion on errors and accuracies in glacier mass balance measurements). The mass balance components of a glacier are comprised of spatially averaged mass gains or losses measured over the glacier surface, during one glaciological year, which in the Northern Hemisphere is considered from 1st October to the 30th September. The glaciological year is then subdivided into two seasons, winter (1st October to 30th April) and summer (1st May to 30th September). However, access to individual glaciers may mean that these dates vary from year to year. The measurement of snow (ice and firn) accumulated on the surface of the glacier at the end of the winter season, winter mass balance (bw), minus the ablation of snow and ice at the end of the summer season, summer mass balance (bs), is termed the annual or net balance (bn) (Figure 3).

Mass balance data for both the accumulation and ablation seasons was obtained for a number of glaciers in Norway (Figure 2). The data, obtained from the Norwegian Water Resources and Energy Directorate (NVE) who have the overall responsibility for the monitoring of glaciers and glacier mass balance in Norway, spanned the same time period as the meteorological data, 1968-1997. As the mass balance of a glacier reflects the climatic setting and site-specific glacier morphology it is therefore an important link between climatic inputs and glacier behaviour (Benn & Evans 1998).

Methodology

Derivation of the Temporal Synoptic Index (TSI) was carried out as a two-step procedure. Firstly, the daily data was analysed using PCA and secondly, the loading scores from the PCA were then clustered using a hierarchical and agglomerative clustering algorithm.

PCA is primarily used to reduce a large number of intercorrelated variables to a smaller number of orthogonal and uncorrelated principal components that explain a large proportion of the variance of the original dataset (Kalkstein et al. 1990, Jolliffe 1990). Although PCA produces as many components as original variables, much of the variation in the data is explained in the first number of components (Yarnal 1993). PCA is largely a variable reduction technique, which is achieved through a linear transformation of the original standardised and correlated data onto orthogonal axes (Kalkstein et al. 1990).

Rotation of the components was not performed as the PCA served primarily as a data reduction technique in this analysis. While orthogonal rotation can aid interpretability of the resultant components, this is mainly a consideration for mapping procedures that utilise an eigenvector technique. Oblique rotation removes the orthogonal nature of the principal components, a requirement for clustering (Johnston, 1978) and was therefore not employed.

Components accounting for less than the variation in the original variable, that is any component with an eigenvalue < 1.0, were discarded. Table 1 shows the results for Flesland, located in south-western Norway. A number of methods can be used to determine the correct number of components to retain, such as natural breaks in slope or the scree plot, which indicate breaks in slope and hence the number of components to retain (Yarnal 1993). As no one individual test will give the 'correct' number of components, a combination of techniques should be employed. However, the correct specification of components to retain is not as critical to the synoptic typing procedure as to studies whose goal is regionalisation due to the robustness of the synoptic typing procedure (Yarnal 1993).

Principal component scores, derived from multiplication of the original standardised data matrix by the components loading matrix, are shown for Flesland in Table 2. Resultant values of the component scores should exhibit similar scores for days in which a similar combination of weather elements has occurred (Kalkstein et al. 1990). The component scores matrix, comprised of daily values for each retained component, which in the case of Flesland accounted for 80.7% of the variance of the original data matrix of 28 variables in just 6 components, all with an eigenvalue of greater than 1.0. This represents a significant reduction in 'noise' and the removal of any collinearity that may have existed in the original data matrix.

For the purposes of this study, the following standardisation of components was applied-

$$\sum_{i=1}^{p} \alpha_{ki}^{2} = \lambda_k ,$$

λ_k is the variance of z_k

a linear function of the p variables will be of the form $z=\alpha_1 x_1+ \alpha_2 x_2+ \ldots\ldots +\alpha_p x_p$

For a correlation matrix then,

α_{kj} is the correlation between x_j and the k^{th} PC

p is the number of variables

(Jolliffe 1990)

The use of this constraint has the effect of increasing the loadings on the primary or leading Principal Components (PC) while decreasing those of the latter, according to the components eigenvalue while maintaining the relative loadings of each variable (Jolliffe 1990). This technique can be justified for use in this research as variables that are considered key determinants of air mass characterisation, such as temperature and moisture, load on the leading PCs and therefore their influence is weighted as more important than variables that load on the latter PCs.

In order to classify days with similar component scores and hence, characteristics, an automated, agglomerative and hierarchical clustering technique was then performed on the normalised component scores matrix. The between-group average linkage clustering method attempts to minimise the within-group variance while maximising the between group variance (Kalkstein et al. 1987) by assessing the average squared Euclidean distance between all possible pairs of observations between two clusters and joining those that have the minimum average distance between them (Kalkstein et al. 1987). Ultimately the number of synoptic types identified and their characteristics will depend on the specification of the clustering algorithm and selection of a cut-off point in the clustering procedure (Yarnal 1993).

Once the number of clusters to retain has been determined, each case representing a particular day can then be assigned to a cluster or homogenous synoptic type, which can then be assessed in terms of the mean values of its meteorological elements (Table 3). In a similar manner to the methodology employed by Kalkstein et al. (1990), any cluster or synoptic category that contained more than 15% of the total number of days was further subdivided by passing it through a second average-linkage clustering procedure, employing the original normalised component scores for those days. The results of this additional sub-clustering for Flesland are shown in italics in Table 3.

The resultant synoptic clusters were then compared to weather maps to determine the large-scale circulation in operation associated with the synoptic types. These are identified as ‘Circ Type’ or circulation type in Table 3. Changes in frequencies of air mass types can also be assessed. In addition, and a major advantage of using the synoptic typing methodology, is that within type changes in air mass characteristics can be assessed. This is an important part of the methodology of the ‘Temporal Synoptic Index’, while air mass frequencies may remain constant over time, internal modifications, such as increasing temperatures, may be occurring as a consequence of climate change. Thus, any study, which analyses air mass frequency changes in isolation could incorrectly conclude that, in the absence of a significant change in the frequencies of occurrence of particular air mass types, climate change may not be occurring.

RESULTS FROM TEMPORAL SYNOPTIC INDEX

While the number of components extracted from each station for winter varied between four for Nordstraum to six for Flesland and Skåbu, the first principal component for all stations was dominated by the thermal and moisture variables, indicating their relative importance in the air mass classification. This is illustrated in the results from Flesland in Table 2. Cloud amount and its related variable, visibility, also loaded highly on the first component. The primary component at all stations accounted for a minimum of 30% of total variance at Skåbu to a maximum of 41% of total variance at Flesland.

The second component tended to include the *u* and *v* wind scalars for the majority of stations indicating a strong directional component. Pressure also exerted an influence on this component for Flesland, Ørlandet and Skåbu, while for Nordstraum, pressure loaded highest on the third component. Pressure was the dominant variable for all stations, except Bodø, on component three. The wind scalars also have a contribution to this component, again indicating a directional component. Component four is comprised of cloud amount, visibility and the wind scalars, but in contrast to component one, cloud amount loads negatively while visibility is positive for all stations, except Skåbu. Component five and beyond are more difficult to interpret.

In all, extracted components (eigenvalues greater than 1.0) accounted for a minimum of 73% of total variance at Skåbu to a maximum of 82% at Bodø. This represents a substantial reduction in noise and in the data size with very little loss of data for all stations.

The component loadings for the extracted components for the summer months differ from those of the winter loadings. The dominance of the thermal and moisture variables on the first component, evident during the winter months, becomes less apparent. Moisture, cloud amount, visibility and the wind scalars were the dominant variables for the southern station of Flesland, while pressure, which loads negatively, also contributes to this component for the southern station of Flesland. Component one for the central and northern stations is dominated by the thermal variables, unlike their southern counterparts. While for the more continental station of Skåbu, the influence of the thermal variable appears to have a diurnal influence and the component is dominated by the pressure variables. Ørlandet, Bodø and Skåbu show a diurnal strengthening of the thermal variable indicating increased variability possibly due to the warming of the landmass during the day. While no such influence for the southern, maritime influenced stations is obvious, possibly indicating a moderating influence of the ocean on daytime temperature variation during the summer months at these locations.

Component two is essentially a thermal and moisture component, for all but the northern most station, Nordstraum. The influence of pressure also plays an important contribution to this component, especially for the southern, maritime stations. Again there is little consistency across stations for component three. For the southern stations, moisture and the wind scalars appear most important, while for the central stations of Ørlandet and Bodø, the component is dominated by pressure. At Skåbu, visibility and the *v* scalar, with a negative pressure component are the key influences on this component, while humidity, visibility and the scalars, all interrelated variables, are the most important for Nordstraum.

Pressure is again a key ingredient for component four at the southern stations and Nordstraum. The *v* scalar dominates for the central stations. After component four, interpretation again becomes increasingly difficult.

Winter

Nine major synoptic air mass categories, defined as containing 20 or more days, were identified for Flesland (Table 3), three of which contained more than 15% of the total number of days. Clusters containing more than 15% of the total number of days, were entered into a separate clustering procedure in order to allow for the identification of important subclasses. Nine categories were also identified for Ørlandet and Skåbu, with two categories in each requiring further clustering. Eleven synoptic categories were identified for Bodø, one of which contained days greater than 15% of total. Nordstraum produced the least number of categories, eight, with two requiring further clustering. An element common to all stations was that one of the categories requiring further clustering tended to be associated with an easterly wind direction recorded at the station level.

The coldest synoptic categories at all stations during winter were associated with an easterly circulation type. Humidity for these categories was also very low, resulting from cold dry air being advected off the continental land mass, while the warmest synoptic categories were all associated with westerly circulation types. These westerly associated air mass types also produced some of the highest humidity values, associated with warm, moist air advected off the ocean. This maritime-continental divide is evident at all stations during the winter season.

To investigate any changes that may have occurred in the frequencies of the synoptic categories over the observed period, annual frequencies of the coldest and warmest air mass types were examined. The coldest and warmest categories were selected as it is expected that these categories are likely to be more sensitive to any changes that may have occurred in climate as a consequence of global warming.

Figures 4-13 display the frequencies of both the coldest and warmest air mass types for all stations for winter. The frequency occurrences of the identified ‘cold’ air mass types display a large degree of noise, with no strong or clear signal. A 3-period moving average was fitted to the data on order to reduce the effects of noise. If the coldest category at any station contained insufficient data points, they were combined with the frequency occurrences of the next coldest category identified at the station in order to produce graphs. While no overall clear trend exists, there does appear to be a large degree of synchronicity between the occurrences of 'cold' cluster types between stations with increases evident in the late 1970s to early 1980s and a decline afterwards until the 1990s.

An analysis of frequencies of the warmest synoptic categories for winter suggests that the largest occurrences for all stations occurs in the late 1980s and early 1990s, with some stations showing an increase for some years more than double their average during this period. A decreasing trend appears to occur after this. The similarity in the timing of this increase would suggest that a circulation scale as oppose to a regional scale driver was in operation. This assertion would appear to be confirmed when the key air mass frequencies are related to the NAO over the period of study. The frequencies of synoptic types TSI 3, TSI 6 and TSI 8, from Flesland, were found to be significantly correlated (0.01 level) with the NAO during winter. Synoptic types TSI 3 from Flesland, an air mass with a continental source, was found to be negatively correlated with positive phases of the NAO, while TSI 6 and TSI 8, warm, oceanic types, are positively correlated with the NAO. The frequency of these cluster types were also found to be influential on glacier mass balance, discussed in more detail in Section 4.

Summer

Nine major categories were also identified for Flesland during the summer months, three of which required further clustering due to their size. Eleven synoptic categories were uncovered for Ørlandet, two requiring further clustering. The continental station of Skåbu and more northern station of Bodø, both produced seven synoptic categories, again with two requiring sub-clustering for Skåbu and three for Bodø. The northern most station, Nordstraum, produced the least amount of synoptic categories, six, three of which required further sub-clustering.

The warmest air mass types at all stations were associated with an easterly circulation type again reflecting the heat capacity of the landmass, in this case for heat uptake, during the summer months. An analysis of the frequency occurrence of the warmest air mass types during the summer season suggests that the frequency of warm types were decreasing from the beginning of the analysis period, until the mid-1980s, after which increasing frequencies become apparent (Figures 14-18). The synchronicity in timing of the changing frequencies again would suggest the influence of a large scale forcing mechanism.

The degree of consistency between the results from the synoptic stations, is interpreted as an indication of the usefulness of the methodology as the technique is applied to each station independently. A synchronicity in timing between stations occurs during winter, when the frequencies of warm types increase, some dramatically, in the late 1980s early 1990s, consistent with a strengthening NAO during this period. During the summer period, coherence between stations is evident with decreases and increases in warm air mass types occurring simultaneously during the time period analysed.

Within category temperature changes

An analysis of within category temperatures for the winter synoptic types suggests that some degree of modification of the coldest and warmest air mass types may have occurred over the period of analysis. The coldest cluster from Flesland (TSI 3), Bodø (TSI 4) and Nordstraum (sub cluster TSI 1c) appear to have warmed slightly over the 1968-1997 period (Figures 19-21). However, contradictory results are suggested when within category temperatures are assessed for cluster 3 (TSI 3) from Flesland. The temperature of the coldest sub cluster, TSI 3c, appears to be getting increasingly colder. Slight warming in the remaining sub clusters within this category is compensating for the decrease evident in temperature in TSI 3c. In contrast, no obvious trend was detected in the warm cluster types with the exception of Nordstraum, which was the only station to display an increasing trend in the average temperature of its warm cluster types during the winter season.

An examination of within category temperatures for the summer synoptic types reveal some interesting results. Over the 1968-1997 period, it is suggested that summer temperatures have been decreasing for the warmest air mass types at all stations. The rate of decrease is marginal for some stations, namely Flesland, Bodø and Nordstraum, while for Ørlandet (TSI 10 and 11) and Skåbu (TSI 3a, TSI 4 and TSI 6), the decrease over time is more apparent (Figure 22-Figure 23). Despite the decreasing trends found in the warm clusters, an examination of temperatures, independent of their air mass association, suggests no apparent trend. The increasing frequencies of the warm air mass types evident since the early 1990s are likely compensating for within category changes, which in the case of the warm categories are decreasing temperatures.

RELATIONSHIP BETWEEN AIR MASS FREQUENCIES AND GLACIER MASS BALANCE

To examine the effectiveness of the air mass types determined by the previous methodology and whether or not the derived classifications are useful in an examination of glacier mass balance, air mass frequencies produced from the Temporal Synoptic Index (TSI) are related to the mass balance from glaciers in relative proximity to the stations (Figure 2). Results from two of the synoptic stations, namely Flesland and Skåbu are examined further.

Obtaining significant correlations was found to be sensitive to the number of retained clusters but insensitive to the sub-classifications of the larger clusters. Despite this, air mass type frequencies, from all four stations and both seasons, were found to be significantly correlated with glacier mass balance for a selection of glaciers in Norway and also for Storglaciären in Sweden. Correlations from individual stations were found to be consistent across a number of glaciers. Tables 4-6 display the Pearson's *r* correlation coefficients between the winter air mass frequencies from Flesland, Bodø and Nordstraum and the winter glacier mass balance from glaciers located in proximity to these meteorological stations. Three glaciers: Hansebreen, Austdalsbreen and Langfjordjøkelen, appear to display very poor results. However, on investigation these glaciers also have the shortest period of measurements, approximately two-thirds less than the others, which is reflected in the poor correlations.

Correlations between mass balance and Flesland for the winter period indicates TSI 3 and TSI 8 as having the highest correlations. TSI 3 is essentially a cold and very dry synoptic type, reflecting its continental source. As a consequence of the low humidity values, this type negatively impacts or acts to suppress winter accumulation. TSI 8, on the other hand, is a 'warm' type, with relatively high temperatures and humidity, as a consequence of its more maritime source and has the effect of being positively associated with winter mass balance. TSI 6 and 7 also act to enhance winter accumulation, mainly due to high humidity values that would produce increased snowfall at elevation, due to the temperature lapse rate.

For the more northern stations of Bodø and Nordstraum, the maritime versus continental air mass types again reflect the key differentiation between enhanced and suppressed glacier mass balance during winter.

Summer air mass frequencies from Flesland were found to be significantly correlated with summer balance from a number of glaciers (Table 7). In particular, TSI 3 and 6, neither of which are considered to be the warmest, were indicated as being the most influential on summer balance. TSI 3 was associated with a north-westerly circulation type and this air mass type would act to suppress summer melting by drawing down cooler polar air during the ablation season. While TSI 6 is associated with warm continental air during the ablation period and therefore produces enhanced melting during this period.

Air mass frequencies from Skåbu again highlight the varying influences of maritime and continental air mass types, in this case, on summer balance (Table 8). Wind direction associated with TSI 1 suggests a continental influence, but this type is embedded in a westerly circulation type and therefore indicative of cooler maritime air during the summer months. This is again evident at the more northern stations of Bodø and Nordstraum (Tables 9 and 10). When the synoptic air mass frequencies from Skåbu were related to the East-Atlantic Jet Pattern (EA-JP), the dominant mode of atmospheric variability during the summer months, TSI 3 was found to be significantly (0.05 level) and negatively correlated, again reflecting a continental, as oppose to marine, source which acts to enhance summer ablation.

Case study of Rembesdalskåka, an outlet glacier from Hardangerjøkulen

Hardangerjøkulen glacier, situated in southern Norway, has an area of 73km^2 and is Norway's sixth largest glacier. It has been continuously monitored since 1963, initially by the Norwegian Polar Institute (NPI) and since 1985 to the present by the Norwegian

Water Resources and Energy Directorate (NVE). As part of the monitoring strategy, depth to bed and surface elevations were surveyed in 1961 and again in 1995, providing useful additional information on top of the bi-annual mass balance measurements recorded since 1963.

To investigate the relationship between synoptic scale climate and the glacier mass balance of Rembesdalskåka, the results from the previous section, which demonstrated that a relationship existed between the derived air mass frequencies and glacier mass balance, are further investigated in order to determine the key air mass types that influence its mass balance. Having established the key air mass types, empirical relationships are derived to statistically link these to glacier mass balance for the period 1968-1997.

The influence of key air mass types from both the maritime station of Flesland and the continental station of Skåbu were analysed to assess their influence on the mass balance of Rembesdalskåka. Results from which suggested that the synoptic classification from Flesland had the most significant influence on winter balance. For the summer balance, the summer synoptic classification from the more continental station of Skåbu produced the most significant results. The influence of maritime dominated air mass types during the winter accumulation period largely reflects the importance of winter precipitation, while during the summer ablation season, warm continental air is likely to be one of the dominant influences on summer mass balance.

A number of key synoptic types were initially identified as being influential on winter balance from Flesland, namely that of TSI 3 and 8. Partial correlation coefficients were also examined which suggested that TSI 4, which was not identified in the original analysis (Table 4), was also significant to winter mass balance (Table 11). The inclusion of TSI 8 was also ruled out from further analysis, as when this variable was entered into a regression analysis, it resulted in the exclusion of important additional synoptic types. Therefore, only TSI 3 and TSI 4 were considered for further analysis.

When both these variables were input into a stepwise regression analysis as predictors of winter mass balance, the percentage explained variance was 65.9% (removal F-value 2.71). For comparative purposes, winter seasonal precipitation and temperature from Bergen, located close to Flesland, were also entered as predictors into a separate stepwise multiple linear regression of winter mass balance. Only winter precipitation was considered significant with an explained variance of 26.5%. The results of the air mass frequencies offer a significant improvement over these findings.

There key synoptic types, TSI 3, 4 and 5, were selected from Skåbu as being the most influential on the summer mass balance of Rembesdalskåka. Again, correlations between TSI 5 from Skåbu and summer balance do not appear to be statistically significant, but when partial correlations are examined, its relevance becomes more apparent (Table 12). When data for the whole period were included in the analysis, all three predictors enter the equation with a percentage explained variance of 63.9%.

However, for validation purposes which resulted in a reduced number of cases available for calibration, the relevance of TSI 5 becomes insignificant and therefore drops out of the subsequent analysis. As a consequence, only TSI 3 and TSI 4 are considered for input into the subsequent regression analysis, which results in a slight drop of the original R^2 value to 58.9%.

Again for comparative purposes, mean summer temperature from Skåbu was input as a predictor into a separate regression analysis and was found to be negatively and strongly correlated to summer balance on Rembesdalskåka with an R^2 of 55%. While Skåbu is located some distance from Rembesdalskåka, which may reduce the strength of the correlation with temperature, the results from the air mass frequencies are again shown to be comparative.

While it is problematic to validate with only thirty cases as input to a regression analysis, a split sample was used to test the validity of the derived empirical relationships. For this, the regression equations were calibrated over two thirds of the data with the predicted values for the remaining one third being compared with the observed data withheld from the analysis. Figure 24 displays the results from calibration including the reduced sample, after 1990, for winter balance, which are encouraging. Verification of the regression equations for summer was found to be sensitive to selection of cases for calibration and verification. Improved verification results were found when the calibration period included the 1990s (Figure 25), a decade with high year-to-year mass balance variability. In addition to the split-sample approach, a bootstrap analysis was also performed on the regression coefficients. Results from the bootstrap analysis showing bias, mean and standard error of the coefficients from 1,000 replications are shown in Tables 13 and 14.

CONCLUSION

This paper set out to examine the causal mechanisms that resulted in accumulating glacier mass balances on maritime glaciers in Norway at a time when the global glacier signal was one of mass retreat. To achieve this, a synoptic scale climate analysis was undertaken, in order to link large-scale atmospheric circulation changes to glacier relevant climate variables. This classified daily weather elements into homogenous cluster types, derived using an objective and automated technique according to specific air mass types. The derived air mass types were assessed for their frequency of occurrence which were then related to glacier mass balance from a selection of glaciers in Norway. Having determined that an association existed, the relationship was further examined for a specific glacier, Rembesdalskåka, located in southern Norway.

An examination of the frequencies of occurrence of the derived air masses indicated that a number of key air mass types were significantly correlated with both winter and summer glacier mass balance. Changes in frequencies were also found to be linked to larger scale atmospheric changes. Marginal decreases in the occurrence of the cold cluster types, during the winter months, were suggested to have occurred up until the early 1990s. An analysis of the frequencies of the warm clusters, with an increased moisture capacity, indicated an increase in frequency from the late 1970s and early 1980s, with the highest frequencies occurring during the late 1980s and early 1990s. These increases resulted in largely positive net balances being recorded on maritime glaciers throughout the period examined in this paper. Positive net balances on the continental glaciers were evident after the late 1980s, coinciding with the increased frequencies of the warm types after this period. Increases in the frequencies of the warm types during the summer months were also evident after the late 1980s.

Results from the synoptic analysis were found to be in line with findings from previous research. An increase in frequency of the warm cluster types during winter in the late 1980s and early 1990s is consistent with an intensification of westerlies over the North Atlantic for the same time period (Figure 1) (Hurrell at al. 2005). This period also marks the onset of positive net balances being recorded on the more continental glaciers, presumably resulting from a deeper penetration of moist air mass types on to the land mass.

Frequency changes evident during winter in the warm and cold air mass types are also in line with findings of previous research which applied a similar technique to detect climate changes in the western North American Arctic. Kalkstein et al. (1990) found that the frequencies of cold air masses appeared to be decreasing, while the warmest air mass frequencies were found to be increasing over the 40-year period examined, prior to 1990.

Since the mid 1990s, a decreasing intensity of the NAO has resulted in a diminished westerly circulation over Norway. This has resulted in a decline in glacier mass balances evident on both maritime and continental glaciers in Norway since 2000 and that has continued to the present.

Acknowledgements

The authors greatly acknowledge Erik Førland of the Norwegian Meteorological Institute and Liss M. Andreassen at NVE for providing the data employed in this analysis. This research would not have been possible without their assistance. We would also like to thank the two reviewers for their helpful comments.

References

Barry, R.G. and Perry, A.H. 1973 *Synoptic Climatology: Methods and Applications*, Methuen & Co Ltd, London.

Bejarán, R.A. and Camilloni, I.A. 2003. Objective method for classifying air masses: an application to the analysis of Buenos Aires' Argentina. urban heat island intensity, *Theoretical Applied Climatology*, 74, 93-103.

Benn, D.I. and Evans, D.J.A. 1998. *Glaciers and Glaciation*. Arnold, London.

Chen, D. and Hellström, C. 1999. The influence of the North Atlantic Oscillation on the regional temperature variability in Sweden: spatial and temporal variations, *Tellus*, 51A, 505-516.

Cheng, S. and Lam. K-C. 2000. Synoptic typing and its application to the assessment of climatic impact on concentrations of sulphur dioxide and nitrogen oxides in Hong Kong, *Atmospheric Environment*, 34, 585-594.

Davis, R. and Kalkstein, L.S. 1990. Development of an automated spatial synoptic climatological classification, *International Journal of Climatology*, 10, 769-794.

Dyurgerov, M. 2002. *Glacier Mass Balance and Regime: Data of Measurements and Analysis*. Occasional Paper No. 55. *Institute of Arctic and Alpine Research*, University of Colorado, Boulder.

Dyurgerov, M. 2003. Mountain and subpolar glaciers show an increase in sensitivity to climate warming and intensification of the water cycle, *Journal of Hydrology*, 282, 164-176.

Dyurgerov, M.B. and Meier, M.F. 1999. Analysis of winter and summer glacier mass balances, *Geografiska Annaler*, 81A, 4.

Fealy, R. and Sweeney, J. 2005. Detection of a possible change point in atmospheric variability in the North Atlantic and its effect on Scandinavian glacier mass balance, *International Journal of Climatology*, 25, 14.

Førland, E.J, van Engelen, A., Hanssen-Bauer, I., Heino, R., Ashcroft, J., Dahlström, B., Demarée, G., Frich, P., Jónsson, T., Mietus, M., Müller-Westermeier, G., Pálsdottir, T., Toumenvirta, H., and Vdein, H. 1996. *Changes in normal precipitation in the North Atlantic region*. Klima Report no. 7/96, DNMI.

Greene, J.S. and Kalkstein, L.S. 1996. Quantitative analysis of summer air masses in the Eastern United States and an application to human mortality, *Climate Research*, 7, 43-53.

Greuell, W., and Böhm, R. 1998. 2m temperatures along melting mid-latitude glaciers, and implications for the sensitivity of the mass balance to variations in temperature, *Journal of Glaciology*, 44, 146, 9-21.

Hanssen-Bauer, I. and Førland, E.J. 1998. *Annual and seasonal precipitation variations in Norway 1896-1997*. Report no. 27/98 Klima, DNMI.

Hess, P. and Bresowsky, H. 1977 *Katalog der Großwetterlagen Europas (1881-1976)*, Berichte des Deutschen Wetterdienstes, Offenbach am Main.

Hurrell J.W., M. Visbeck, and A. Busalacchi, R. A. Clarke, T. L. Delworth, R. R. Dickson, W.E. Johns, K.P. Koltermann, Y. Kushnir, D. Marshall, C. Mauritzen, M. S. McCartney, A. Piola, C. Reason, G. Reverdin, F. Schott, R. Sutton, I. Wainer, and Wright, D. 2005. Atlantic Climate Variability and Predictability: A CLIVAR perspective. Available on-line at < http://www.cgd.ucar.edu/cas/jhurrell/Docs/jclimclivarnov05.pdf>. Accessed October 2006.

Hurrell, J.W. 1995. Decadal trends in the North Atlantic Oscillation, regional temperatures and precipitation, *Science*, 269, 676-679.

IPCC (2001) *Climate Change 2001: The Scientific Basis.* Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Houghton, J. T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P. J. and Xiaosu, D. (Eds.). Cambridge University Press, UK. 944 pp.

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

Johnston, R.J. 1978. *Multivariate statistical analysis in Geography*, Longman Group Limited, London.

Jolliffe, I.T. 1990. Principal components analysis: A beginner's guide-I. Introduction and application, *Weather*, 45, 375-382.

Kalkstein, L.S. and Corrigan, P. 1986. A synoptic climatological approach for geographical analysis: Assessment of sulphur dioxide concentrations, *Annals of the Association of American Geographers*, 76, 3, 381-395.

Kalkstein, L.S., Barthel, C.D., Greene, J.S. and Nichols, M.C. 1996. A new spatial synoptic classification: application to air mass analysis, *International Journal of Climatology*, 16, 983-1004.

Kalkstein, L.S., Dunne, P.C. and Vose, R.S. 1990. Detection of climate change in the Western North American Arctic using a synoptic climatological approach, *Journal of Climate*, 3, 10, 1153-1167.

Kalkstein, L.S., Tan, G. and Skindlov, J.A. 1987. An evaluation of three clustering procedures for use in synoptic climatological classification, *Journal of Climate and Applied Meteorology*, 26, 717-730.

Kjøllmoen, B. ed. 2003. Glaciological investigations in Norway in 2002, The Norwegian Water Resources and Energy Directorate NVE., Report no. 3.

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

Laumann, T. and Reeh, N. 1993. Sensitivity to climate change of the mass balance of glaciers in southern Norway, *Journal of Glaciology*, 39, 133, 656-665.

Marshall, J., Kushnir, Y., Battisti, D., Chang, P., Czaja, A., Dickson, R., Hurrell, J., McCartney, M., Saravanan, R. and Visbeck, M. 2001. North Atlantic Climate Variability: Phenomena, Impacts and Mechanisms, *International Journal of Climatology*, 21, 1863-1898.

Mayes, J.C. 1991 Regional airflow patterns in the British Isles, *International Journal of Climatology* 11,473-491.

Muller, R.A. 1977 A synoptic climatology for environmental baseline analysis: New Orleans, *Journal of Applied Meteorology*, 16, 20-33.

Nesje, A. and Dahl, S.O. 2000. Are the North Atlantic and Arctic Oscillation reflected in Scandinavian glacier mass balance records?, *PAGES*, 8, 2, 15.

Nesje, A., Lie, Ø., and Dahl, S.O. 2000. Is the North Atlantic Oscillation reflected in Scandinavian glacier mass balance records?, *Journal of Quaternary Science*, 15, 6, 587-601.

Oerlemans, J. and Fortuin, J. P. F. 1992. Sensitivity of glaciers and small ice caps to greenhouse warming, *Science*, 258, 115–117.

Pohjola, V.A. and Rodgers, J.C. 1997a. Coupling between the atmospheric circulation and extremes of the mass balance of Storglaciären, northern Scandinavia, *Annals of Glaciology*, 24, 229-233.

Pohjola, V.A. and Rodgers, J.C. 1997b. Atmospheric circulation and variations in Scandinavian Glacier Mass Balance, *Quaternary Research*, 47, 29-36.

Rasmussen, L.A. and Conway, H. 2004. Climate and glacier variability in Western North America, *Journal of Climate*, 17, 9, 1804-1815

Sheridan, S.C. 2002. The redevelopment of a weather-type classification scheme for North America, *International Journal of Climatology*, 22, 51-68.

Six, D., Reynaud, L. and Letréguilly, A. 2001. Bilans de masse des glaciers alpins et scandinaves, leur relations avec l'oscillation de climat de l'Atlantique nord, *Earth and Planetary Sciences*, 333, 693-698.

Vincent, C. and Vallon, M. 1997. Meteorological controls on glacier mass balance: empirical relations suggested by measurements on glacier de Sarennes, France, *Journal of Glaciology*, 43, 143, 131-137.

Washington, R., Hodson, A., Isaksson, E., and MacDonald, O. 2000. Northern hemisphere teleconnection indices and the mass balance of Svalbard glaciers, *International Journal of Climatology*, 20, 473-487.

Wibig, J. 1999 Precipitation in Europe in relation to circulation patterns at the 500 hPa level, *International Journal of Climatology*, 19, 253-269.

Yarnal, B 1984. Synoptic-scale atmospheric circulation over British Columbia in relation to the mass balance of Sentinel Glacier, *Annals of the Association of American Geographers*, 74, 3, 375-392.

Yarnal, B. 1993. *Synoptic Climatology in Environmental Analysis*, Belhaven Press, London.

Yarnal, B. Comrie, A.C., Frakes, B., and Brown, D.P. 2001 Developments and prospects in synoptic climatology, *International Journal of Climatology*, 21, 1923-1950.

Østrem, G. and Brugman, M. 1991. Glacier Mass-Balance Measurements. Canadian NHRI Science Rep. no. 4.

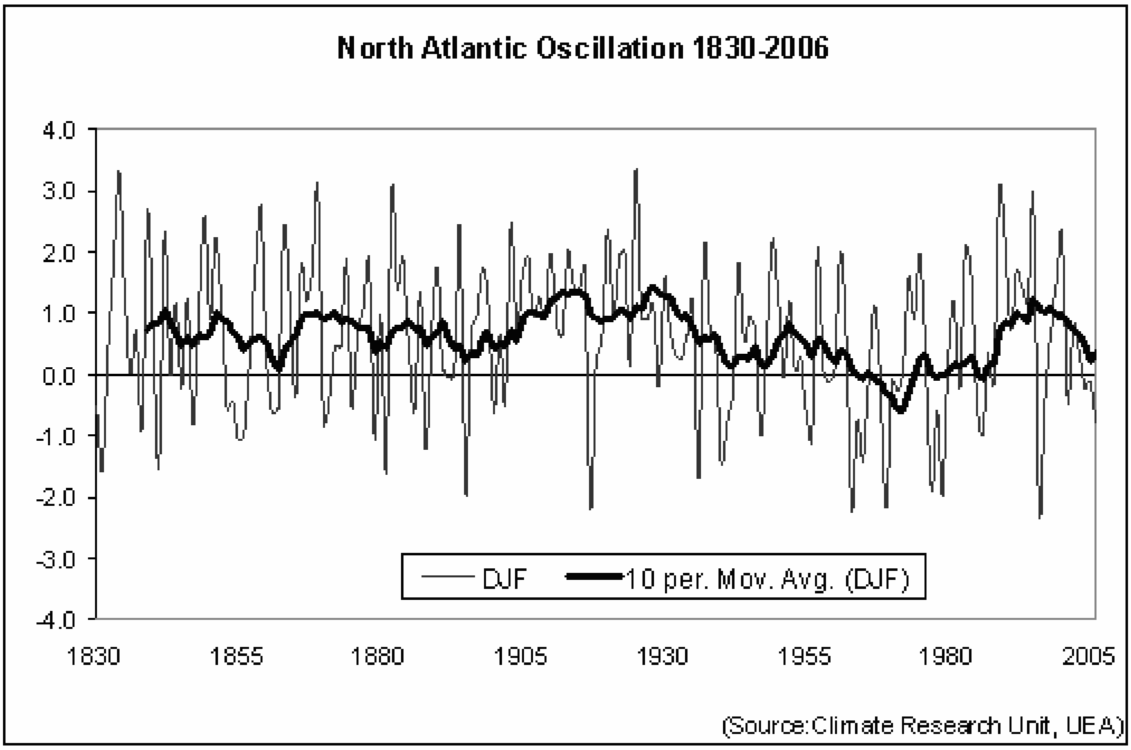

Figure 1 North Atlantic Oscillation Index 1830-2000. Thick line repents the 10-year moving average for the winter period.

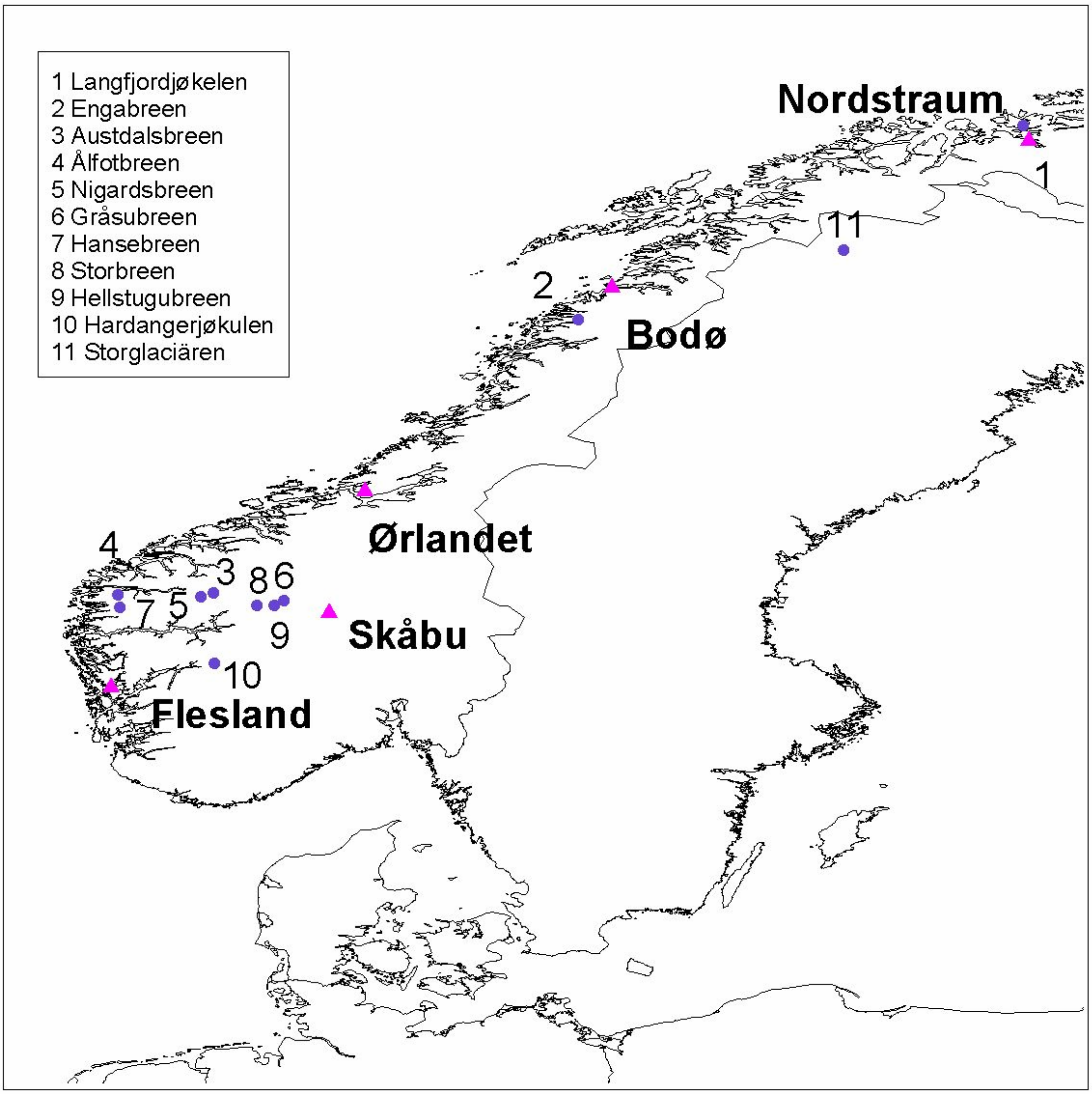

Figure 2 Location of synoptic stations ▲-named) and glaciers ●-numbered)

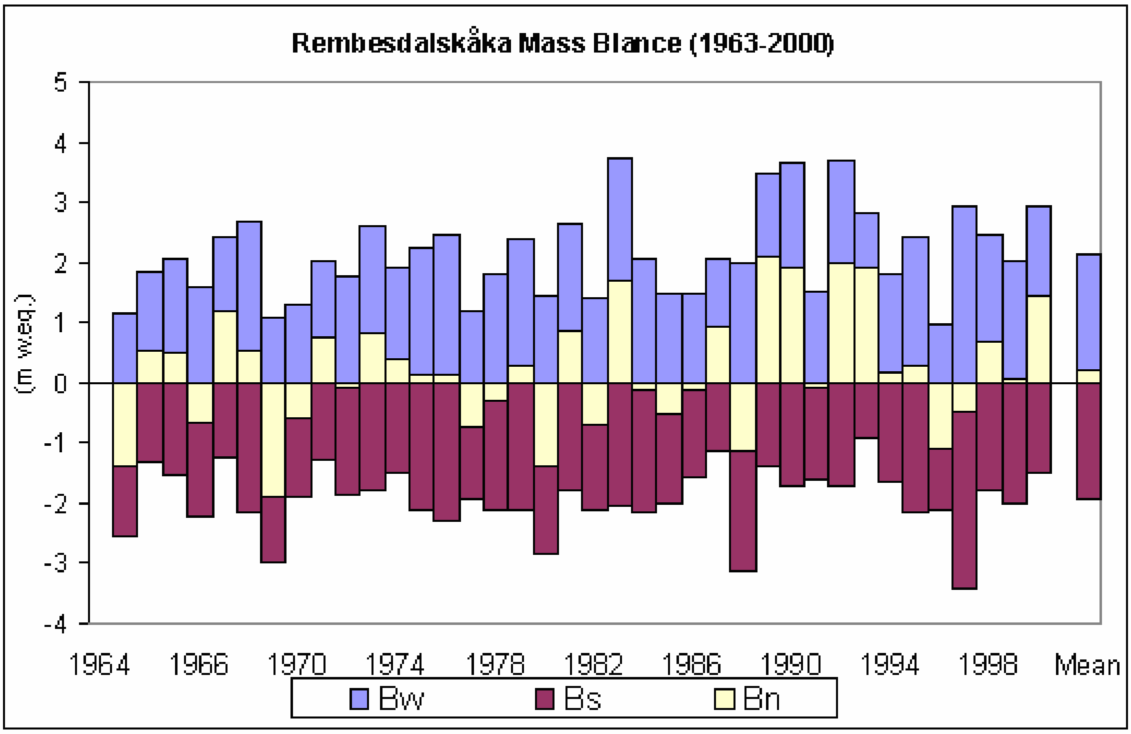

Figure 3 Mass balance for Rembesdalskåka 1963-2000.

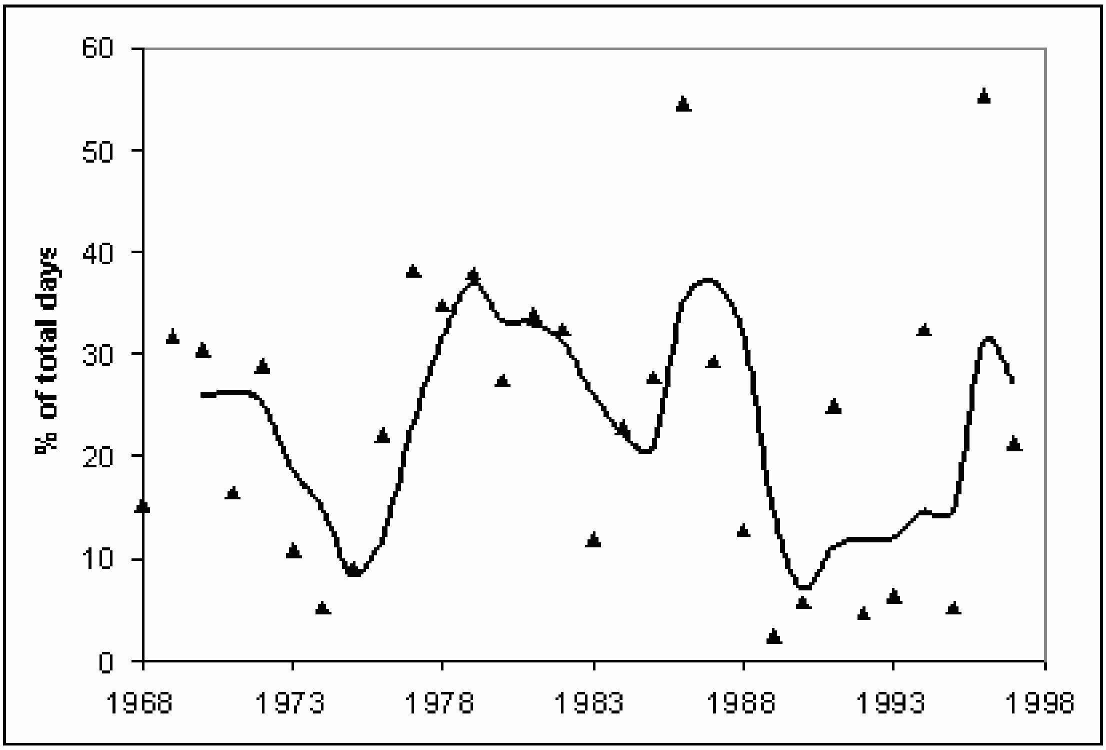

Figure 4 Flesland winter 'cold' cluster-TSI 3.

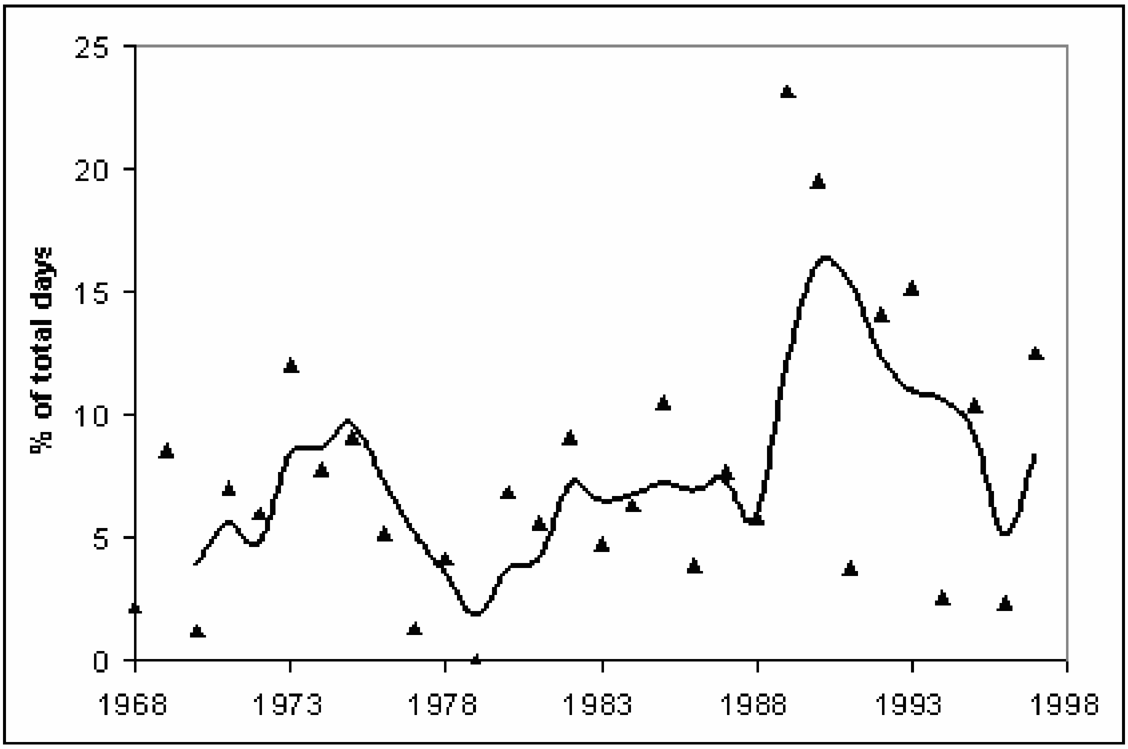

Figure 5 Flesland winter 'warm' cluster TSI 7 + TSI12 cluster frequencies from a number of clusters were combined due to few days occurring in the coldest category cluster).

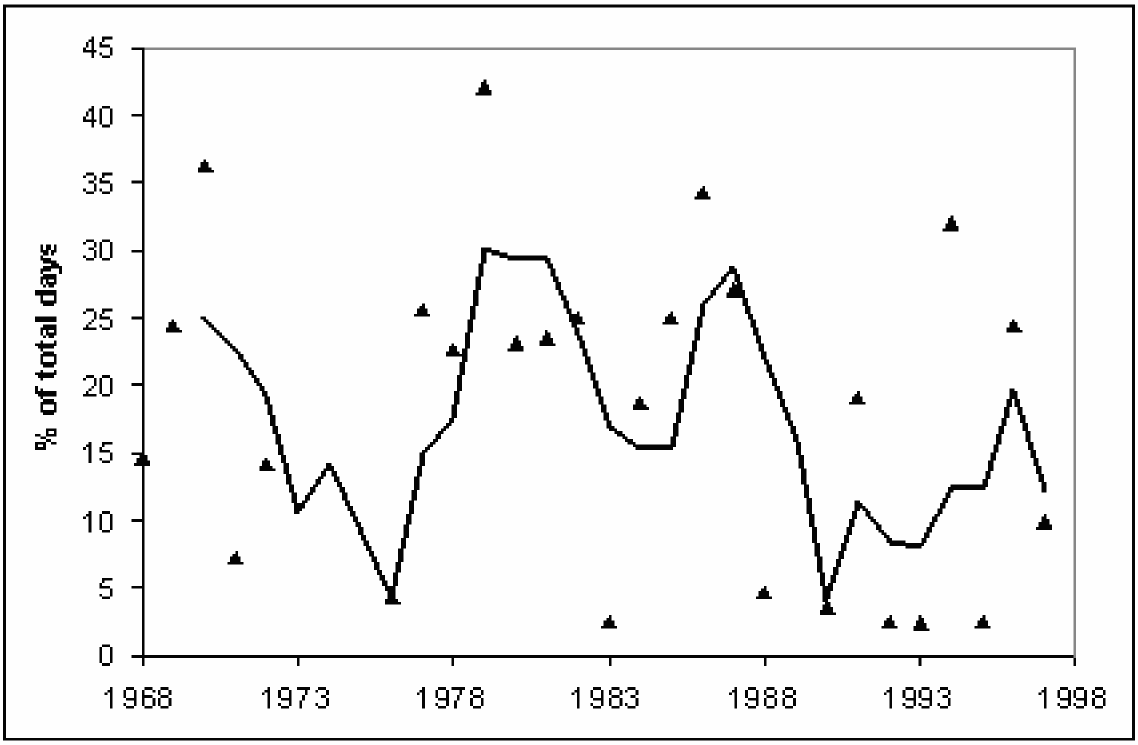

Figure 6 Ørlandet winter 'cold' clusters-TSI 2 + TSI5 + TSI9 cluster frequencies from a number of clusters were combined due to few days occurring in the coldest category cluster).

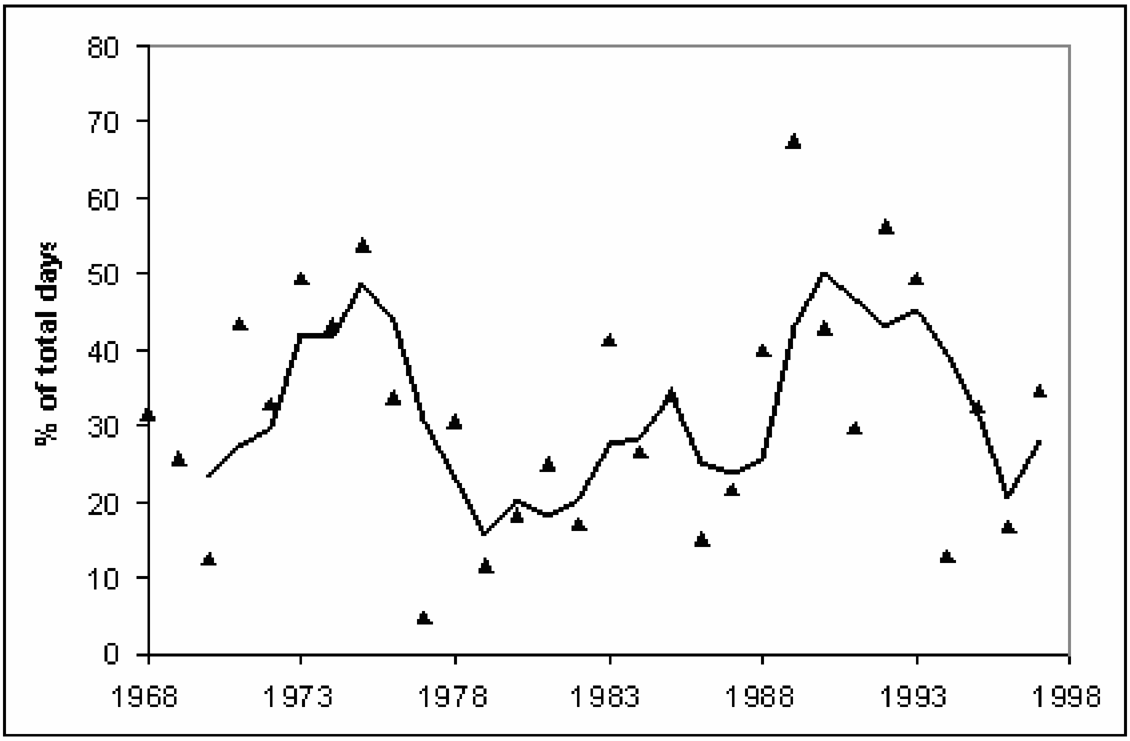

Figure 7 Ørlandet winter ‘warm’ cluster TSI 6 + TSI8 cluster frequencies from a number of clusters were combined due to few days occurring in the coldest category cluster).

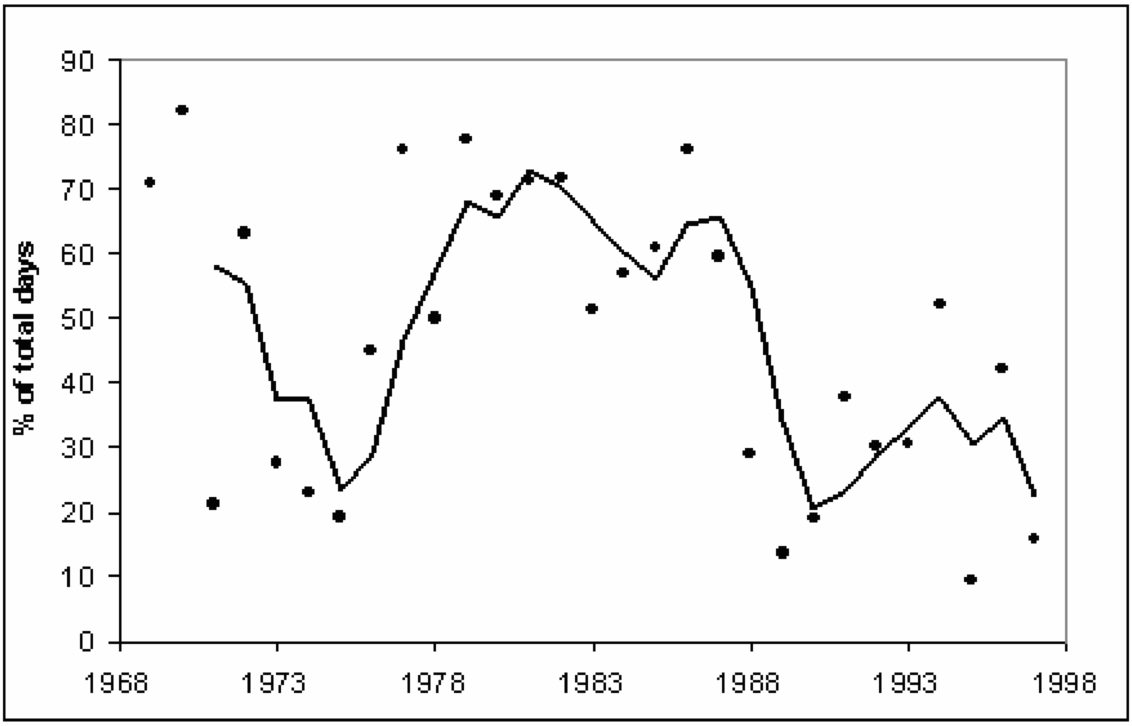

Figure 8 Skåbu winter ‘cold’ clusters- TSI4 + TSI1 cluster frequencies from a number of clusters were combined due to few days occurring in the coldest category cluster).

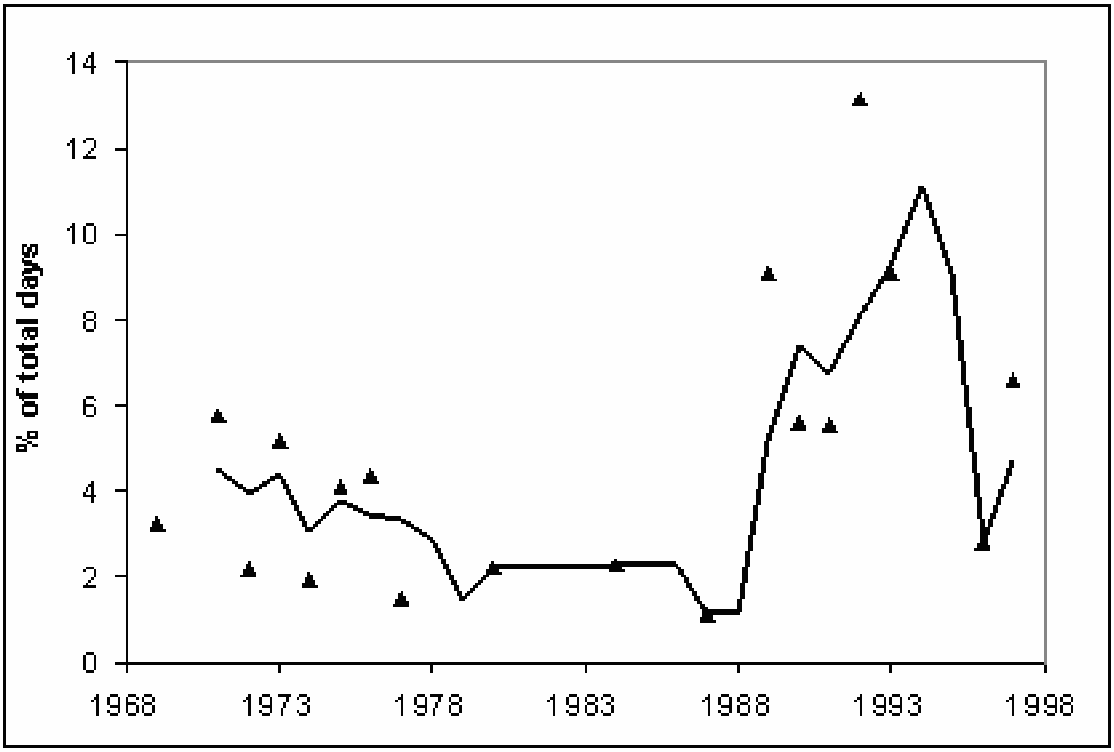

Figure 9 Skåbu winter 'warm' cluster -TSI 3 + TSI10 cluster frequencies from a number of clusters were combined due to few days occurring in the coldest category cluster).

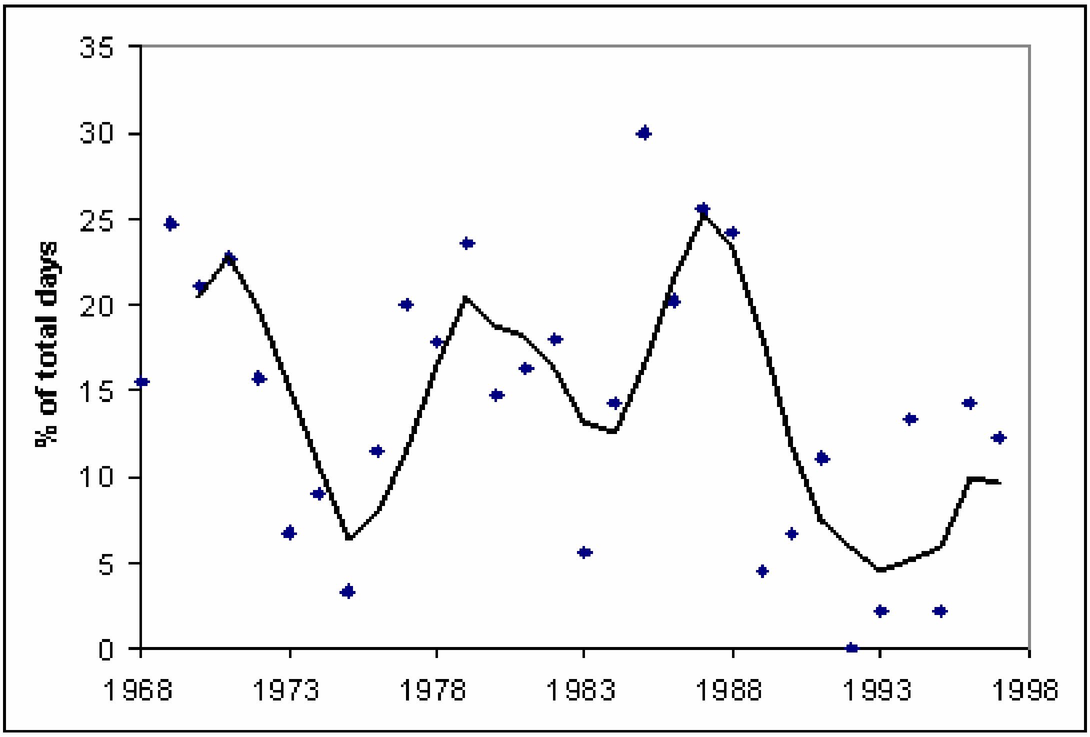

Figure 10 Nordstraum winter 'cold' clusters- TSI 1b + TSI1c cluster frequencies from a number of clusters were combined due to few days occurring in the coldest category cluster).

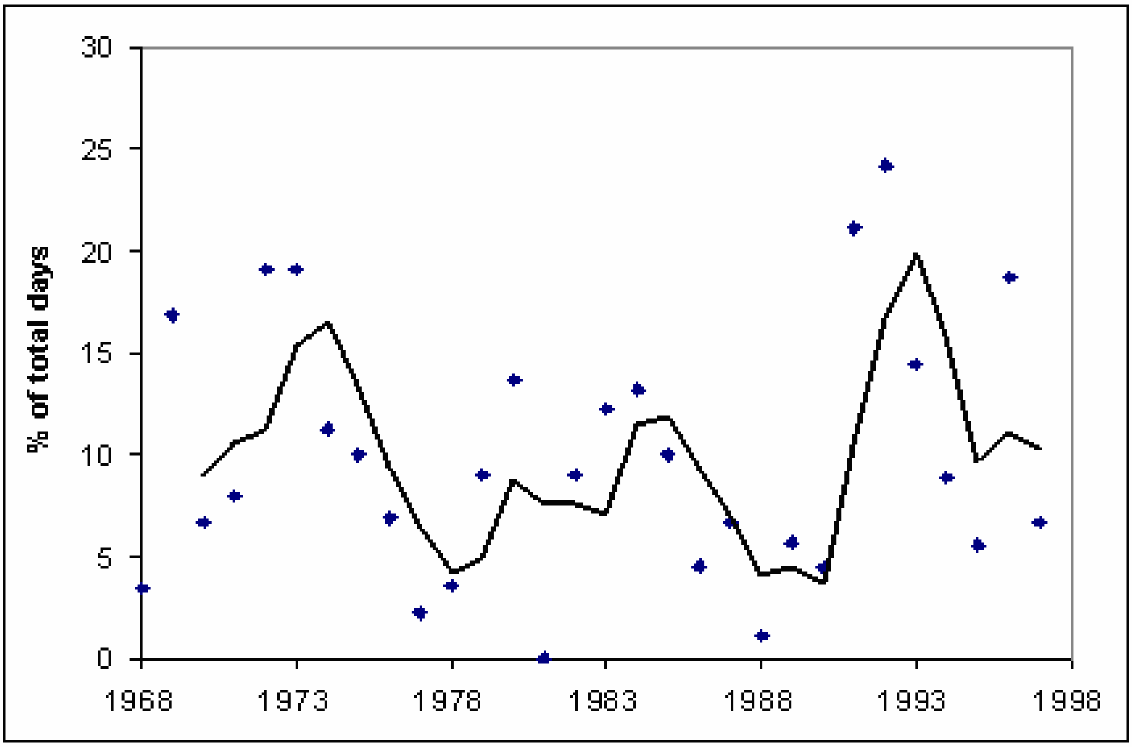

Figure 11 Nordstraum winter 'warm' clusters -TSI 6+ TSI7 cluster frequencies from a number of clusters were combined due to few days occurring in the coldest category cluster).

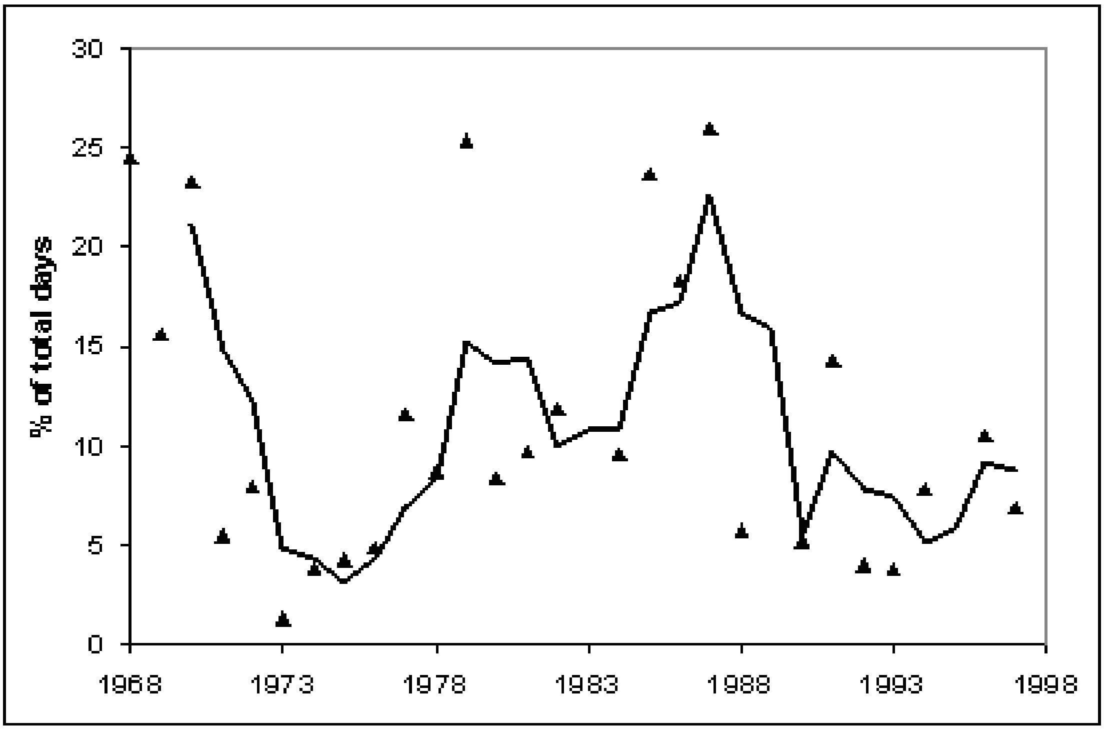

Figure 12 Bodø winter 'cold' clusters-TSI 4.

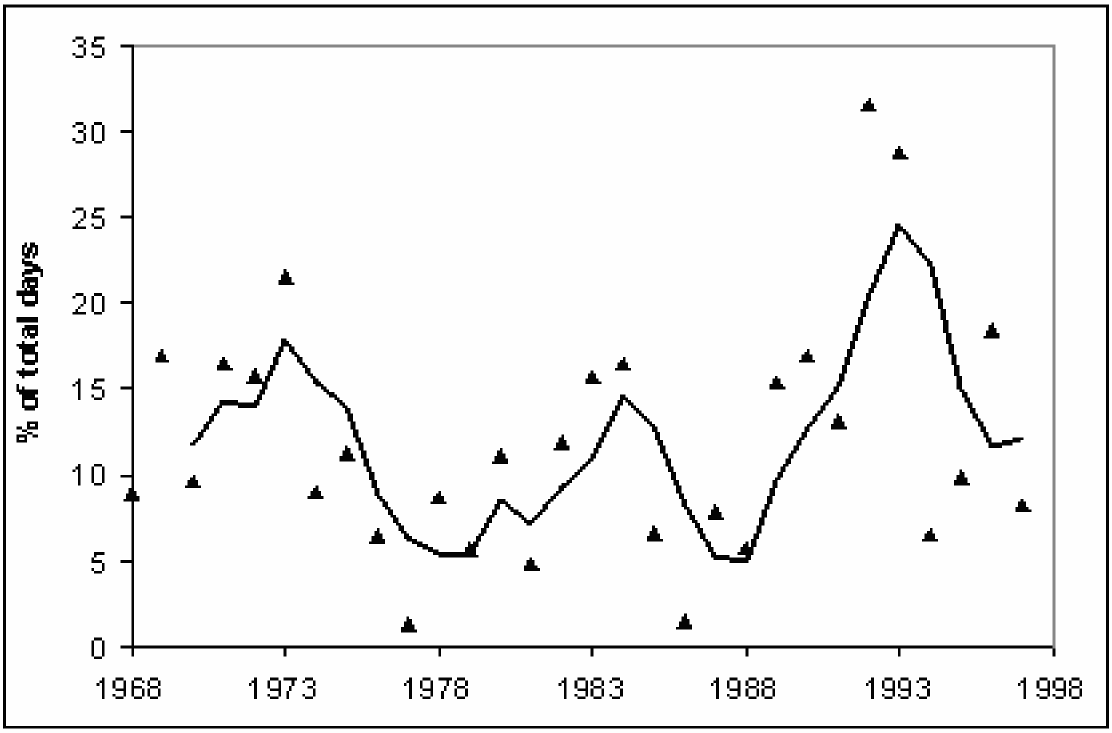

Figure 13 Bodø winter 'warm' cluster -TSI 5 + TSI10 cluster frequencies from a number of clusters were combined due to few days occurring in the coldest category cluster).

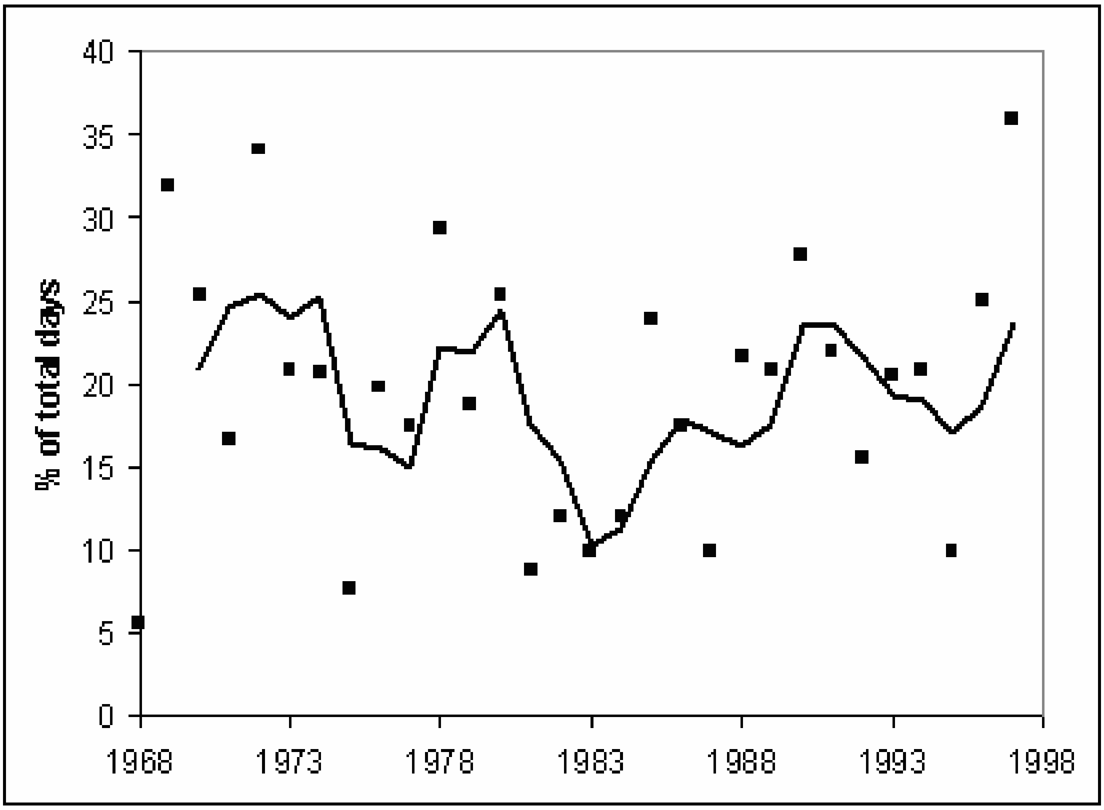

Figure 14 Nordstraum summer warm cluster -TSI 3+TSI6 cluster frequencies from a number of clusters were combined due to few days occurring in the coldest category cluster).

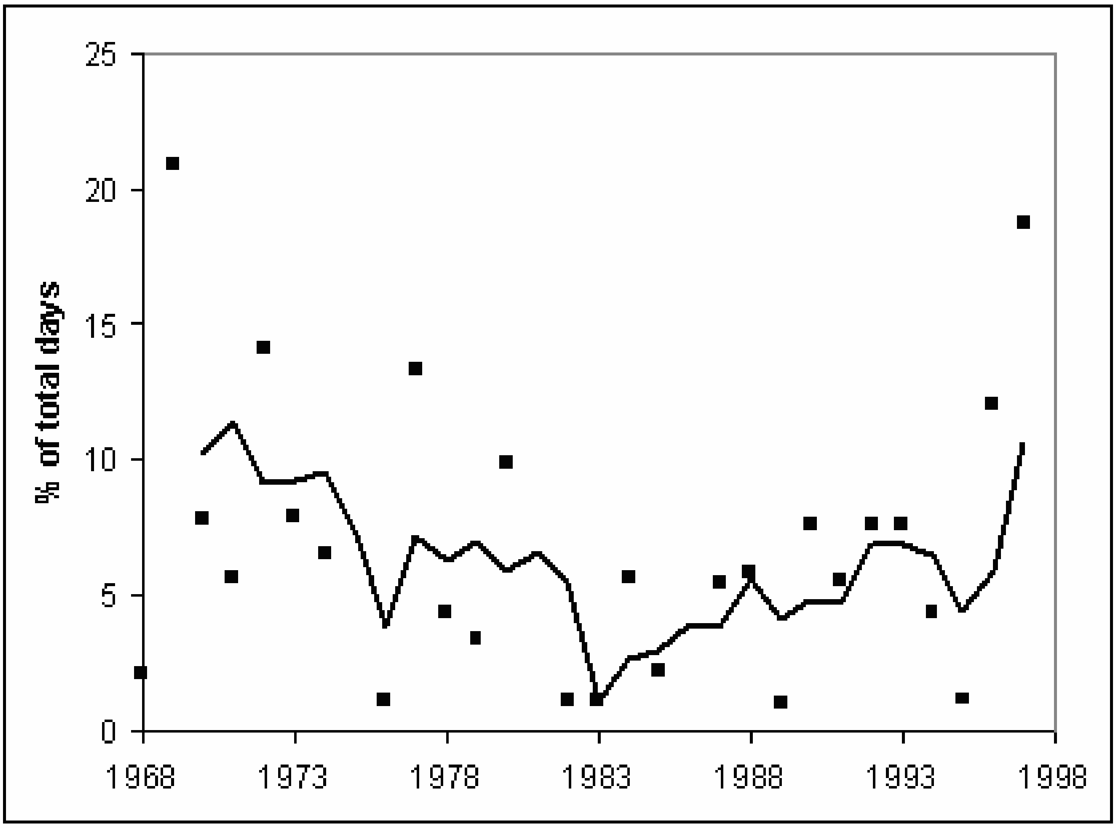

Figure 15 Bodø summer warm cluster-TSI 2.

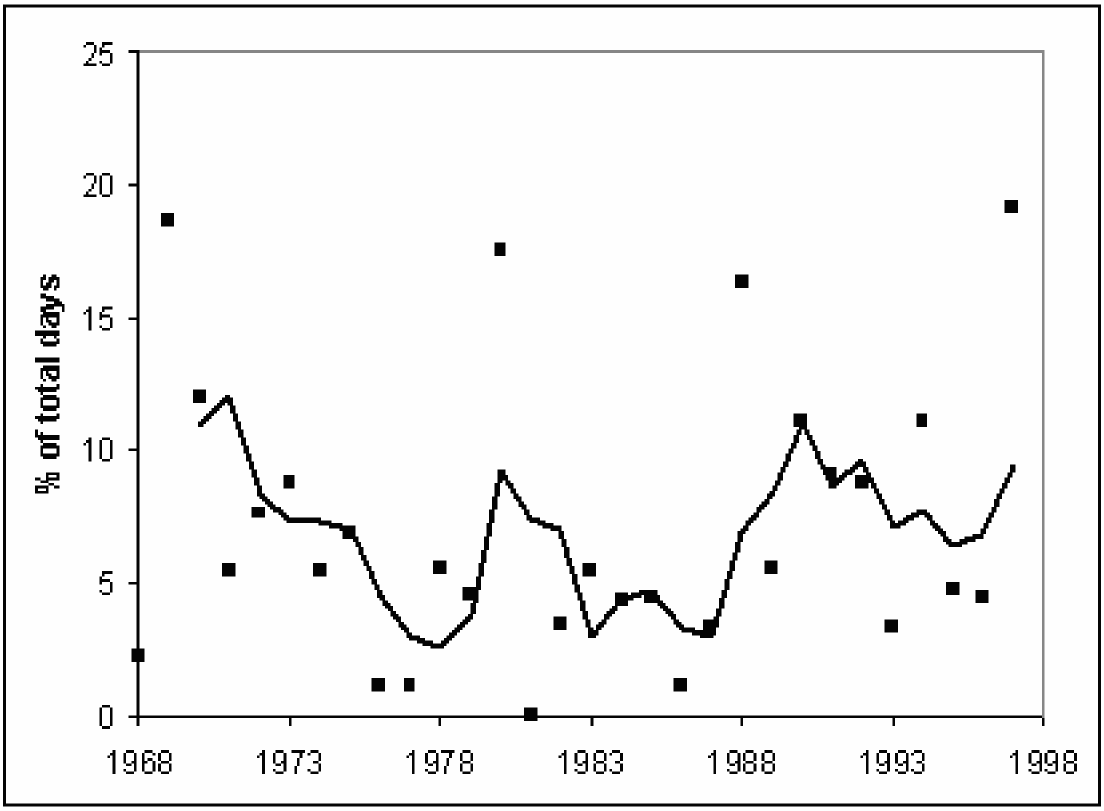

Figure 16 Ørlandet summer warm cluster -TSI 10 + TSI14 cluster frequencies from a number of clusters were combined due to few days occurring in the coldest category cluster).

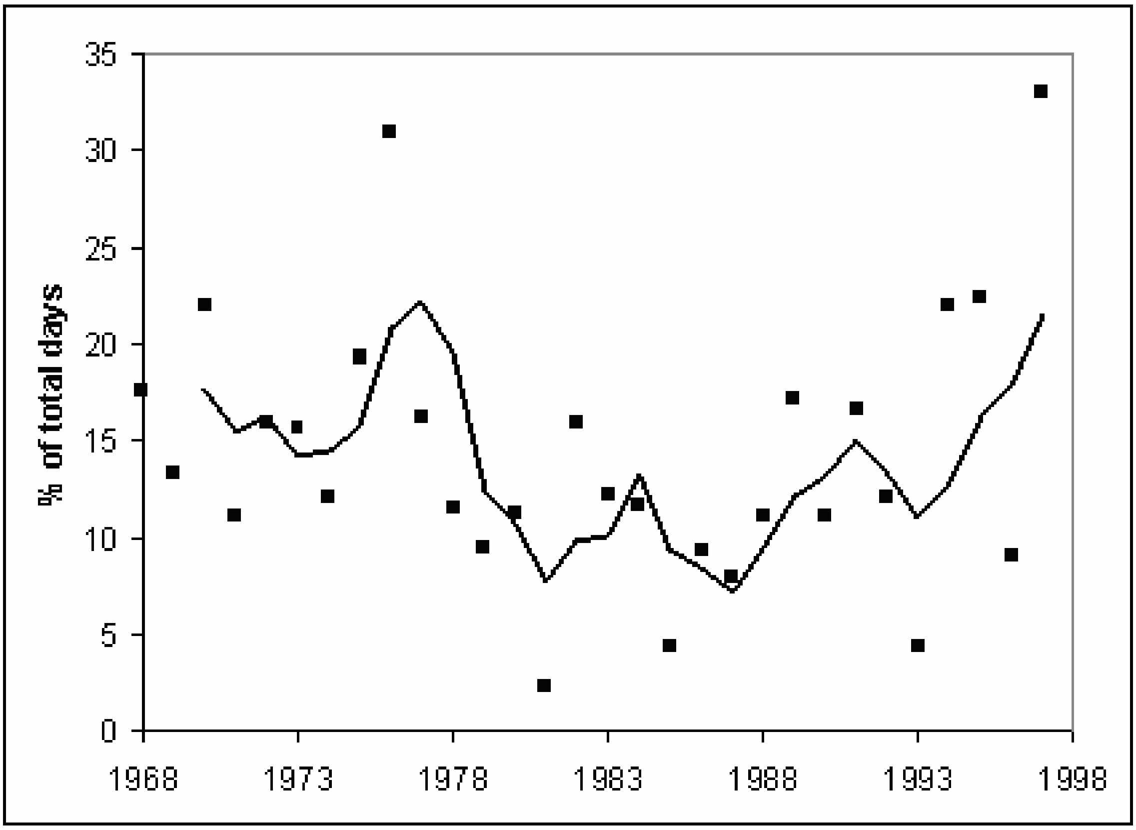

Figure 17 Flesland summer warm cluster-TSI1 + TSI9 cluster frequencies from a number of clusters were combined due to few days occurring in the coldest category cluster).

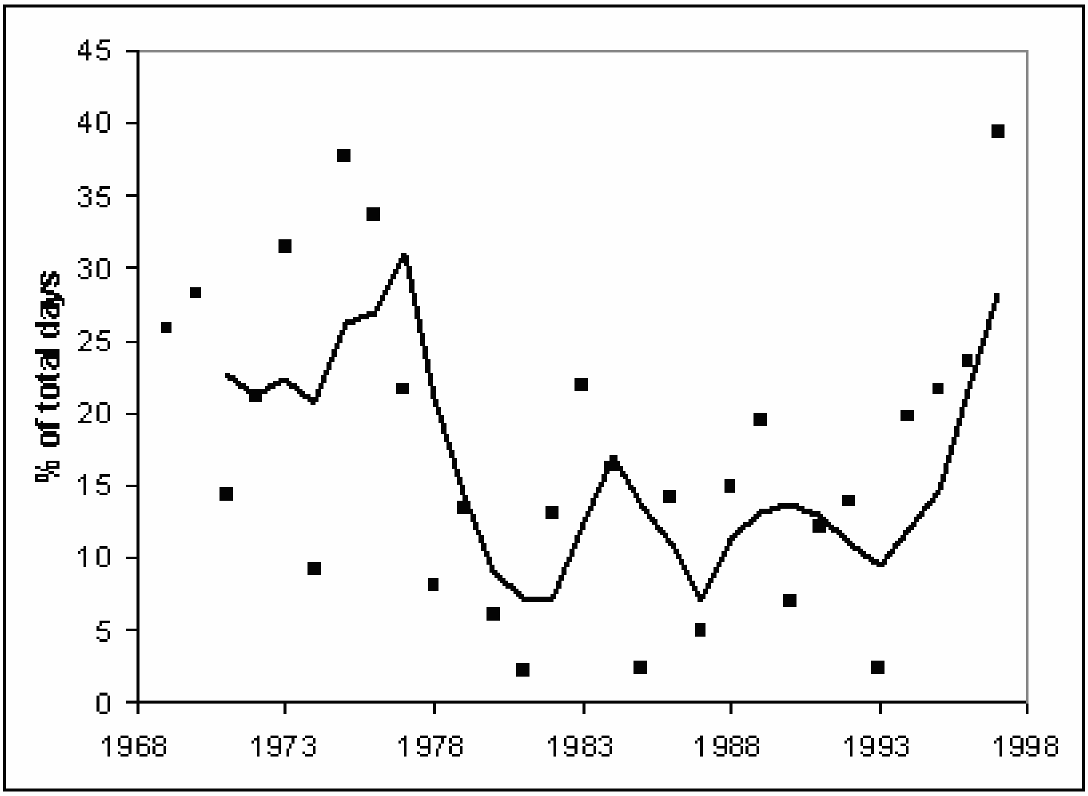

Figure 18 Skåbu summer warm cluster-TSI 3.

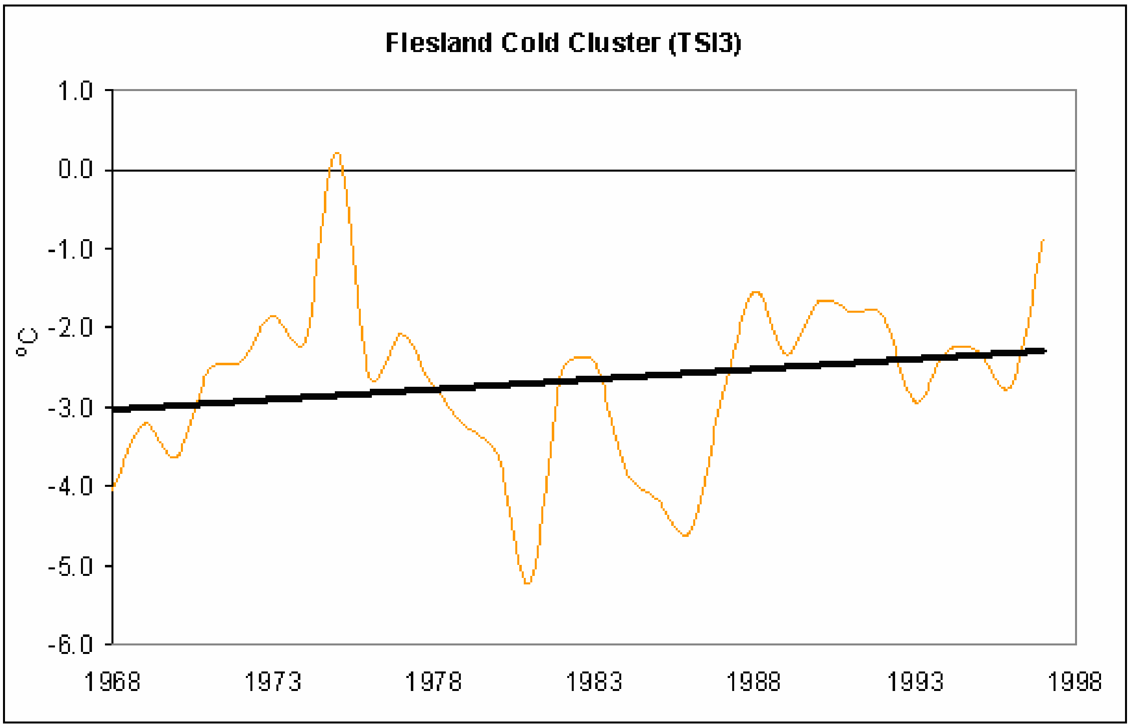

Figure 19 Mean temperature of cold cluster TSI3 from Flesland winter.

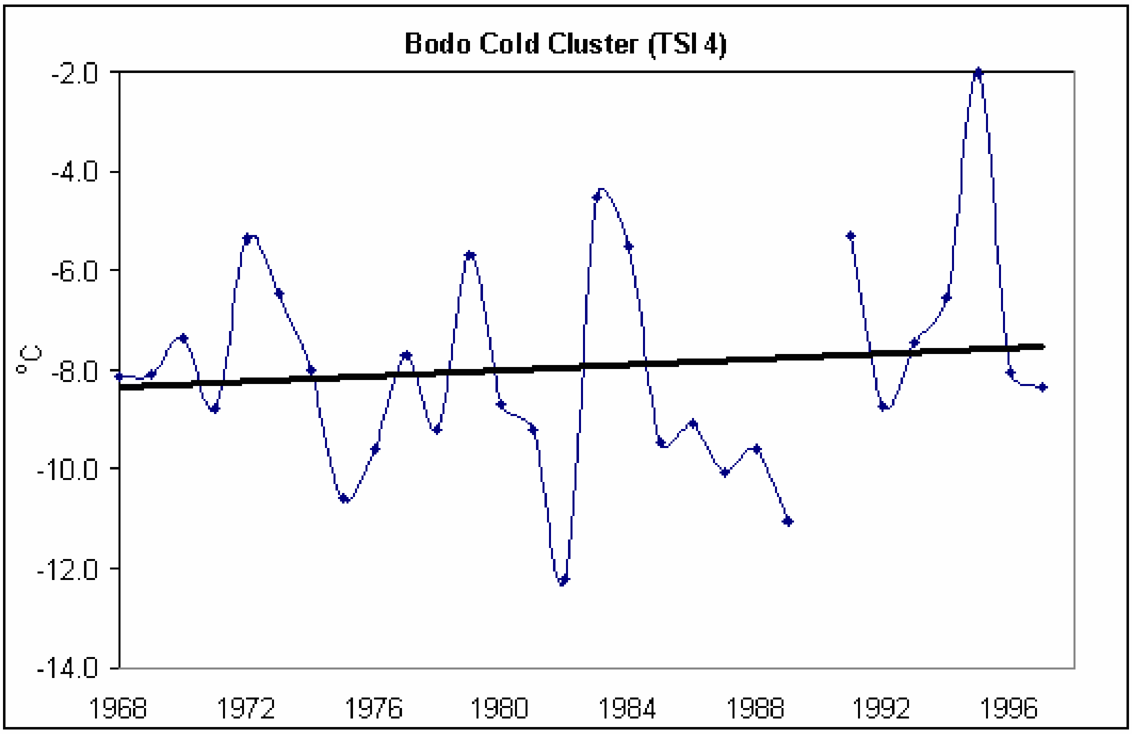

Figure 20 Mean temperature of cold cluster TSI4 from Bodø winter.

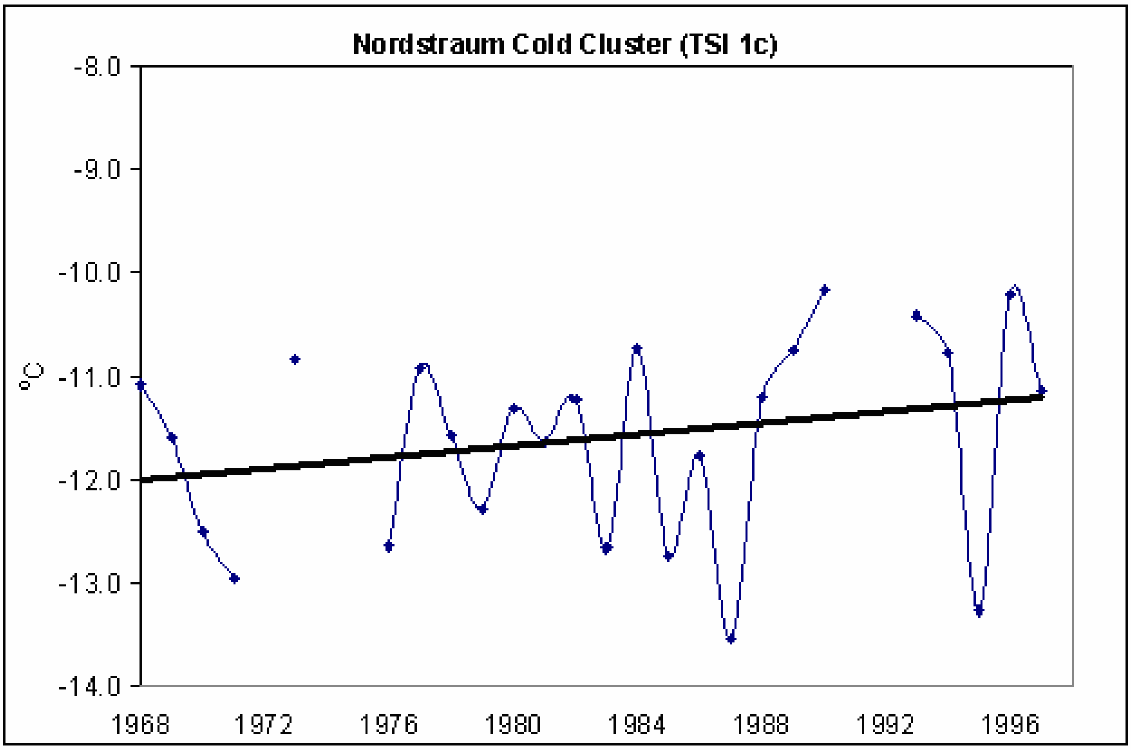

Figure 21 Mean temperature of cold cluster TSI 1c from Nordstraum winter.

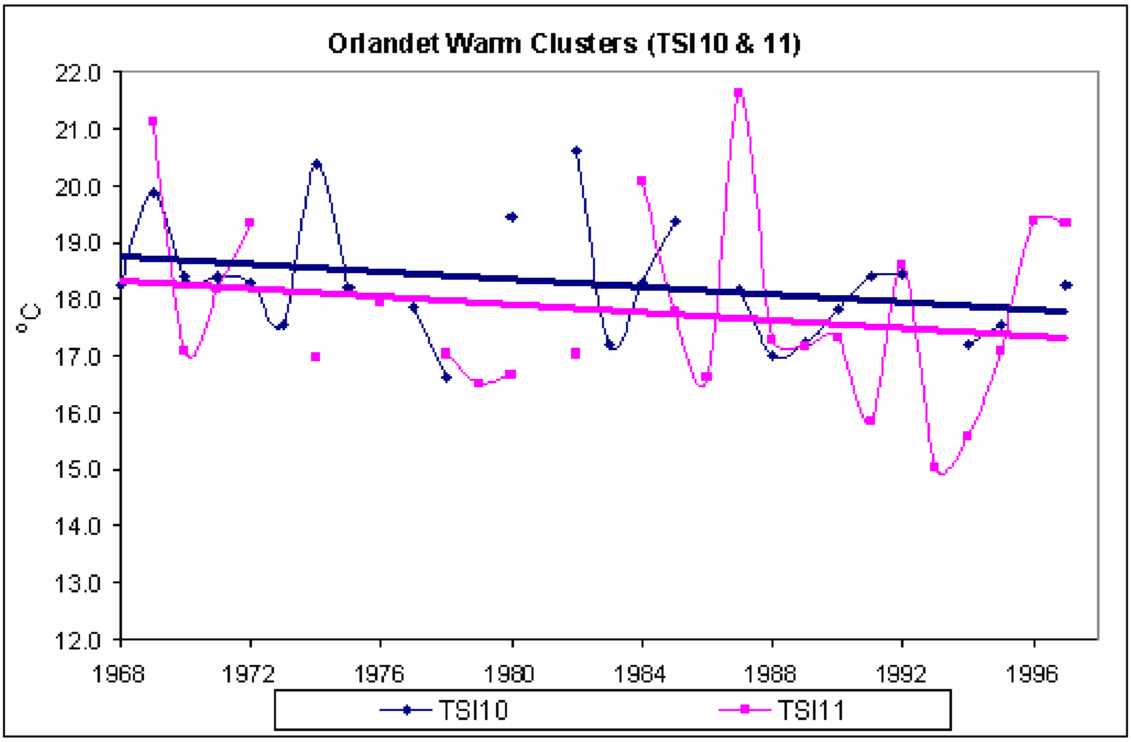

Figure 22 Mean temperature of warm clusters TSI10 & 11 from Ørlandet summer.

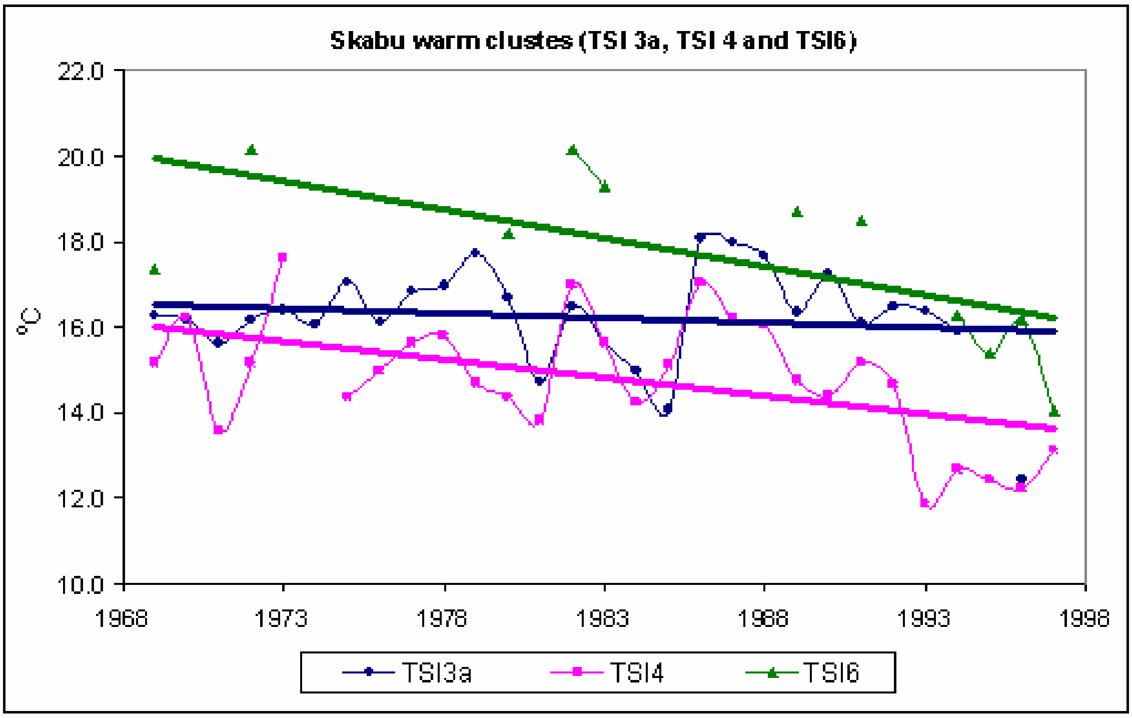

Figure 23 Mean temperature of warm clusters TSI 3a, TSI4 and TSI 6 from Skåbu.

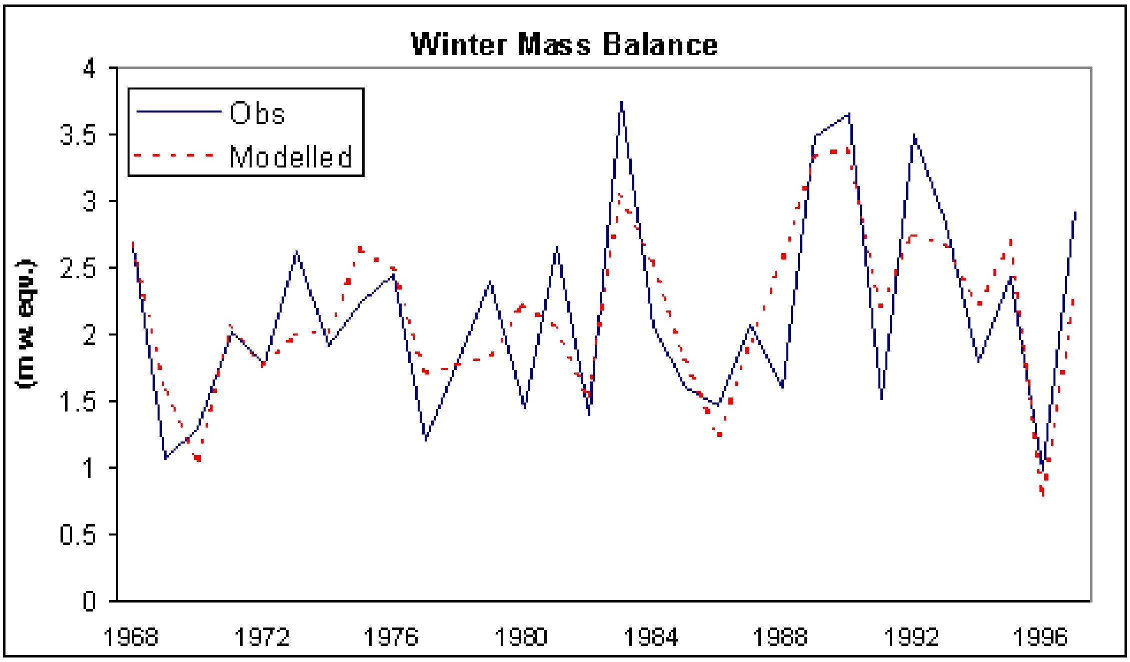

Figure 24 Observed and modelled mass balance for winter based on a split sample.

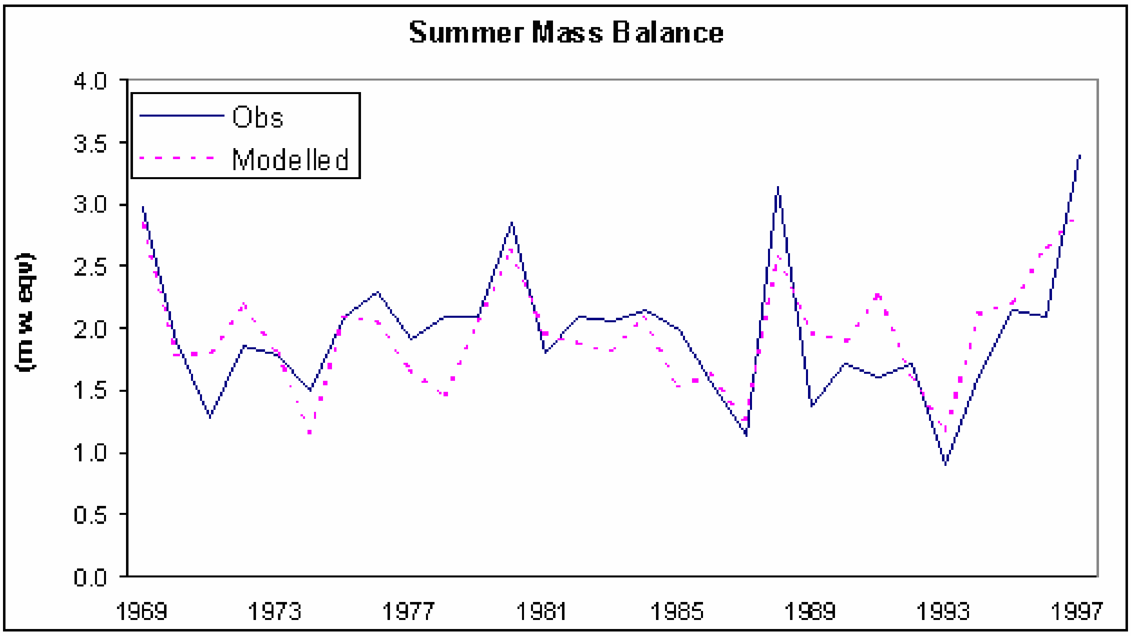

Figure 25 Observed and modelled mass balance for summer based on a split sample.

Total Variance Explained			
	Initial Eigenvalues		
Component	Total	% Variance	Cumulative %
1	**11.6**	**41.7**	**41.7**
2	**3.8**	**13.7**	**55.4**
3	**3.2**	**11.5**	**66.9**
4	**1.4**	**5.3**	**72.2**
5	**1.2**	**4.3**	**76.6**
6	**1.1**	**4.1**	**80.7**

Extraction Method: Principal Component Analysis.

Table 1 % Explained variance of each extracted component from Flesland (winter) 1968-1997 with an eigenvalue >1.0.

	Extracted Principal Components					
Component	**1**	**2**	**3**	**4**	**5**	**6**
p 00	-0.32	0.68	0.61			
p 06	-0.37	0.65	0.65			
p 12	-0.40	0.59	0.68			
p 18	-0.42	0.52	0.70			
t 00	0.85		0.13	0.23		-0.29
t 06	0.89		0.11	0.21		-0.24
t 12	0.81	0.11	0.16	0.35	0.12	-0.19
t 18	0.85	0.18	0.08	0.19	0.23	-0.11
q 00	0.83	-0.15	0.24	0.20		-0.15
q 06	0.88		0.23	0.17		
q 12	0.88		0.19	0.13		
q 18	0.86	0.11	0.13		0.19	
n 00	0.74			-0.19	-0.26	-0.28
n 06	0.75			-0.27	-0.15	-0.11
n 12	0.69	0.19	-0.16	-0.36	0.18	
n 18	0.62	0.23	-0.14	-0.35	0.37	0.14
vis 00	-0.69	0.11	-0.15	0.24	0.33	0.18
vis 06	-0.72		-0.12	0.34	0.34	
vis 12	-0.76			0.42	0.09	-0.13
vis 18	-0.71	-0.15		0.45	-0.13	-0.19
v 00	0.56	0.31	-0.22	0.28	-0.40	0.25
v 06	0.54	0.49	-0.28	0.26	-0.26	0.32
v 12	0.45	0.60	-0.33	0.17		0.31
v 18	0.34	0.58	-0.31	0.11	0.29	0.17
u 00	0.16	-0.50	0.45		0.42	0.13
u 06	0.24	-0.59	0.48		0.15	0.25
u 12	0.28	-0.54	0.50		-0.16	0.38
u 18	0.37	-0.42	0.37		-0.19	0.45

Table 2 Component matrix for Flesland (winter) 1968-1997 with six extracted components. Values less than 0.1 are not displayed. P-pressure; t-temperature; q-specific humidity; n-cloud amount; vis-visibility; *v*-south scalar; *u*-west scalar.

Cluster #	Number of days	Pressure (hPa)	Temperature (°C)	Specific Humidity	Cloud Cover	Visibility (km)	Wind Direction and Speed	Circ Type
1								SW
1a	98	1006	0.6-1.9	0.35-0.38	6-7	29-32	ESE, Light Air	
1b	17	1015-1013↓	-1.3- 1.0	0.28-0.33↑	5-7	27-33	SE-SSE, Light	
1c	105	1021	-1.2- 0.9	0.32-0.33	4-6↑	31-35	ESE-SE, Light Air	
1d	107	1027	0.9-2.1	0.42-0.47↑	7	25-18↓	SE, Light Air	
1e	16	1035	0.0-2.3	0.42-0.46	4-6↑	26-35	E/ESE, Light Air	
1f	34	1017-1024↑	1.8-3.2	0.51-0.43↓	3-6	26-41	SW-SSE, Light Air	
1g	14	1024-1027↑	3.0-5.4	0.63-0.51↓	7-3↓	17-36	ESE-SSW, Light Air	
2	173	998-1001	-1.7-0	0.33-030↓	4-5	33-43	SSE-SE, Light Air	NW
3								AE
3a	199	1012-1014↑	-3.1– -1.0	0.24-0.26	3-4	40-52	E, Light Air	
3b	170	1024-1025	-5.0– -1.5	0.19-0.20	1-2	53-61	E, Light Air	
3c	64	1002-1004↑	-7.3– -3.5	0.17-0.19	1-2	55-64	E, Light Air	
3d	80	1031	-1.8- 1.6	0.30-0.33	2-3	38-47↑	ESE-SE, Light Air	
3e	19	1022-1026	-2.6- 1.2	0.23-0.27↑	2-7↑	51-39↓	SE, Light	
3f	9	1030-1027↓	-5.0- 0.0	0.21-0.28↑	0-8↑	70-35↓	E-SSE, Light	
4								SW
4a	230	1020-1018↓	3.4-4.4	0.55-0.61↑	7	17-15↓	S/SSE, Light	
4b	127	1007-1003↓	2.9-4.0	0.42-0.48↑	7	28-23↓	SE/SSE, Gentle	
4c	25	990-989	1.4-2.7	0.34-0.37↑	7	24-28	ESE/SE, Light	
4d	9	1029-1024↓	2.9-3.9	0.41-0.46↑	6-8↑	18-29	SSE, Gentle	
5	145	988-984↓	4.4-4.8	0.62-0.64	7-8	17-19	SSE/S, Gentle	SW
6	296	993-997↑	2.7-1.9↓	0.52-0.47↓	6-7	22-27	S, Light	CS
7	171	1013-1008↓	5.7-6.5	0.72-0.80	8	11-14	S, Gentle	ASW
8	189	1001-1003	5.1-5.9	0.73-0.64↓	7-8	13-18↑	SW/WSW, Light	AW
9	15	1004-1010↑	5.0-3.4↓	0.65-0.47↓	5-7	18-25↑	WSW/WNW, Gentle	ANW
10	20	1025-1027	-11.2– -6.8	0.10	0-1	63-68	E/SE, Light Air	SE
11	5	967-971	5.4-3.5	0.78-0.53↓	6-8	11-20	SW-WNW, Gentle	CW
12	14	989-991	6.6-7.8	0.92-1.0	8	10-15	S-SSW, Gentle	CSW

Table 3 The mean meteorological characteristics for each identified air mass cluster for Flesland for the winter months of December, January and February for the period 1968-1997 (↓ indicates increasing or decreasing diurnal trend or change in variable over the four daily measurements). Clusters with greater than 15% of the total number of days were entered into a separate clustering procedure and are indicated by italics. Circ type is the large-scale circulation type associated with the main clusters determined from plotting the daily average sea-level pressure for each cluster from the NCEP/NCAR Reanalysis data.

	TSI1	TSI2	TSI3	TSI4	TSI5	TSI6	TSI7	TSI8	TSI9	TSI10	TSI11	TSI12	TSI13	TSI14
Ålfotbreen	-0.12	-0.43**	-0.78*	-0.03	0.40*	0.61*	0.61*	0.69*	0.54*	-0.09	0.37**	0.26	0.14	0.29
Nigardsbreen	-0.25	-0.32	-0.72*	-0.19	0.33	0.64*	0.64*	0.77*	0.51*	0.06	0.39**	0.37**	0.07	0.23
Rembesdalskåka	-0.09	-0.36*	-0.68*	-0.19	0.27	0.53*	0.58*	0.76*	0.54*	-0.02	0.43**	0.27	0.35	0.33
Storbreen	-0.24	-0.34	-0.70*	-0.26	0.44**	0.69*	0.64*	0.70*	0.52*	-0.01	0.34	0.39**	0.06	0.06
Hellstugubreen	-0.24	-0.15	-0.69*	-0.25	0.47*	0.71*	0.51*	0.62*	0.42**	0.08	0.19	0.27	0.11	0.02
Gråsubreen	-0.27	0.01	-0.54*	-0.26	0.50*	0.67*	0.34	0.41**	0.23	0.03	0.09	0.31	-0.01	-0.06
Hansebreen	-0.12	-0.08	0.06	-0.44	0.00	0.13	-0.06	0.35	0.28	-0.34	0.14	-0.03		0.24
Austdalsbreen	-0.04	-0.41	-0.82*	-0.07	0.35	0.38	0.90*	0.70**	0.74**		0.19	0.40		0.17

Table 4 Pearson's correlation coefficients between the frequencies of occurrence of the winter air mass types from Flesland (TSI- Temporal Synoptic Index) and winter balance from a selection of glaciers, 1968-1997 (* Significant at 0.01, ** Significant at 0.05). Only 13 years of data available for Hansebreen and Austdalsbreen.

	TSI3	TSI4	TSI5	TSI6	TSI7	TSI9	TSI11	TSI18
Engabreen	-0.58*	-0.47**	0.56*	0.58*	0.45**	-0.40	0.34	0.40**
Storglaciären	-0.59*	-0.47*	0.61*	0.68*	0.29	-0.60*	0.56*	0.22

Table 5 Pearson's correlation coefficients between the frequencies of occurrence of the winter air mass types (TSI- Temporal Synoptic Index) from Bodø and winter balance from Engabreen and Storglaciären, 1968-1997 (* Significant at 0.01, ** Significant at 0.05). (Non-significant cluster types were removed for space purposes). 28 years of data available for Engabreen.

	TSI1	TSI2	TSI3	TSI4	TSI5	TSI6	TSI7	TSI8	TSI9	TSI10
Storglaciären	-0.527*	-0.514*	0.057	0.690*	0.556*	-0.092	0.148	0.492*	-0.783	-0.167
Langfjordjøkelen	-0.582	-0.547	0.390	0.530	0.648	-0.012	0.373	0.104	.	-0.936

Table 6 Pearson's correlation coefficients between the frequencies of occurrence of the winter air mass types (TSI- Temporal Synoptic Index) from Nordstraum and winter balance from Langfjordjøkelen and Storglaciären, 1968-1997 (* Significant at 0.01, ** Significant at 0.05). Only 9 years of data available for Langfjordjøkelen.

	TSI1	TSI2	TSI3	TSI4	TSI5	TSI6	TSI7	TSI8	TSI9	TSI10	TSI11
Ålfotbreen	0.00	0.11	-0.58*	-0.22	-0.12	0.42**	0.09	0.493*	0.25	0.28	0.42**
Nigardsbreen	0.17	-0.15	-0.42**	-0.15	-0.03	0.49*	0.07	0.25	0.27	0.24	0.42**
Rembesdalskåka	0.21	-0.22	-0.49*	-0.33	-0.16	0.71*	-0.03	0.38**	0.42**	0.50*	0.34
Storbreen	0.21	-0.32	-0.44**	-0.35	-0.17	0.81*	-0.11	0.29	0.49*	0.55*	0.43**
Hellstugubreen	0.33	-0.21	-0.53*	-0.34	-0.04	0.69*	-0.01	0.30	0.38**	0.56*	0.32
Gråsubreen	0.45**	-0.34	-0.57*	-0.30	0.05	0.65*	0.12	0.17	0.48*	0.55*	0.36
Hansebreen	0.22	0.14	-0.62**	-0.13	-0.34	0.37	0.23	0.71*	0.05	0.10	.
Austdalsbreen	0.21	0.04	-0.80*	-0.51	-0.41	0.73**	-0.24	0.63	0.25	0.46	.

Table 7 Pearson's correlation coefficients between the frequencies of occurrence of the summer air mass types (TSI- Temporal Synoptic Index) from Flesland and summer balance from a selection of glaciers, 1968-1997 (* Significant at 0.01, ** Significant at 0.05). Only 12 and 10 years of data available for Hansebreen and Austdalsbreen, respectively.

	TSI1	TSI2	TSI3	TSI4	TSI5	TSI6	TSI7
Ålfotbreen	-0.38**	0.01	0.19	0.67*	0.02	0.10	-0.38**
Nigardsbreen	-0.33	-0.08	0.27	0.54*	-0.15	0.11	-0.29
Rembesdalskåka	-0.51*	-0.01	0.43**	0.61*	-0.07	0.19	-0.40**
Storbreen	-0.61*	0.08	0.45**	0.63*	0.05	0.32	-0.38**
Hellstugubreen	-0.56*	0.08	0.51*	0.55*	-0.04	0.10	-0.30
Gråsubreen	-0.74*	0.24	0.75*	0.37**	0.10	0.23	-0.41**
Hansebreen	-0.16	0.08	0.14	0.04	0.15	0.18	-0.06
Austdalsbreen	-0.30	-0.03	0.45	0.65**	-0.22	-0.09	-0.42

Table 8 Pearson's correlation coefficients between the frequencies of occurrence of the summer air mass types (TSI- Temporal Synoptic Index) from Skåbu and summer balance from a selection of glaciers, 1968-1997 (* Significant at 0.01, ** Significant at 0.05). Only 12 and 10 years of data available for Hansebreen and Austdalsbreen, respectively.

	TSI1	TSI2	TSI3	TSI4	TSI5	TSI6	TSI7	TSI8	TSI9	TSI10	TSI11	TSI12
Engabreen	-0.53*	0.38**	0.52*	-0.37	-0.06	0.51*	0.36	-0.23	-0.15	0.19	-0.38**	0.47**
Storglaciären	-0.39**	0.55*	0.31	-0.51*	-0.15	0.59*	0.40**	-0.22	0.01	0.06	-0.37**	0.28

Table 9 Pearson's correlation coefficients between the frequencies of occurrence of the summer air mass types (TSI- Temporal Synoptic Index) from Bodø and summer balance from two glaciers, 1968-1997 (* Significant at 0.01, ** Significant at 0.05). 28 years of data available for Engabreen.

	TSI1	TSI2	TSI3	TSI4	TSI5	TSI6
Storglaciären	-0.61*	0.02	0.64*	-0.50**	0.21	0.44**
Langfjordjøkelen	-0.56	-0.09	0.74**	-0.67**	0.14	0.53

Table 10 Pearson's correlation coefficients between the frequencies of occurrence of the summer air mass types (TSI- Temporal Synoptic Index) from Nordstraum and summer balance from two glaciers, 1968-1997 (* Significant at 0.01, ** Significant at 0.05). 9 years of data available for Langfjordjøkelen.

	TSI3	TSI4
Winter Balance	-0.804 P=0.000	-0.602 P=0.001

Table 11 Partial correlations for TSI 3 and TSI4 and winter balance at Rembesdalskåka (27 degrees of freedom, n=30).

	TSI3	TSI4	TSI5
Summer Balance	0.695 P=0.000	0.766 P=0.000	-0.394 P=0.042

Table 12 Partial correlations for TSI 3 (with TSI 4 and TSI 5 hen constant) and summer balance at Rembesdalskåka (25 degrees of freedom, n=29).

	Observed	Bias	Mean	SE	2.5%	97.5%
Intercept	3.976	0.01110	3.988	0.2740	3.40	4.44
TSI3	-0.045	-0.00034	-0.046	0.0057	-0.057	-0.034
TSI4	-0.046	-0.00083	-0.047	0.0106	-0.066	-0.026

Table 13 Results from a bootstrap with 1000 replications on the coefficients derived in relating TSI 3 and TSI4 from Flesland to the winter balance from Rembesdalskåka.

	Observed	Bias	Mean	SE	2.5%	97.5%
Intercept	0.934	0.00450	0.938	0.1939	0.576	1.347
TSI3	0.027	-0.00016	0.027	0.0068	0.013	0.039
TSI4	0.054	-0.00111	0.053	0.0114	0.030	0.073

Table 14 Results from a bootstrap with 1000 replications on the coefficients derived in relating TSI3 and TSI4 from Skåbu to the summer balance from Rembesdalskåka.