Synoptic Forcing of Precipitation over Greenland: Climatology for 1961–99

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ABSTRACT

Analysis of the synoptic climatology and precipitation patterns over the North Atlantic region allows for a better understanding of the atmospheric input to the mass balance of the Greenland ice sheet. The self-organizing map (SOM) technique was applied to the 40-yr European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-40) daily sea level pressure (SLP) data from 1961 to 1999 to objectively identify synoptic SLP patterns over the North Atlantic region. A total of 35 different SLP patterns were identified. Patterns common to the winter season are characterized by deep low pressure systems that approach Greenland through an active North Atlantic storm track, whereas patterns most common to the summer months are generally weaker and approach the ice sheet from the west through Baffin Bay. The blocking, splitting, and intensification of cyclones by the high elevations of the Greenland ice sheet were identified in this analysis.

Analysis of ERA-40 precipitation associated with each SLP pattern revealed that the largest precipitation events were associated with passing cyclones that created onshore flow, allowing the air to be lifted orographically by the steep margins of the ice sheet. The ERA-40 annual mean precipitation over Greenland from 1961 to 1999 was 35.8 cm yr⁻¹. Greenland was divided into five subregions, and the preferred synoptic patterns for receiving precipitation in each region include cyclones positioned to allow dynamic and orographic lift in each region. Annual precipitation contributions from each SLP pattern were isolated to reveal that half of the annual mean precipitation over Greenland comes from only 11 of the 35 identified synoptic patterns (31.4%), highlighting the importance of studying Greenland precipitation on an event-by-event basis on a daily time scale.

1. Introduction

The Greenland ice sheet (GrIS) consists of a volume of 2.93 × 10⁶ km³ of ice (Bamber et al. 2001). The topography of the ice sheet is characterized by steep margins rising to two elevation maxima: one in central Greenland with an elevation of 3208 m at the summit and another in southern Greenland with an elevation of more than 2800 m (Fig. 1; and Serreze and Barry 2005). The grounded ice on Greenland, including the ice sheet, glaciers, and small ice caps, has the potential to raise sea level by 7.2 m (Church et al. 2001) on a millennial time scale (Alley et al. 2001) on a millennial time scale (Alley et al. 2001). The ice sheet is maintained by input from precipitation nearly balancing output from evaporation, sublimation, melt, and ice discharge from glaciers (Rignot and Thomas 2002).

Recent changes of the GrIS include not only a thickening of the interior of the ice sheet but also a thinning along the edges (Thomas et al. 2006; Alley et al. 2007a). The most recent analyses have shown an overall net loss of mass because of increasing melt and ice discharge, and it has been concluded that the GrIS has very likely contributed to the rise in sea level (Alley et al. 2007b). The GrIS holds the capacity to influence global climate by affecting the thermohaline circulation, radiative forcing due to surface albedo, and the blocking, genesis, and intensification of passing cyclones. The repercussions of changing the mass balance of the ice sheet have the potential to affect society worldwide. Thus, further analysis and understanding of all the processes contributing to the mass balance of the GrIS is imperative.

Analysis of the mechanisms leading to precipitation over Greenland is important for understanding the atmospheric input to the mass balance of the GrIS and will be the focus of this paper. Because of limited in situ
observations on the ice sheet, with their own set of uncertainties, it has been historically difficult to accurately quantify the amount of precipitation that falls over Greenland (Bromwich et al. 1998). Numerous studies have used a variety of methods to infer the annual mean precipitation over Greenland (Bender 1984; Ohmura and Reeh 1991; Bromwich et al. 1993, 1998, 2001; Robasky and Bromwich 1994; Chen et al. 1997; Ohmura et al. 1999; Bales et al. 2001a,b; Cassano et al. 2001; Box et al. 2004, 2005, 2006). The general features of the precipitation maps produced by each of these studies include maximum precipitation (greater than 165 cm) along the southeast coast, large values (greater than 100 cm) along the southwest coast, moderate precipitation (greater than 50 cm) in western Greenland near Baffin Bay, and a precipitation minimum (~10 cm) in the central interior of the northern half of the ice sheet at high elevations. Although the average annual Greenland precipitation estimates among these studies range from 27.6 to 39.0 cm yr\(^{-1}\), Bromwich et al. (1998) found a general agreement on a long-term Greenland annual mean precipitation of 35.0 cm yr\(^{-1}\) and estimates since 1998 have generally fallen near this value.

Global atmospheric reanalysis products provide an alternative source for Greenland precipitation data, with several advantages over the previously referenced Greenland precipitation data sources. Such reanalyses provide readily accessible and widely evaluated datasets longer than 40 yr with subdaily temporal resolution and consistent dynamic and thermodynamic fields. For these reasons, we have analyzed precipitation and circulation fields from the ERA-40 reanalysis here.

Greenland precipitation often forms as a result of the interactions between cyclonic forcing, onshore flow, and topography (Chen et al. 1997; van der Veen et al. 2001). Monthly-mean synoptic maps hide the details of individual precipitation events by way of averaging, so further analysis of the daily synoptic patterns over a long period of time would undoubtedly prove beneficial (Chen et al. 1997; Rogers et al. 2004). Several studies have tried to find a correlation between the North Atlantic Oscillation (NAO) and precipitation or accumulation over Greenland (Appenzeller et al. 1998; Bromwich et al. 1999; Rogers et al. 2004; Johannessen et al. 2005; Mosely-Thompson et al. 2005; Hanna et al. 2006; Reusch et al. 2007), but they found little or no correlation between Greenland precipitation and the NAO over long periods of time, except for a weak correlation for western region precipitation. Therefore, the NAO is not a comprehensive indicator of Greenland precipitation (Mosely-Thompson et al. 2005). However, Hutterli et al. (2005, 2007) did find a relationship between ice core accumulations in some regions with distinct large-scale atmospheric circulations. Schneidereit et al. (2007) found an increase in the number and intensity of cyclones southeast of Greenland from 1957 to 2002, consistent with an increasing NAO.

The North Atlantic storm track is the main source of cyclones near Greenland, although cyclones can also approach Greenland from the west through Baffin Bay and from the north via the Arctic Ocean. The North Atlantic storm track weakens in the spring until summer, when the Icelandic low, the center of action over Reykjavik, is at its weakest (Serreze and Barry 2005). In examining the influence of cyclonic activity on Greenland precipitation, Chen et al. (1997) divided Greenland into five regions based on precipitation characteristics: northern, western, central, eastern, and...
southern regions (Fig. 1). Using years 1987 and 1988, they then created composite maps of monthly-mean sea level pressure (SLP) during high precipitation months in each of the regions. The southern region received heavy precipitation when a cyclone passed close to the southern tip of Greenland, but if the cyclone was farther east in the Icelandic low region, little precipitation would be received on the ice sheet. Rogers et al. (2004) concluded similarly that it is important to distinguish between cyclones in the lee of southeastern Greenland and Icelandic cyclones that have centers farther from the coast, as they produce opposite precipitation patterns over the ice sheet. These general conclusions of cyclone location and precipitation created a useful basis for research on synoptic patterns in relation to precipitation over Greenland and provided motivation for a further, detailed look at the synoptic patterns that drive these different precipitation regimes. Thus, to study high temporal resolution (daily) data and to retain information on the position and intensity of individual cyclones, the method of self-organizing maps (SOM) is employed here to allow for the objective identification of SLP patterns, and thus cyclones, over the North Atlantic in the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) daily data and to assess the role of synoptic forcing of Greenland precipitation.

The following section explains the data and methods used in this research including a description of the domain, the ERA-40 reanalysis data, and the SOM technique. Sections 3a and 3b introduce the SLP patterns identified by the SOM algorithm and discuss the frequency of occurrence of the SOM-identified weather patterns. The precipitation associated with each SLP pattern is presented in section 3c. A discussion of agreement with earlier work appears in section 4, and a summary of the conclusions is presented in section 5.

2. Data and methodology

a. Data and domain

Data from the ECMWF 2.5° × 2.5° resolution ERA-40 (Uppala et al. 2005) is used here to analyze the synoptic forcing for precipitation over Greenland as a result of its superior performance over the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis in this region (Serreze and Hurst 2000; Hanson et al. 2004; Serreze et al. 2005). Specifically, daily average SLP and daily average precipitation data from 1961 to 1999 are used. The time period, as well as the spatial and temporal resolution of the data, was chosen in anticipation of future work that will compare ERA-40 with data from 15 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) models. The model data was archived with daily resolution for the period of 1961–99. Figure 2 shows the ERA-40 annual mean precipitation over the study domain from this period. A precipitation maximum is located over southeastern Greenland, with maximum values greater than 130 cm. A comparison between ERA-40 precipitation and maps of precipitation over Greenland presented in previous studies (Ohmura and Reeh 1991, their Fig. 2; Bromwich et al. 1993, their Fig. 5; Chen et al. 1997, their Figs. 3a,b; Bromwich et al. 2001, their Fig. 2b; Cassano et al. 2001, their Fig. 4a; Box et al. 2004, their Fig. 6a) shows that ERA-40 Greenland precipitation is broadly consistent with previous estimates of Greenland precipitation, despite some localized differences. More recently, Hanna et al. (2006) compared snow accumulation for the GrIS, defined as snowy precipitation minus evaporation and sublimation derived from the ERA-40 reanalysis, to 58 ice core accumulation datasets. They found that ERA-40-calculated accumulation was too dry (~10%–30%) in central and northern interior Greenland but too wet (>50%) in southern interior Greenland and correct in southeastern Greenland, which is the area of maximum precipitation over the ice sheet (Fig. 2). Overall, temporal variability of ERA-40 accumulation was signifi-
cantly correlated to 47 of the 58 ice core sites. Despite local differences among the precipitation data in various studies, ERA-40 Greenland precipitation is considered a reasonable approximation of reality and is used in this study. The synoptic climatology of SLP over the North Atlantic presented below will cover the domain shown in Fig. 1. This domain is broad enough to include the major North Atlantic storm tracks and synoptic systems that contribute to precipitation over Greenland. As suggested by Chen et al. (1997), Greenland is divided into five regions (Fig. 1) to study regional precipitation patterns. The close proximity of the 2000-m ice sheet elevation contour to the coast (Fig. 1) highlights the rapid increase in elevation along the ice sheet margin.

The 2.5° × 2.5° ERA-40 average daily SLP and precipitation data from 1961 to 1999 were interpolated to the Equal Area Scalable Earth (EASE) grid with 200-km grid spacing over the North Atlantic domain (Armstrong and Brodzik 1995). An equal area grid allows for equal weighting of data in the SOM algorithm. SLP data directly over Greenland was ignored because of the difficulty of reliably calculating sea level pressure over regions of high elevation (Streten 1980). All calculations for the SLP synoptic climatology will use anomaly SLP because the atmospheric circulation depends on SLP gradients and not the actual magnitudes of the SLP. Daily SLP anomalies at each point were calculated by subtracting the daily, domain average SLP from the SLP at each grid point for each day. Use of anomaly SLP will allow the analysis of the lower atmospheric circulation to focus on the gradients that drive the circulation.

b. Description of the self-organizing map technique

The first stage of a synoptic climatology analysis is to categorize atmospheric circulation types into a manageable number of groupings (Barry and Perry 2001). There are several methods in the field of synoptic climatology to create such an organization of data: cyclone and anticyclone event tracking, principal component analysis, and other methods mentioned in detail in Barry and Perry (2001). One such method used to study synoptic weather patterns is the SOM method, a form of artificial neural networks, which is used here to categorize average daily SLP anomalies over the North Atlantic domain to analyze the synoptic forcing for precipitation over Greenland. The SOM technique can be used to create an objective synoptic climatology based on high-resolution atmospheric data (Hewitson and Crane 2002).

The SOM algorithm is a neural network algorithm that uses an unsupervised iterative training procedure to analyze large amounts of data. It groups these data into a user-selected number of clusters (also referred to as patterns or nodes) that span the full range of conditions present in the dataset. The identification of these patterns is unsupervised and objective, in that no user input regarding what patterns will be selected or assumptions about the structure of the patterns are made. The algorithm produces an organized map, a two-dimensional array of patterns that represent the range of conditions found in the input data. Figure 3 shows the SOM created for this study. Each panel on the map represents a single SLP pattern identified by the SOM algorithm and is referred to as a node.

Kohonen (2001) offers a full description of the details of the SOM algorithm, whereas Hewitson and Crane (2002), among others, introduce applications to climate data. The SOM analysis presented in this paper used the SOM-PAK software that is freely available for downloading (available online at http://www.cis.hut.fi/research/som-research). Liu et al. (2006) and Reusch et al. (2005, 2007) evaluate the performance of SOMs in climate data. Reusch et al. (2005, 2007) used an analysis of a North Atlantic domain to compare the SOM technique to the well-established method of principal component analysis. Using SLP data, they concluded that the SOM technique is more robust and offers advantages over the well-established method of principal component analysis. The principal component analysis failed to extract patterns, created mixed patterns represented by one component, and also extracted patterns that never occurred in the input data, whereas the SOM technique represented the patterns in the input data without these issues. Liu et al. (2006) used artificial data representative of known patterns and found that a SOM extracted essential patterns from noisy data, and they found that it offered advantages over an empirical orthogonal function method.

The SOM training algorithm requires some user input, including the number of patterns to be identified (the SOM size) and several training parameters (learning rate, radius, and training length). Hundreds of SOMs were created by varying these parameters with the goal of identifying a SOM that best describes the range of synoptic patterns contained in the input data. An optimal SOM best represents all of the synoptic patterns in the domain without having too many patterns that are indistinguishable from one another. On the other hand, SOMs with too small of dimensions have nodes that represent a broad range of synoptic patterns and thus becomes too general for our intended application. One common technique used in cluster analysis is the elbow criterion, which is a rule of thumb that assists in determining the optimal number of clus-
Fig. 3. Master SOM of SLP anomalies (hPa) based on ERA-40 SLP data from 1961 to 1999. Anomaly SLP contour interval is 2 hPa. Blue shades and dashed contours represent negative SLP anomalies, whereas red shades and solid contours represent positive SLP anomalies.
ters in a dataset by finding the limit at which additional clusters fail to add a significant amount of information. Here, quantization errors for all of the SOMs created with varying sizes and parameters were plotted against the number of clusters. An average quantization error for each SOM is the average squared distance between all of the training data and the resulting SOM and can be used as a performance index. The elbow criterion, as well as visual inspection, supported the choice of a 35-cluster SOM, or $7 \times 5$. Later, it will be shown that each of these patterns is necessary, as the synoptic patterns each produce different amounts of precipitation over Greenland. To then choose the best $7 \times 5$ SOM, several low quantization error SOMs, which are SOMs with the best fit to the training data, were compared. Overfitting in SOMs, or misrepresenting the underlying probability density of the data, is avoided by having a large number of samples; this study used 14,204 days of data. This can also be shown by the frequent occurrence of each of the SOM patterns in the data, which will be presented later in section 3b.

Another issue to be considered when selecting the SOM is the organization of the nodes relative to each other. Sammon mapping (Sammon 1969) can be used to visualize the spatial relationship between nodes (Fig. 4). The Sammon maps for several of the SOMs indicated that nodes were folded over onto each other, revealing that some $7 \times 5$ SOMs were not as well organized as others. After balancing the need for a SOM that adequately represents the range of SLP patterns without being either too general or too specific, having a low quantization error, and having a relatively flat Sammon map (Fig. 4), the $7 \times 5$ SOM shown in Fig. 3 was selected. The training parameters used here are a learning rate of 0.01, a radius of two, and a training length of one million steps.

Each daily average SLP anomaly field from ERA-40 can be associated with a single node on the SOM. To find this node, the mean squared difference between each daily SLP anomaly sample and the SLP anomalies of each node are calculated. Each daily sample is associated with (or mapped to) an individual node that gives the smallest mean squared difference. The frequency with which a node occurs can be calculated by mapping each daily SLP anomaly to the master SOM and summing the number of times each node occurs. The percent of occurrence, or frequency, of each node over a period is the number of occurrences divided by the total number of daily samples. The probability that any daily SLP anomaly would map to any particular node is $1/N$, where $N$ is the number of nodes. For the $7 \times 5$ SOM used in this study, the probability is equal to 1/35 or 2.86%. The significance of the frequency for which the daily SLP anomalies map to each node can be determined by calculating a 95% confidence interval around the expected probability of 2.86%. Assuming that the process is binomial, the 95% confidence limits are calculated by

$$p \pm 1.96 \left[ \frac{p(1-p)}{n} \right]^{1/2},$$

where $p$ is the probability that any daily sample would map to any node, and $n$ is the number of daily samples; this study used 14,204 samples. If the observed frequency of a node is outside this calculated interval of 2.58%–3.13%, it is considered significantly different, at the 95% confidence level, from the expected value of 2.86%. Frequencies for a seasonal time scale can be isolated by mapping only daily SLP anomaly data from a season to the master SOM and summing the occurrence of each node to calculate the frequency for that season. When determining the significance of the difference between seasonal frequencies and the frequencies for all seasons, the test statistic

$$\left| \frac{(p_1 - p_2) \left[ \frac{p_2(1-p_2)}{n_2} + \frac{p_1(1-p_1)}{n_1} \right]^{1/2}}{n_1} \right|$$

is used, where for each node $p_1$ is the annual node frequency, $p_2$ is the node frequency for the season of interest, $n_1$ is the number of samples in the annual data, and $n_2$ is the number of samples in the seasonal data [3481 for December–February (DJF) and 3588 for June–August (JJA)]. If the test statistic is greater than 1.96, the seasonal node frequency is considered statistically different, at the 95% confidence level, from the annual node frequencies.
Precipitation data were also stratified in the existing SOM. The ERA-40 daily average precipitation rate was interpolated to the same EASE grid as the SLP data used to make the master SOM. The precipitation data for the days that mapped to each node were averaged at each EASE grid point to find the average gridpoint precipitation for all days associated with each node. Precipitation anomalies were then calculated by subtracting the 1961–99 average precipitation at each grid point from the node average gridpoint precipitation. The precipitation anomalies show departures from the average precipitation associated with each synoptic pattern (node) identified in the SOM.

3. Results
a. Master SOM

The SOM obtained using the training procedure described above is displayed on a 7 × 5 grid referred to as the master SOM (Fig. 3). Each of the 35 patterns in the master SOM is referred to as a node and represents a single SLP anomaly pattern representative of a portion of the daily data in the training dataset. Each pattern is labeled with a row and column number to allow compact reference to any pattern on the SOM. The primary distinction between the different synoptic patterns represented on the master SOM are the position and intensity of the low and high pressure centers in the SLP field. The master SOM displays all of the expected climatological features of the North Atlantic region including the North Atlantic storm track, the Icelandic low, and the Azores high.

General patterns within the organization of the SOM (Fig. 3) include a northward shift of the cyclone centers when moving from the bottom to the top of the SOM. When moving from left to right across the SOM, the cyclone centers tend to move eastward and are located closer to Greenland. The weakest cyclones are located in the top rows of the SOM, whereas stronger cyclones are found near the bottom, and the strongest cyclones appear in the bottom right corner of the SOM. Nodes with the highest pressures over the Azores high, in the southeast corner of the domain, occur along the right columns of the SOM. Nodes with a strong Icelandic low and Azores high, characteristic of positive NAO values, are located in the bottom right portion of the SOM and also include nodes (0, 0) and (0, 1) in the extreme upper left corner of the SOM. Node (6, 4) in the bottom right corner has the highest seasonally averaged NAO value, which is emphasized by the lowest pressure over the Icelandic low and the highest pressure over the Azores high. The remainder of the nodes on the SOM are characteristic of negative NAO index values. The node with the most negative seasonally averaged NAO value is (0, 4), which is easily understood given the small SLP anomalies that occur at both Reykjavik, Iceland, and Ponta Delgada, Azores.

The evolution of the synoptic weather over the North Atlantic for some period of time would correspond to daily SLP data mapping to various nodes on the SOM as low and high pressure centers move and vary in intensity over time. The time evolution of the SLP patterns in a region ultimately makes up the synoptic climatology of that region, which can be assessed in the SOM framework by tracking the temporal evolution of nodes associated with each daily SLP pattern. For any given day, the previous day’s SLP pattern may correspond to the same node associated with that day’s SLP pattern, to an adjacent node, or to a nonadjacent node. An analysis of these daily node transitions throughout the period of interest provides information on the typical synoptic evolution in the region of interest (i.e., the frequency with which each node maps to the same node the next day, moves to an adjacent node, or skips to a nonadjacent node; Fig. 5). Figure 5 illustrates several important synoptic transitions, or cyclone tracks, around Greenland, where each box represents the node in the same position and with the same label as in Fig. 3. The extreme elevations of the ice sheet and the unique temperature field along the ice edge have an effect on passing cyclones by blocking (arrow 1), splitting (arrow 2), or reintensifying the circulation (arrow 3).

Cyclones approaching Greenland from the west can be blocked by the high elevation of the central ice sheet (Fig. 1) and subsequently dissipate in Baffin Bay (Chen et al. 1997). One example of blocking is evident in the nodes labeled with arrow 1 on Fig. 5. The percentage of daily cases in which the daily SLP sample does not move from the current node are high in both nodes (2, 0) and (3, 0), with values of 46.8% and 46.9%, respectively (Fig. 5), indicating that these similar patterns with a cyclone in Baffin Bay (Fig. 3) may persist for several days. The sizes of the circles in these two nodes are larger than most of the other nodes, suggestive of a notable case. For node (2, 0), the next day will map to an adjacent mode 27.7% of the time and 25.5% of the time for node (3, 0). Nodes (2, 0) and (3, 0) (Fig. 5) both have long flags pointing to each other, which indicates that when mapping to an adjacent node, these modes would likely map to each other the next day. This supports the suggestion of a cyclone being blocked by the ice sheet. Blocked cyclones in Baffin Bay produce precipitation over the western half of Greenland.

Cyclones approaching Greenland from the south or southwest can be split by the high elevation of the
southern region ice sheet (Fig. 1) and as the parent cyclone continues west of Greenland into Baffin Bay, a new cyclone redevelops off of the southeast coast of Greenland (Chen et al. 1997; Doyle and Shapiro 1999; Kristjansson and McInnes 1999; Petersen et al. 2003; Doyle et al. 2005; Tsukernik et al. 2007). This splitting of cyclones by the ice sheet is called bifurcation. The synoptic patterns in the nodes labeled with arrow 2 in Fig. 5 show one representative case of bifurcation in the SOM framework. Cyclones split by the southern tip of Greenland produce precipitation over much of the ice sheet, with the highest amounts falling in the southern region.

Other cyclones approach the ice sheet from the south but do not interact directly with the ice sheet and instead move northeastward through the Icelandic low region, where cyclones often intensify and new cyclones may also develop. Node transitions across the bottom row of the SOM show an example of this cyclone track through the Icelandic low region, labeled with arrow 3 in Fig. 5. Development and intensification of cyclones near the Icelandic low region and off the southeast coast of Greenland occur as a result of the presence of several unique features of this region including the high elevation of the ice sheet, the presence of an ice margin, and its position in relation to the long-wave pattern of the Northern Hemisphere (Tsukernik et al. 2007). These intensification mechanisms allow cyclones approaching from the west and blocked by the ice sheet to occasionally redevelop on the other side. They also help explain the development and intensification of new cyclones east of the ice sheet in the bifurcation case. Thus, although the prevailing atmospheric circulations are found to influence precipitation and accumulation over the ice sheet, Greenland’s topography itself can also have a significant influence on the formation, propagation, and intensification of cyclones and the atmospheric circulations in the North Atlantic.
b. Node frequency

The frequency of occurrence of each SLP pattern (node) from Fig. 3 for the period 1961–99 is given in Fig. 6a. Each number in Fig. 6 (and later in Figs. 8–10) represents the node in the same position on the master SOM (Fig. 3). Node (6, 4), for example, can be found by following the numbers 0–6 on the x axis at the bottom of the plot in Fig. 6a and then following the y axis labeled 0–4 on the left side of the plot. Node (6, 4) is, therefore, located in the bottom right corner of Fig. 6a and has a frequency value of 2.96%. This frequency value corresponds to the frequency of the SLP anomaly pattern in the bottom right corner of Fig. 3, labeled (6, 4). These number plots (Figs. 6, 8, 9, and 10) are then contoured and shaded to easily pick out where high and low values exist in the spatial context of the master SOM. Node (6, 4) in Fig. 6a, for example, is shaded medium gray, indicating that it is neither a particularly high nor low value compared to other node frequencies. Here, 31 of the 35 nodes have node frequencies that are significantly different from the expected value of 2.86%, emphasizing that not all synoptic patterns on the SOM are weighted equally and that the frequency of occurrence is an important value to consider. Node (0, 0), in the upper left corner of the SOM, and nodes (6, 0), (6, 1), and (6, 2), in the upper right corner of the SOM, occur most frequently. A general pattern of higher node frequencies along the edges of the SOM is evident from Fig. 6a, which is a characteristic of the SOM.

Seasonal node frequencies for winter (DJF) and summer (JJA) are shown in Figs. 6b and 6c, respectively. Here, 69% of the nodes in DJF and 86% of the nodes in JJA differ significantly from the annual node frequencies. During the winter season, the nodes across the bottom of the master SOM are most frequent (Fig. 6b). These are nodes that are characterized by SLP patterns with deep low pressure systems approaching Greenland. The North Atlantic storm track is most active and the Icelandic low is at its deepest in wintertime (Serreze and Barry 2005). During the summer, however, the more neutral synoptic patterns represented by the nodes in the upper rows and upper right corner of the master SOM (Fig. 6c) are most common. These patterns are characterized by weaker cyclones located near the ice sheet and in Baffin Bay. During the summer the tropics-to-pole temperature gradient becomes smaller, which weakens the general circulation, and with it, the North Atlantic storm track.

The transitional seasons of spring [March–May (MAM)] and fall [September–November (SON), frequencies not shown] indicate frequencies of nodes that
transition from a winter to a summer state and vice versa. The nodes most common during spring are located along the left column and left half of the top row of the SOM. These patterns indicate a transition from the active North Atlantic cyclone track and deep Icelandic low of the winter to the more neutral circulation patterns of the summer and a westward shift of cyclones. Fall season frequencies are highest along the bottom right corner, up the right column, and across the top row of the SOM. Patterns common in fall include intense cyclones mostly east of Greenland. The seasonal shift in weather patterns, represented by the maximum frequencies in each season, takes a clockwise path through the master SOM (Fig. 3), starting at the bottom of the SOM in winter, shifting to the left in spring, to the top in summer, and to the right in fall, then back to the bottom in winter.

c. Precipitation

Using the master SOM described above, average precipitation patterns for each node were analyzed. Precipitation anomalies stratified at each node on the master SOM are shown in Fig. 7. Atmospheric processes that cause precipitation involve a complex interaction between atmospheric features at all levels in the troposphere. Although these interactions are important, they are reflected in the surface circulation, and any given precipitation pattern is well explained by focusing on one measure of the synoptic atmospheric circulation at the surface, represented here by SLP anomalies. A comparison between SLP anomalies and precipitation in Fig. 7 shows a close relationship between the surface circulation and precipitation. The positive precipitation anomalies tend to fall in areas of the negative SLP anomaly (cyclones), where upward vertical motions are expected and also along typical positions of the cyclones’ warm and cold fronts. Orographic enhancement of precipitation is also evident along the steep margins of the Greenland ice sheet.

1) PRECIPITATION OVER GREENLAND

The precipitation falling only over Greenland can be isolated and quantified to focus on precipitation contributing to the mass balance of the GrIS over the reanalysis period. The amount of precipitation that fell over Greenland for days that mapped to a given node was averaged to determine the node averaged daily precipitation (cm day
\(^{-1}\); Fig. 8a). Nodes with the largest daily average precipitation, greater than 0.13 cm day
\(^{-1}\), are nodes (2, 0), (1, 1), (2, 2), and (3, 2) in the upper left and nodes (6, 0), (6, 1), and (6, 2) in the upper right portions of the SOM. Figure 7 reveals that the heavy precipitation over the southern portion of the ice sheet contributes to the large amount of precipitation over Greenland in nodes (1, 1), (2, 2), (3, 2), and (6, 0). Each of these nodes has synoptic SLP anomaly patterns that include a cyclone with its center in the neighborhood of the southern region of Greenland. These SLP patterns indicate cyclonic flow that advects moist air onshore from over the open North Atlantic Ocean. Upon reaching Greenland, this air is orographically lifted from sea level to a maximum elevation of 2800 m in less than 200 km from the southeast coast. As this moist air is lifted, it cools adiabatically, becomes saturated, and ultimately produces heavy precipitation over the ice sheet. The moist air combined with strong onshore, upslope flow is critical to creating the large amounts of precipitation. Nodes (2, 0), (6, 1), and (6, 2) are characterized by high precipitation amounts over a broader area of the ice sheet as a result of low pressure systems located on either or both sides of the ice sheet or in Baffin Bay (Fig. 7).

The nodes with the smallest precipitation amounts, with daily precipitation less than 0.1 cm day
\(^{-1}\), are located in the left column, bottom two rows, and a section in the top center of the SOM including nodes (3, 0), (4, 0), (5, 0), (3, 1), and (4, 1) (Fig. 8a). Although most of these nodes do have high amounts of precipitation over a large portion of the analysis domain (Fig. 7), the precipitation amounts over Greenland for these nodes is relatively small due to a lack of ideal interaction between the cyclones and the ice sheet, particularly in the southern region. These low Greenland precipitation nodes fall into one or more of the following three categories that explain the reasons for low precipitation: 1) the cyclone center is located too far from Greenland to result in strong onshore flow (e.g., the left column of the SOM and nodes (1, 4), (2, 4), (3, 4) along the bottom row); 2) the cyclone center sits east of southern Greenland and isobars are oriented so that onshore flow is onto the eastern region of Greenland rather than the southern region [e.g., (4, 4), (5, 4), and (6, 4) in the bottom right corner of the SOM]; and (3) the weather patterns are characterized by weak low pressure systems and weak onshore flow [e.g., (3, 0), (4, 0), (5, 0), (3, 1), and (4, 1) in the upper middle area of the SOM].

Each of the 35 weather patterns identified on the SOM is necessary to distinguish between subtle differences in SLP patterns and thus the magnitude and position of precipitation that each weather pattern creates. The position of a cyclone is important for identifying where precipitation will fall. The ideal lower atmospheric circulation for producing large magnitudes of precipitation over Greenland results from the flow
Fig. 7. Node-averaged precipitation anomaly (cm day$^{-1}$; shaded contours) and node anomaly SLP (hPa; solid contour lines for positive SLP anomalies and dashed contour lines for negative SLP anomalies with 2 hPa contour intervals). Blue shading indicates positive precipitation anomalies and orange shading indicates negative precipitation anomalies.
from the Irminger Sea, which is free of sea ice, unlike Baffin Bay, Davis Strait, and portions of the Denmark Strait, Greenland Sea, Fram Strait, and the Arctic Ocean near Greenland, during the wintertime. An air mass originating or passing over the higher sea surface temperatures of the Gulf Stream current or the mid-latitude North Atlantic Ocean will have higher precipitable water values than an air mass that originates over colder northern sea surface temperatures, land, or sea ice. Slight changes in cyclone position can change the source region of the flow and, therefore, the precipitation amounts, for example, nodes (2, 2), and (2, 3).

Fig. 8. The regionally averaged daily precipitation (cm day$^{-1}$) for each SOM node for (a) Greenland and for the five regions of Greenland shown in Fig. 1: (b) north, (c) west, (d) central, (e) south, and (f) east. Contour interval is 0.0175 cm day$^{-1}$. Numbers along the bottom and left edges of each plot are used to identify the nodes and correspond to the node numbers given in parenthesis in Fig. 3.
Node (2, 2) produces 0.043 cm day$^{-1}$ more precipitation than node (2, 3) (Fig. 8a). Node (2, 2) has a cyclone center sitting just south of the tip of Greenland, whereas node (2, 3) has a cyclone center sitting slightly east (Fig. 7). Even though node (2, 3) has a deeper central pressure, the orientation of the isobars results in a near-surface flow from a more northern latitude and produces less precipitation, whereas node (2, 2) has an ideal lower atmospheric flow from the lower latitudes of the North Atlantic Ocean and results in larger magnitudes of precipitation.

Precipitation distribution is also sensitive to slight changes in cyclone intensity. This can be seen by considering nodes (0, 0) and (0, 2) along the left edge of the SOM. These nodes show a weak cyclone in the southwest corner of the domain in node (0, 0), producing much less precipitation than node (0, 2), which represents a deeper cyclone in the same position. The stronger cyclone in node (0, 2) not only produces larger magnitudes of precipitation, but also the precipitation extends farther from the center of low pressure. These two examples support the contention that it is necessary to distinguish between a large number of weather patterns when studying precipitation as a result of the large precipitation differences from small changes in cyclone position and intensity. As a result, an analysis of the forcing for precipitation over Greenland that uses broadly defined atmospheric patterns will not adequately resolve the details of the precipitation distribution. The SOM analysis is ideal for identifying subtle variations in the SLP and, therefore, precipitation patterns such as these.

Because 31 of the 35 nodes have a statistically significant frequency of occurrence, it is necessary to take frequency into consideration when calculating the contribution by node of precipitation over Greenland. The node averaged daily precipitation (cm day$^{-1}$; Fig. 8) multiplied by the node frequency of occurrence (Fig. 6a) and 365 day yr$^{-1}$ gives the node contribution to yearly precipitation (cm yr$^{-1}$) over Greenland (Fig. 9).

On average the weather pattern associated with node (6, 1) makes the largest contribution to annual Greenland precipitation, with days mapping to this node accounting for 2.7 cm of precipitation per year. This corresponds to 7.46% of the total yearly precipitation despite node (6, 1) having a frequency of occurrence of 3.98%. Figure 9a shows the node contributions to annual precipitation over all of Greenland, the sum of which is 35.8 cm yr$^{-1}$. This is similar to the value of 35.0 cm yr$^{-1}$ given by Bromwich et al. (1998). Nodes that occur most frequently and have large node average precipitation make the largest contribution to annual Greenland precipitation. Here, 50% of the average yearly precipitation falls on days that map to slightly more than 11, or more than 31.4%, of the nodes. Thus, a relatively small number of synoptic weather patterns contribute most of the precipitation to Greenland.

The synoptic patterns that have the greatest average daily precipitation (greater than 0.13 cm day$^{-1}$; Fig. 8a) are the same nodes that make the largest contribution to annual precipitation (greater than 1.25 cm yr$^{-1}$) over Greenland (Fig. 9a). The days that map to a particular node can also make a large contribution to Greenland’s annual precipitation without large daily average precipitation values if the node has a high frequency of occurrence. Node (0, 0) is an example of this situation, with relatively low node average daily precipitation values (Fig. 8a) but a large contribution to annual precipitation (Fig. 9a) as a result of its high frequency of occurrence (Fig. 6a).

2) REGIONAL GREENLAND PRECIPITATION

It is evident from the spatial pattern of ERA-40 annual precipitation shown in Fig. 2 that the southern region dominates the precipitation signal over Greenland, with the largest magnitudes of precipitation falling along the southeast coast. The southern region has the largest domain averaged annual mean precipitation (63.8 cm) of the five regions shown in Fig. 1, whereas the western region has an annual mean precipitation of 29.6 cm, the eastern region 18.2 cm, the central region 16.7 cm, and the northern region 16.4 cm. SLP patterns in the master SOM that favor heavy precipitation over the southern region are the same patterns that favor large precipitation amounts over Greenland. The large precipitation values in the southern region hide the details of the forcing for precipitation in the other regions of Greenland. Analyzing Greenland precipitation on a regional scale is, therefore, useful to seeing the smaller but significant precipitation contributions by the other regions.

Nodes (2, 2) and (3, 2) in the center and nodes (6, 0) and (6, 1) in the upper right corner of the SOM have the highest average daily precipitation values in the southern region (Fig. 8e). These four nodes represent SLP patterns with cyclones that bring onshore flow of moist air to southern Greenland (Fig. 7). With the addition of node (6, 2), these five nodes contribute the most to annual precipitation in the southern region (Fig. 9e).

The largest node averaged daily precipitation amounts and annual precipitation contribution for the northern region are found in nodes in the upper left and right columns of the master SOM (Figs. 8b and 9b). The high precipitation nodes are characterized by SLP patterns with low pressure located east or northeast of Greenland, with the cyclonic flow bringing air onshore
in the northern region. The flow in these nodes transports generally cold, dry air from the Arctic onto the ice sheet, resulting in smaller node averaged daily precipitation amounts.

Nodes with the greatest average daily precipitation values in the western region are located in the upper left and right portions of the SOM (Fig. 8c). Each of these nodes is characterized by low pressure in Baffin Bay (Fig. 7). The surface convergence associated with the low pressure and, in some cases, onshore flow, enhances upward vertical motion and precipitation production over the western region. Generally, the average

![Graphs showing precipitation distribution](image)

**Fig. 9.** (a) Average annual contribution by node to precipitation (cm yr\(^{-1}\)) over all of Greenland, and the regionally averaged annual contribution by node to precipitation (cm yr\(^{-1}\)) over the five regions of Greenland shown in Fig. 1: (b) north, (c) west, (d) central, (e) south, and (f) east. Contour interval is 0.25 cm yr\(^{-1}\). Placement of numbers is the same as Fig. 8.
daily precipitation values in this region are greatest during the summer as a result of the absence of sea ice in Baffin Bay during the warm season. The contribution to annual precipitation from all nodes is 6.09 cm during the winter and 8.96 cm during the summer. The higher summer contributions are partly due to the increased frequency of high precipitation nodes associated with low pressure over Baffin Bay during the warm season.

The central region of Greenland includes the highest elevations on the ice sheet (>3000 m) (Fig. 1), which have a consequent blocking effect on cyclones that approach this region (Chen et al. 1997). The nodes with the largest daily precipitation and yearly contribution values in the central region are similar to those of the western region (Figs. 8c and 8d and Figs. 9c and 9d). The largest node average daily precipitation falls over the central region when a broad area of low pressure surrounds Greenland [nodes (5, 1), (6, 0), (6, 1), or (6, 2)] or when low pressure approaches western Greenland [nodes (1, 0), (2, 0), and (1, 1); Figs. 7 and 8d].

Synoptic patterns with the highest amounts of average daily precipitation and yearly contribution to Greenland precipitation in the eastern region are located in the bottom right corner of the master SOM (Figs. 8f and 9f). These nodes are characterized by intense low pressure systems located east of Greenland (Fig. 3). The cyclonic flow associated with these cyclones results in onshore, upslope flow over the east coast of the ice sheet leading to large precipitation amounts in the eastern region (Fig. 7). The cyclonic flow of air east of Greenland generally brings air from the northeast, which is drier than air from the south and, therefore, the daily precipitation values are lower in the eastern region than in the southern region (Figs. 8f and 8e). The southward flowing East Greenland Current off the coast of the eastern region also keeps cooler waters nearby, promoting less evaporation of moisture into the air than from the comparatively warmer waters farther south. The daily precipitation values are slightly larger during the summer compared to the winter, likely as a result of reduced sea ice extent along the east coast of Greenland.

4. Discussion

The results of the analysis presented here support the motivation for this research to expand on past studies that used limited data to explain precipitation patterns over Greenland. This study uses a more comprehensive dataset (39 yr of data) and higher temporal resolution data (daily resolution) than most past Greenland precipitation studies. It is important to view synoptic patterns around Greenland at this temporal resolution, as slight changes in cyclone position, which can be masked by averaging over longer periods of time, can produce drastically different precipitation patterns over Greenland. Rogers et al. (2004) discussed the need for a better understanding of the processes by which precipitation arrives on Greenland. They also concluded, along with Chen et al. (1997), that there is a need to distinguish between cyclones in the lee of Greenland and cyclones with centers farther east near Iceland, as they produce opposite precipitation patterns. The synoptic climatology created here distinguishes between these subtle patterns, for example, node (3, 2) in contrast to node (4, 4) in Fig. 7.

Chen et al. (1997) created SLP composites from high precipitation months in five different Greenland regions. Our regional precipitation analysis confirms the positions of cyclones that produce large amounts of precipitation in each region found in their paper but offers further details. Rather than one composite map showing an average SLP that contributes to precipitation in the eastern region, for example, our SOM shows several different examples of cyclone positions that produce precipitation over that region and quantifies the precipitation amounts resulting from each synoptic pattern.

Greenland has long been known to affect passing cyclones. The bifurcation or splitting of cyclones by the high elevation of the southern tip of the GrIS has been mentioned in past literature but mostly by way of case studies and hypothetical model runs (Chen et al. 1997; Doyle and Shapiro 1999; Kristjansson and McInnes 1999; Petersen et al. 2003; Doyle et al. 2005; Tsukernik et al. 2007). By viewing the temporal evolution of the day-to-day synoptic patterns using the SOM framework, the bifurcation of cyclones emerged as a common cyclone track through the SOM. This analysis also confirmed the presence of blocking by the ice sheet and the reintensification of cyclones in the lee of Greenland.

Although Chen et al. (1997) divided Greenland into five regions (used in this paper) that are useful because of their cumulative properties, Hutterli et al. (2005) found four different accumulation regions that had highly independent accumulation variability and could be correlated with large-scale circulation patterns based on ERA-40 data. These regions then could be used with ice core accumulation records to reconstruct atmospheric circulation patterns. To add to the applicability of our SOM climatology, we have used these regions for some additional analysis. The four regions are the central-west (CW; 70°–75°N, 40°–50°W), the northeast (NE; 76°–82°N, 30°–40°W), the southwest (SW; 63°–66°N, 47°–48°W), and the southeast (SE; 63°–65°N, 44°W, 64°–66°N, 43°W, and 65°–66°N, 42°W); however, these are to
be representative of larger general areas (Fig. 2 of Hutterli et al. 2005). After creating regions in our domain that nearly match that of Hutterli et al. (our resolution is 200 km but their resolution was $1^\circ \times 1^\circ$), annual precipitation contribution by node for each of the four regions was calculated and is plotted in Fig. 10. Note that our study uses precipitation, not accumulation data; therefore, evapo-sublimation as well as blowing snow would have to be taken into consideration before a direct accumulation comparison could be made. Also, Hutterli et al. use upper atmospheric 500-hPa geopotential height as a large-scale circulation indicator, whereas we used SLP. Even with these differences, a comparison between synoptic patterns on the SOM that create the most precipitation over each of the four new regions and the circulation patterns found in Hutterli et al. reveals some similarities. Hutterli et al. found that there was a slight correlation between accumulation in the northeastern region and a circulation pattern of low geopotential heights over Greenland and high geopotential heights south of Greenland. Our analysis reveals that nodes (6, 2) and (6, 3) contribute most to annual precipitation in this region (Fig. 10b), and these two patterns also include both high pressure south of Greenland and low pressure surrounding Greenland (Fig. 3). In the southwestern region, nodes along the upper right edge of the SOM as well as nodes around (2, 0) contribute the most precipitation to this region (Fig. 10c). These patterns include low pressure west of Greenland (Fig. 3). Hutterli et al. found that accumulation in this region was correlated with an upper atmospheric pattern of low geopotential heights over

![Fig. 10. Average annual contribution by node to precipitation (cm yr$^{-1}$) over Hutterli et al. (2005) regions: (a) CW, (b) NE, (c) SW, and (d) SE. Contour interval is 0.5 cm yr$^{-1}$. Placement of numbers is the same as Fig. 8. Total values above each plot indicate the sum of all nodes and, therefore, the total annual precipitation over that region.](image-url)
Greenland and west of Greenland. It is possible that these cyclones that appear in the SOM west of Greenland are in the late stages of their development, have occluded, and are vertically stacked from the surface to 500 hPa. This would suggest an agreement between the two analyses. Hutterli et al. also find that accumulation in this region correlated with a high pressure ridge from the central North Atlantic to Scandinavia. Although our domain does not cover this whole area, nodes in the upper right portion of the SOM do suggest high pressure southeast of Greenland. The southeastern region receives the most precipitation from nodes (6, 0) and (6, 1) as well as nodes (2, 2) and (3, 2) (Fig. 10d). There is most agreement between nodes (2, 2) and (3, 2) with Hutterli et al.’s atmospheric circulation, which shows low geopotential heights southwest of Greenland. This may indicate that the cyclones south of Greenland in these nodes have the common westward shift, with height to the center of low geopotential heights at 500 hPa west of these centers.

Applications of this synoptic climatology of the North Atlantic region are the focus of ongoing research. The climatology is being used as a basis for understanding the synoptic forcing responsible for past and predicted future Greenland precipitation trends as well as evaluating IPCC model output by comparing them to ERA-40 reanalysis in the region.

5. Summary and conclusions

The self-organizing map algorithm was used to create a synoptic climatology of the North Atlantic region from 1961 to 1999 to study the precipitation over Greenland, and thereby, further our understanding of the atmospheric input into the mass balance of the ice sheet. ERA-40 daily SLP anomaly data was summarized by the 35 synoptic patterns identified by the SOM algorithm. These spatially organized synoptic patterns showed various locations and intensities of cyclones and anticyclones in the North Atlantic domain. Precipitation was overlayed onto the SLP anomaly patterns in the SOM, and then precipitation over Greenland was isolated and broken into five regions. The following are the key findings:

- Thirty-five synoptic patterns were created by the SOM algorithm, each of which is necessary to distinguish between different precipitation patterns over Greenland.
- Patterns with intense cyclones approaching Greenland from the south through the North Atlantic storm track were most frequent during the winter.
- During the summer the synoptic patterns with less intense cyclones and cyclones in Baffin Bay occurred more frequently.
- Three common storm tracks—the blocking of cyclones by the ice sheet, bifurcation (splitting) of cyclones by the high elevations of the GrIS, and the reintensification of cyclones in the lee of Greenland—are substantiated by using the SOM technique.
- ERA-40 reanalysis annual mean Greenland precipitation from 1961 to 1999 is 35.8 cm yr⁻¹.
- Patterns contributing the highest amounts of precipitation over five regions of Greenland are those that promote onshore and upslope flow of moist air over that region.
- Half of the annual mean precipitation over Greenland is produced by only 11 of the 35 identified synoptic patterns on the SOM, demonstrating the importance of viewing the production of precipitation over Greenland by synoptic weather systems on a daily time scale.

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