EUROPEAN SNOWCOVER EXTENT VARIABILITY:

A CLIMATOLOGY FROM 1967-2002

by

Gina R. Henderson

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Geography

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ABSTRACT

Snowcover in Europe represents an important component of the region's climatic system. Variability in its extent can have major implications on factors such as low-level temperatures, the amount of heat released from soil to the overlying atmosphere and energy allocation involved in the warming and melting of the snow pack. The majority of studies investigating Northern Hemisphere snowcover identify European snowcover extent as a subset of the Eurasian record, possibly masking complexities of this subset. This study explores the variability of European snowcover extent from 1967-2000, with the region in question including that area of Europe extending eastward to the Ural Mountains (60°E). Using the 89x89 gridded NOAA Northern Hemisphere weekly snowcover product, area estimates of seasonal snowcover were calculated, and their relationship to gridded temperature, precipitation and sea level pressure data analyzed. The spatial variability of snowcover extent was also explored using GIS mapping techniques. The influence of 500-hPa geopotential heights, sea-surface temperature and sea-level pressure variability on snowcover area was also investigated. Results indicate strong associations between snowcover extent and these variables, with a distinctive north/south di-pole pattern evident in the sea-level pressure.

Chapter 1

THE SIGNIFICANCE OF SNOWCOVER

The presence of snowcover in the Northern Hemisphere represents an important component of the global climatic system. High reflectivity associated with fresh snow affects the energy balance of a region by increasing surface albedo and thermal emissivity and consequently the amount of infrared radiation lost to the atmosphere (Wagner 1973, Robinson and Kukla 1985, Walland and Simmonds 1997). Snow also acts as a thermal insulator due to its low thermal conductivity resulting in decreased sensible heat flux from the ground into the lower atmosphere. Energy allocation involved with the warming and melting of a snow pack serves as a sink for latent heat (Cohen and Rind 1991), thus making snowcover a useful tool for detecting changes in climate (Scialdone and Robock 1987). Snowcover also plays a key role in the hydrologic cycle by acting as the frozen storage term in the water balance (Derkson and LeDrew 2000), therefore directly affecting human and economic activities. For these reasons, trends in snowcover extent and variability are of great significance for any region with snow present in the seasonal cycle.

Snowcover variability is also linked with atmospheric circulation patterns, with changes in upper level flow possibly contributing to anomalous snowcover, which could produce a feedback type situation leading to subsequent changes in upper level flow. The relationship between temperature and snowcover has shown that larger snow areas can cause diabatic cooling of overlying air leading to geopotential height

anomalies (Walsh et al. 1982), consequently altering upper level trough and ridge location.

Northern Hemisphere snowcover extent analysis has been considered on several scales, with relationships between snow extent and other climate variables being explored. Continental scale studies have been carried out for North America and Eurasia, with some localized investigation taking place for regional areas. European snowcover extent has rarely been focused on independent of Eurasia, despite its record of large seasonal and interannual variability. Comprehensive knowledge of snowcover extent trends throughout Europe could have implications for the region's climate, hydrology and economic activity.

Numerous industries operating throughout Europe can be directly or indirectly linked to the region's climate. Tourism associated with snow conditions in the Alps or winter weather in northern Mediterranean countries are directly influenced by the region's climate. Availability and storage of water in snow pack and spring runoff has major implications for agriculture and stream flow across the continent. Also throughout Scandinavia, production of hydroelectric power that accounts for more than 99% of Norway's electricity in particular, is greatly dependent on peak flow in summer associated with high altitude snowmelt. For reasons such as those briefly mentioned above, research on trends associated with European snowcover variability and extent is a necessary and important endeavor.

The purpose of this study is to produce a climatology of European snowcover extent from a Northern Hemisphere satellite snowcover dataset. Analysis of snowcover from this dataset has been conducted on both hemispheric and continental scales to date, however the area of Western Europe has never been isolated

for intense investigation. The period from 1967 to 2002 is included in this study as it includes the period for record of the satellite snow data. Relationships between additional climatic variables and snowcover are explored in order to gain a greater understanding of the factors contributing to variability in the record and the role of snow in the cold season climate of Europe.

Chapter 2

EVOLUTION OF SNOWCOVER EXTENT ANALYSIS AND MONITORING

2.1 Snowcover extent analysis to date:

Studies exploring snowcover variability and extent have been conducted throughout the Northern Hemisphere on various scales. The scales of these studies have been extremely dependent on the accuracy and temporal extent of the data available. To date, the two core data types used in the field of snowcover analysis have been those of *in situ* or station data and satellite data. Some of the earliest studies used station data of daily snowcover and depth measurements, the resulting information being averaged to create weekly and monthly snow areas. Advantages associated with this type of data include the detail in which observations are recorded and the historical nature of the record available, in some cases dating back to before the turn of the 20th century. The main disadvantages of such measurements include subjective interpretation of spatial snowcover extents due to varying station distribution, topography, and local factors, leading to inaccurate representations of snowcover extent throughout study regions.

The use of satellite data for snowcover extent analysis has become more prevalent in recent years. This method of data acquisition allows consistent collection standards and has large-scale spatial capabilities. The primary disadvantage of satellite records is the relatively short temporal range as most products' history are brief in

duration and suffer from inaccuracies in the beginning stages of the record as acquisition techniques were being refined.

2.2 In Situ Studies:

In an early study by Wagner (1973) weekly North American snow depth maps dating back to 1965 were used to study the influence of average snow depth on mean monthly temperature anomalies. The resulting correlations suggested a more dependant relationship between the two variables at locations with little to no maritime influence present in their climate. Leathers et al. (1995), considered the effects of snowcover on surface air temperature. The region used contained an array of surface conditions, from Maine to West Virginia in the U.S., allowing for potential insight into surface-air temperature and topographic interactions. Results indicated a significant dependence on geographic position and air mass type when considering the relationship between snowcover and surface air temperature.

In a larger scale study by Brown and Braaten (1998), the inherent problems associated with in situ data were encountered when analyzing monthly snow depth over fifty years in Canada. The newly expanded station-based daily snow depth database provided the opportunity to isolate a significant relationship between snowcover duration and depth. However due to the inconsistent density and location of stations across the country, especially throughout the higher latitudes, a bias towards lower latitudes and elevations was evident in the results. Snow depth and snowcover variability were found to be closely related along with a rapid transition in the late 1970s characterized by reduced depths and a shorter spring snowcover season.

Further limitations regarding station data were encountered by Brown (2000), in attempts to reconstruct North American and Eurasian snowcover variations for the 20th century. Historical datasets from the People's Republic of China, the former Soviet Union, Canada and the U.S. were used in a snow area index approach. Temporal coherence and station coverage restricted those stations included, as a large number were subject to incomplete records and large data gaps. Reconstruction over Eurasia was the least successful for this reason, limiting the study in this region to October, March and April.

On the other end of the scale, Falarz (2002) conducted a local study based on temperature, precipitation and nival records from two first-order climatological Polish stations, Cracow and Zakopane. Both were located in the southern part of Poland, Cracow at 206 meters above sea level and Zakopane at 857 meters. From this information, the snowcover record was extended back to the turn of the 20th century and the variability explored. Results showed a more accurate reconstruction possible in Cracow, as the lowland nature of the station highlighted the strong temperature dependence of snowcover in its vicinity. No significant long-term trend in snowcover was evident from the study. Similarly, Beniston et al. (2003) analyzed snow pack duration on a local scale in the Swiss Alps. A total of 18 sites spanning altitudes from 300-2500 meters above sea level were included with relationships between snow pack duration and temperature, precipitation and altitude considered. A trend towards longer snow seasons at higher elevations emerged as increased precipitation amounts due to warmer winters within the region was indicated.

On a larger scale, changes and variability in long-term snowcover for the whole Polish territory was explored in a later study by Falarz (2004). Number of days

with snowcover and snow depth were considered for the region throughout the 20th century. Once again, little to no change in snowcover was evident; however variability in days with snowcover decreased significantly to the east and also increased in general throughout the 20th century.

While the aforementioned studies discussed snowcover variability as a function of temperature in particular, more recent studies have attempted to explore the physical processes regulating the snowcover itself. One such study was conducted by Ueda et al. (2003), which focused on Eurasian snowcover's interannual and seasonal variability. In addition to the primary study, Ueda investigated the springtime retreat of snowcover throughout the study region based on atmospheric circulation patterns. Historical in situ data from the former Soviet Union for the period 1966-1990 was analyzed. Resulting trends showed an inconsistent retreat rate across the continent, with snowcover to the west of the Urals dissipating rapidly throughout the spring. This was largely connected to abrupt surface air temperature increases in this area during the month of March, possibly driven by the intrusion of southwesterly winds in the lower troposphere during March and April in the region.

In Eastern Europe, Bednorz (2004) considered the basic characteristics of snowcover occurrence in relation to "active" areas, being those areas having a snowcover probability between 10 and 90%. The influence of temperature, precipitation and atmospheric circulation represented by the NAO index on days with snowcover (DSC) and average snow depth was analyzed. Results indicate a strong relationship between DSC and air temperature at the beginning and end of the snow season throughout the active areas while snow depth and precipitation are strongly linked during the winter season. The relationship between DSC and the NAO was

robust in nature throughout central Europe while its signal diminishes to the east of 30º.

2.3 Satellite Studies:

Work by Dewey and Heim (1982) represents one of the earliest usages of digital data in snowcover area mapping. Prior to this study, snowcover analysis had exclusively been conducted using either station or visual data. Northern Hemisphere Snow and Ice Charts, a product of the National Earth Satellite Service (NESS), have been available since the early 1960s and represent the earliest analog (photographic) data. Limitations associated with these charts include the cumulative nature by which week-to-week updates were recorded; with the previous week's chart used in the creation of the following week's conditions. This information was then converted to monthly and yearly averages. Digital data employed in Dewey and Heim's (1982) study explored the potential of digitized versions of these charts in creating a snowcover area frequency climatology of the Northern Hemisphere for the period 1966-80. An 89 x 89 polar stereographic grid was used to digitize the snow and ice charts. During this process, a grid box that was at least half covered was considered completely covered, and a grid box less than half covered was considered snow free. This was compared with several other climatologies produced using different techniques. From these comparisons a significant improvement in accuracy was evident in two areas, the North American mid-latitudes and the Tibetan Plateau.

Numerous studies in recent years have been conducted using satellite snowcover information, the earlier focusing on general spatial variability over time either on regional or continental scales while subsequent studies have a tendency to be

more specialized in considering snowcover variability in relation to specific climatic factors such as temperature or atmospheric circulation patterns.

2.4 Satellite snowcover extent studies: regional and continental variability

The potential for continental and hemispheric snowcover extent analysis was first identified by Matson and Wiesnet (1981), with the introduction of the new satellite dataset from NOAA. Although in its early stages, a brief history of mapping sensors used in Northern Hemisphere snowcover detection was described. Results emerging from this pioneering study included the identification of greater seasonal variability in Eurasian snowcover area and a possible cyclic pattern during the winter season. An increase in summer Eurasian snow extent throughout the course of time was evident; however this was thought in part to result from the improved detection by higher resolution sensors.

The theme of improved satellite-derived hemispheric snow detection over time was explored further in a later study, where the associated strengths and weaknesses of the NOAA weekly charts and NASA microwave charts (Robinson 1993). Primary weaknesses relating to the NOAA charts included area underestimation and decreased accuracy under certain conditions such as clouds, low zenith angle and heavy forest cover. The microwave charts in comparison calculated anywhere from less than one to greater than thirteen million square kilometers below the NOAA charts. This leads to the main limitation of the snowcover product, in its inability to recognize wet or patchy snow consistently. In order to improve the accuracy of the NOAA weekly estimates, a new routine developed at Rutgers was applied to the data, involving consistent weekly area calculations and application of a

weighting factor not previously considered. Improvement of the charts by the new routine is acknowledged in a subsequent report updating global snowcover progress, with the aim of building an all-weather and all-surface snow chart record to benefit future snow monitoring efforts (Robinson et al. 1993). The possibility of re-charting northern hemisphere snowcover from 1966-72, when the detection technique was still being refined, was also suggested. All efforts leading to the improvement in accuracy of the northern hemisphere snowcover record were aimed at making available a robust dataset from which hemispheric snowcover monitoring could be achieved and the natural variability of snowcover extent observed. Only then would the potential for snow as an indicator of climate change be possible.

Variability of Northern Hemisphere snowcover was considered in a later study by Robinson et al. (1995), where the distribution and temporal variation within and between regions was explored. Monthly mean snowcover areas were calculated from the NOAA weekly charts using a new routine described fully in Robinson (1993). Significant findings of this study include identifying the late 1980s as the longest interval of subnormal snowcover in the previous two decades. Winter was identified as the most stable season when considering snowcover, while autumn was the most variable. Negative snowcover anomalies were dominant during spring. The relationship between regional and hemispheric variations suggests possible broad hemispheric forcings influencing snowcover while intercontinental variations imply an association with atmospheric teleconnections. Cross-continental variability on the other hand, appeared to closely follow regional variation in jet stream location.

When considering snowcover extent variability on a continental scale, the work of Walland and Simmonds (1997) considered the relationship between North

American and Eurasian snowcover and their possible interactions. Using the NOAA monthly data, a significant association was evident especially during the January through March and June through August seasons. The idea of atmospheric teleconnections influencing winter snow trends was also noticeable as anomalous snowcover was present concurrently over both continents, tending to be larger when North America was leading. Snowcover and sea ice variability were more closely linked over North America than Eurasia, most likely due to proximity to oceans and a lesser degree of continentality. The observed difference in time scales by which snowcover and sea ice varied, highlights the sensitivity of snowcover to changing climatic conditions reinforcing its potential use as a valuable indicator of climate change in large scale studies.

With the idea of using snowcover variability as an indicator of climate change throughout a region, the issue of record length becomes a major consideration as without a sufficient record, observed variability of a region or continent's snowcover extent is without context. For this reason, Frei et al. (1999) considers the historical variability of North American winter snowcover by reconstructing it back to 1900, almost tripling the previous satellite record. Using the results of principal components analyses from a companion study (Frei and Robinson 1999), remotely sensed data were combined with historical station data. Fluctuations on a regional and continental scale were identified back to 1900 including such trends as a decrease in North American spring snow extent for the last three decades, suggesting a possible shift in the snow season. Continental-scale variation in snowcover was driven mainly by western North America throughout December while in January, fluctuations in the east and to a lesser degree the central Plains were the primary influence on continental

variability. Accuracy in snow extent reconstruction only allowed interannual variability to be considered during the month of February, where snowcover extent displayed the highest interannual variability of the century in the period since the mid-1970's.

2.5 Atmospheric circulation and snowcover:

Variability of large-scale snowcover extent analysis has not been limited to regional, continental or hemispheric studies only. In considering the variability of snowcover extent, it seems logical to investigate the association between atmospheric circulation patterns and snowcover in order to better understand fluctuations in both. One such study explored the interannual variability of snowcover on sub-continental scales and compared the fluctuations with large-scale atmospheric circulation (Gutzler and Rosen 1992). Using the NOAA satellite product first described in Matson and Wiesnet (1981), the northern hemisphere was divided into seven sectors allowing sub continental comparisons. Atmospheric circulation patterns were identified from 700-mb heights for the period 1950-1991 (Barnston and Livezey 1987). A strong positive correlation of interannual fluctuation was present between North America and Eurasia while European snowcover was particularly variable. Correlation between anomalous snowcover in western North America and the Pacific-North American (PNA) pattern was highest, however this signal was not associated with intercontinental fluctuations. A North Atlantic Oscillation (NAO) –like pattern was the only atmospheric mode that displayed a relationship with continental or hemispheric scale snowcover variability.

Clark et al. (1999) expanded on this study by looking at other circulation modes and considering the role of synoptic activity and temperature on Eurasian

winter snowcover variability. Three different teleconnections emerged as playing a significant role with snowcover; the NAO, the Eurasian Type 1 (EU1) and the Siberian pattern (SIB). Throughout Europe and southwestern Asia, snowcover variability was primarily controlled by temperature while in eastern Asia, precipitation availability was more central. The NAO continued to prevail as a key control throughout transient snow regions such as central Europe.

A similar atmospheric circulation investigation was carried out over North America by Frei and Robinson (1999). Active areas of snowcover extent, having snowcover frequencies between 10%-90%, in the northern hemisphere were identified and using a rotated principal component analysis, coherent regions of fluctuation established. From September to June, regional and continental scale variability was analyzed along with circulation patterns associated with snowcover over North America. Active areas were largest throughout October and November while from December to March, they mostly occurred south of 47ºN. During this mid winter timeframe, the active areas accounted for only 2-6% of the land area, but explained sometimes as much as 60% of the variance in continental snowcover, particularly over North America. Two indices of atmospheric conditions were developed from 500-mb height composite difference charts for both the east and west of the continent. When there was a 20-30º longitudinal shift to the west of the mean North American ridge, substantial snowcover was present over western regions of the continent, while over the east snowcover variability displayed a dipolar oscillation in 500-mb heights between southern Greenland and the mid-latitude north Atlantic.

Large-scale accumulation and ablation events occurring over the timescale of one week or less over North America were examined by Leathers and Robinson

(1997). Four case studies for accumulation and four for ablation episodes were evaluated along with the associated atmospheric conditions. Results served to substantiate the weekly chart information as large fluctuations in snowcover reflected the associated atmospheric conditions.

While this work was aimed at providing general validation of the synergistic relationship between continental snowcover and atmospheric conditions, a more specialized study was conducted to investigate associations between air mass frequencies and large-scale snowcover anomalies over eastern North America (Leathers et al. 2002). Throughout the winter season, anomalous snowcover was found to be associated with atypical air mass conditions. Results indicated that air mass frequency anomalies were associated with snowcover and circulation anomalies early (November through January) and late (April) in the snow season. During February and March, the lack of consistent circulation anomalies may indicate that surface snowcover anomalies are forcing changes in air mass frequencies.

2.6 Temperature and snowcover:

Another variable frequently studied for associations with snowcover extent is surface temperature. The nature of the relationship between snowcover and temperature can be considered on different temporal scales, the most common being a direct temporal association, or as an indirect or lagged relationship. The latter was the basis for a continental scale study conducted over North America and Eurasia dealing with autumn snowcover and subsequent winter temperatures (Foster et al. 1983). For each continent, station data from the interior of each landmass was averaged, resulting in an average winter temperature. This was then correlated with autumn snowcover

extent. Eurasian correlations were more significant than those over North America, with excessive autumn snowcover leading to extreme cold winter temperatures. While almost half of the variance in early winter temperatures was accounted for by autumn snowcover in Eurasia, no significant relationship was found for North America. The reverse was true when winter snowcover and winter temperature was considered. The chief explanation for this disparity was the greater continentality of Eurasia.

When considering a lagged snowcover-temperature relationship, a cause and effect dilemma emerges. Is a winter with anomalous snowcover colder because of the snow present or were the cooler temperatures in place initially, leading to greater snowcover? Cohen and Rind (1991) tackle this difficulty in a study using a General Circulation Model (GCM) to alter the snow directly. Two model runs were implemented with both large and small snowcover extents. No alterations in atmospheric conditions were made other than that resultant from snowcover itself. Contrary to expected temperature decreases during the large snowcover run, anomalous snowcover tended to diminish rather that perpetuate itself as the initial cooling due to increased albedo tended to be confined to a shallow layer. This layer served to restrict sensible and latent heat transport away from the surface allowing for heating at the surface, which effectively cancelled out the albedo effect.

In practice however, the principal factor complicating the relationship between temperature and snowcover is atmospheric conditions. This was evident from Leathers and Robinsons' (1993) work with extremes in North American snowcover and temperatures in the United States. General agreement between anomalous positive (negative) snowcover and negative (positive) temperatures was evident. However at different periods throughout the winter, correlations between snowcover, temperature

and 500-hPa height anomalies varied. A strong association was present during December with positive temperature and negative snowcover anomalies being associated with anomalously high heights. In January and February no strong circulation anomalies were present, suggesting snowcover as a major driver of temperature anomalies.

One of the few studies of Europe and snowcover in particular, attempted to investigate the influence of snowcover on spring and summer temperatures throughout the area (Chaoimh 1998). Three regions with significant correlation between maximum winter snow extent and temperature emerged. Central Europe displayed the greatest variation in snow extent while being most highly associated with temperatures during April. Eastern Europe's snow extent correlated strongly with temperature anomalies in July and as this region was always snowcovered at maximum annual extent, snow depth was suggested as playing a role in this relationship. Northwestern Europe had the weakest relationships, as this area is greatly influenced by maritime influences. Circulation patterns were thought to explain the main temperature variations throughout the region.

The work reviewed above provides a strong theoretical basis for the present investigation. A mixture of the most appropriate methodological procedures will be used to complete this in-depth study of European snowcover.

Chapter 3

DATA DESCRIPTION

3.1 Snowcover extent data:

The snowcover extent data used in this study were extracted from the NOAA Northern Hemisphere snowcover product. This dataset is unique as it dates back to 1966 and is the only such hemispheric product available, using human interpretation of visible satellite imagery. The resolution of this product has improved significantly over the years from 4 kilometers in 1966, to the current 1.1 kilometers. This development has been possible due to the launch of the VHRR satellite in 1972 and the AVHRR satellite in 1978.

With this increased resolution has come greater accuracy in snowcover area estimation. In early years in particular, overestimation or underestimation of snowcover extent was a limitation of the satellite product as under certain physical conditions, visible imagery detection techniques were lacking. Estimations were reliable however under conditions including; clear skies, low solar zenith angles with high illumination and slowly changing or stable snowcover extent. Due to this last factor in particular, underestimations during the autumn were considerable, as areas located close to the snowline tend to display great variability in snow coverage during this season (Robinson 1993).

From visible images of the Northern Hemisphere, weekly digitized maps were produced using the National Meteorological Center limited-area fine mesh grid.

This is an 89 x 89 Northern Hemisphere grid with cell size ranging from 16,000-42,000 square kilometers (Figure 3.1). This grid is laid over a polar stereographic projection of the hemisphere. Each weekly chart is analyzed for snowcover area, with a grid box being considered snow-covered if 50% or more of its area is occupied by snow. This binary data is then converted into an area calculation for the week in question.

Reanalysis of the early year maps (1967-1971) has been carried out by the Rutgers Global Snow Lab (http://climate.rutgers.edu/snowcover/) in order to correct for initial inaccuracies due to inferior sensing devices. Using a revised land mask and additional station reports from the United States, Canada, China and the former Soviet Union, weekly hemispheric snow extent maps were produced for the Northern Hemisphere. This reanalysis was combined with the NOAA raw gridded data to produce the Northern Hemisphere product. Both weekly and monthly charts are available.

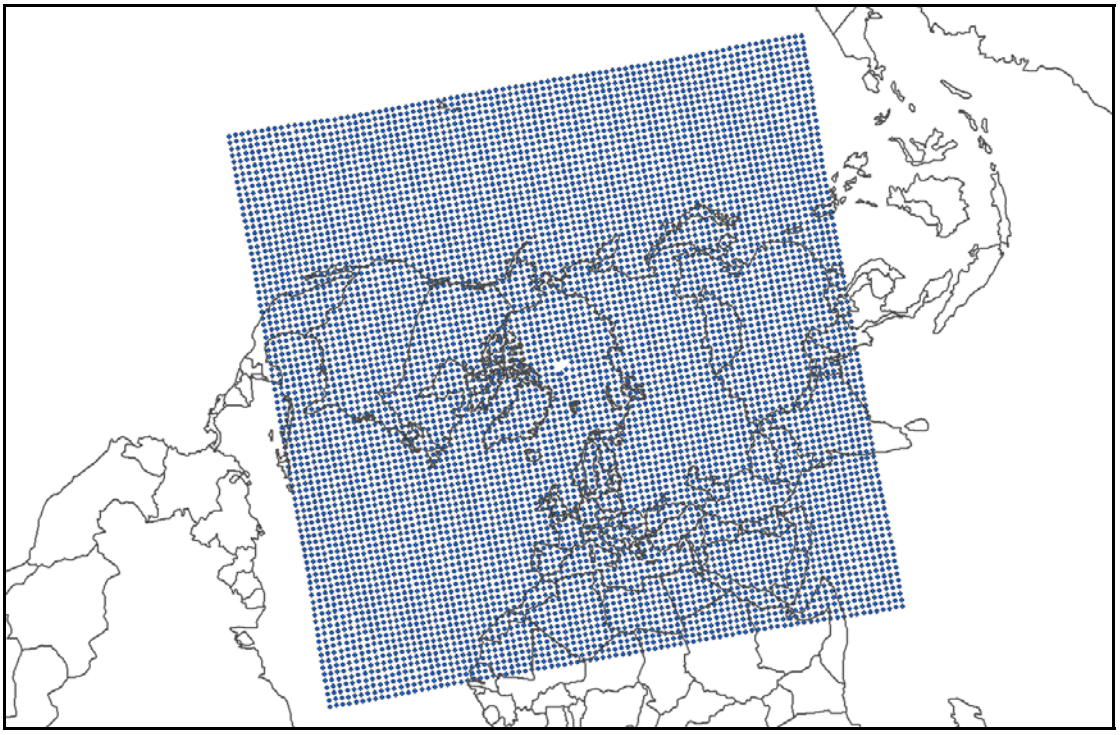

Figure 3.1- The Northern Hemisphere 89 x 89 snowcover extent grid.

3.2 Additional climate data:

3.2.1 Sea Level Pressure Data:

Monthly mean sea-level pressure data (MSLP) was obtained from the University of East Anglia Climatic Research Unit (http://www.cru.uea.ac.uk/cru/data /pressure.htm). This data is available on a 5° latitude by 10° longitude grid for the Northern Hemisphere. MSLP grid-point data from 130°E to 70°E longitude and 15°N to 70°N latitude were extracted from the dataset, amounting to 252 total grid-points (Jones 1987, Figure 3.2). The period of record for which this dataset is available is from 1873-2000 with various combinations of sources contributing throughout its history. During the period of this study, the Central Forecasting Office charts were the primary source for the sea-level pressure data.

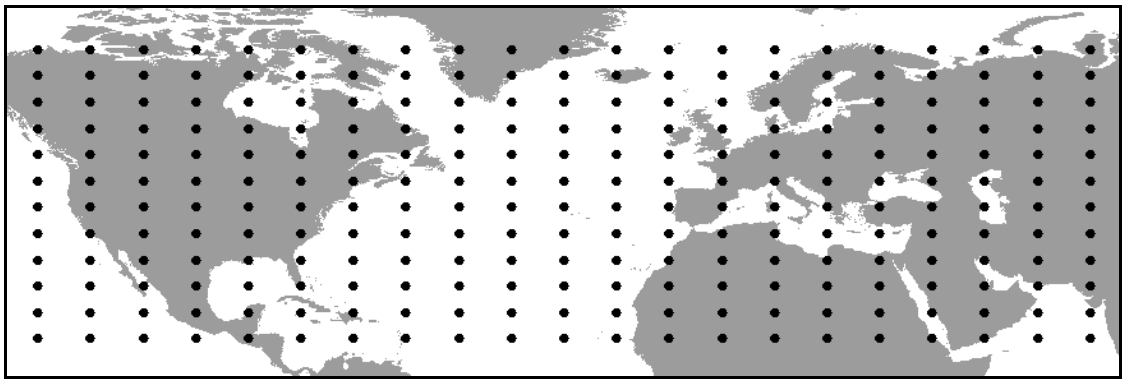

Figure 3.2- Sea level pressure grid boxes included for the study.

3.2.2 Temperature Data:

Surface air temperature data, also from the University of East Anglia Climate Research Unit (http://www.cru.uea.ac.uk/cru/data/temperature/), was obtained for the study region. The data is available on a 5° latitude by 5° longitude grid-box format. It is a global dataset that was developed from over 3000 monthly station temperature time series. Station density varies with population density, with the sparsest coverage occurring throughout the Southern Hemisphere. The number of stations available varies through the data set's history, with the period 1951-90 having the most abundant number of stations (Jones and Moberg 2003).

Values are expressed as anomalies from the 1961-90 mean in order to avoid possible biases due to varying station elevation and differences in temperature estimation from country to country. Sea surface temperatures are used over the oceans due to greater availability and more consistent measurements. A total of 95 grid boxes were isolated for the purposes of this study, ranging from 25°W to 60°E longitude and 35°N to 75°N latitude (Figure 3.3).

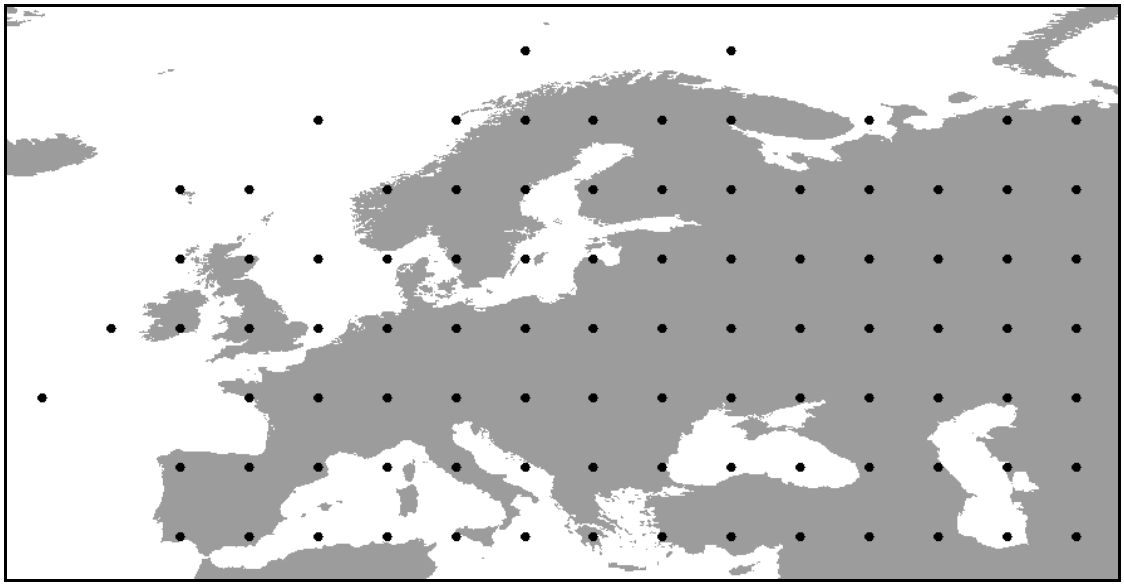

Figure 3.3- Temperature grid boxes included for this study.

3.2.3 Precipitation Data:

Precipitation data, also from the University of East Anglia Climate Research Unit (http://www.cru.uea.ac.uk/~mikeh/datasets/global/), was utilized in this study. This is a historic monthly dataset for global land areas from 1900-98 available on a 5° latitude by 5° longitude grid-box resolution (Hulme 1992). The gridding technique used to arrive at grid box monthly averages involved a Thiessen polygon weighting method to average gauge data. When missing data occurred, interpolation from surrounding station values was used to complete the record. No correction for gauge undercatch or for topographic adjustment has been applied. In some regions however, alteration for high latitude time series accounting for varying sensitivities of different gauges to snow measurement was applied. As with the surface temperature data field, the area from 35°N to 75°N latitude and 25°W to 60°E longitude was

included. A total of 99 grid boxes with precipitation values were located within this area (Figure 3.4).

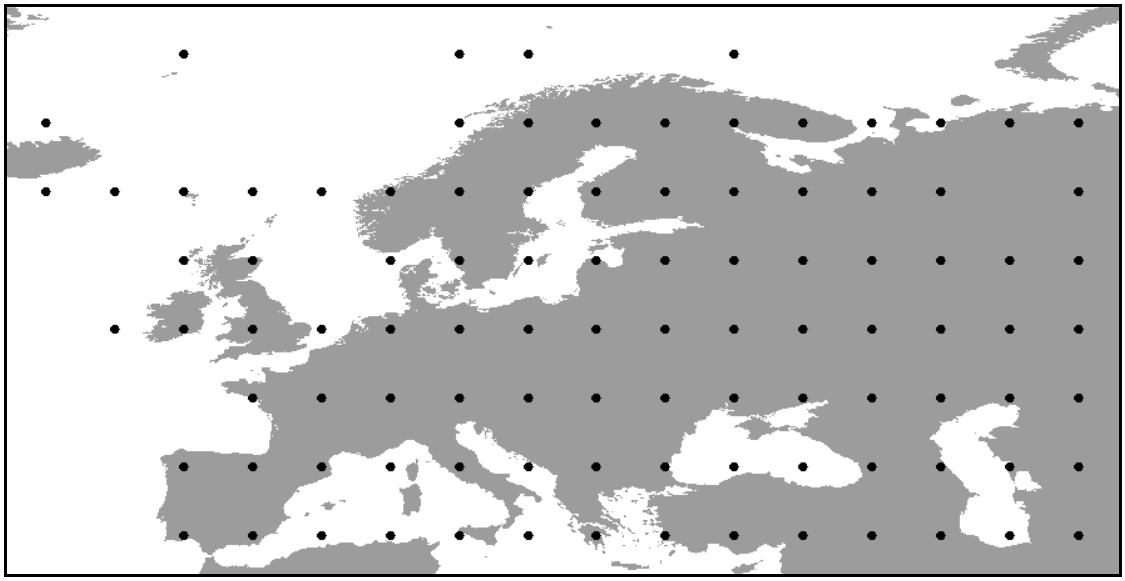

Figure 3.4- Precipitation grid included in this study

3.2.4 Monthly Composite Data:

Monthly climate composites available from the NOAA-CIRES Climate Diagnostics Center, Boulder Colorado (http://www.cdc.noaa.gov/) were also used for analysis. Plots of both mean and anomalous conditions for a selection of climate variables are available through this website. The variables being plotted for this study included 500-hPa geopotential heights, sea level pressure and sea surface temperature. This data is part of the NCEP/NCAR Reanalysis project that uses data assimilation of the historical data from 1948 to present. It is based on averaging observational data taken four times daily. The spatial coverage of the pressure fields is on a 2.5° x 2.5°

global grid (Kalnay et al. 1996). Sea surface temperatures are based on a new extended series derived from the latest Comprehensive Ocean-Atmosphere Data Set (COADS) and are in the form of a 2° x 2° grid (Smith and Reynolds 2003).

Chapter 4

METHODOLOGY

4.1 European Snowcover Area:

The goal of this study was to understand the snowcover extent record of Europe, which has more frequently been analyzed as a sub-section of Eurasia. Due to the significant difference in continentality between Europe and Asia, it is reasonable to assume that their respective snowcover extent records may also vary greatly.

The area of Europe being considered consists of Western Europe, with the eastern boundary denoted by the approximate location of the Ural Mountains at 60ºE longitude. The associated snowcover extent data for this region was extracted from the Northern Hemisphere product with the resulting grid displayed in Figure 4.1. A total of 635 cells out of the 89 x 89 grid are included in the area, 375 of which are considered land cells. This amounts to an approximate area of 12.04 million square kilometers for the portion of Western Europe to be studied in this research. Thus, a maximum snowcover area for the entirety of Western Europe is 12.04 million square kilometers.

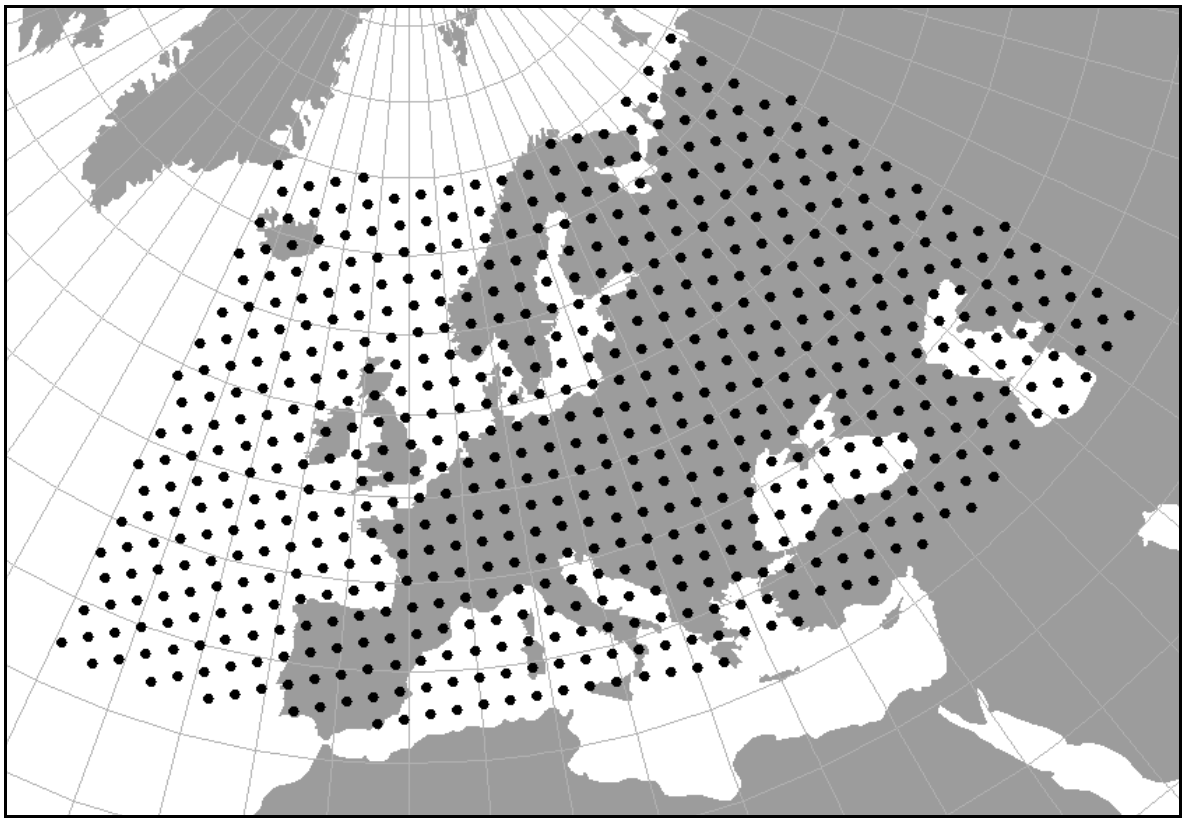

Figure 4.1- The study area of Western Europe with an eastern boarder of 60ºE with the snowcover extent grid overlaid. Total land area ~ 12.04 million km².

4.2 Snowcover extent data preprocessing:

A series of FORTRAN programs were developed in order to extract and manipulate the raw Northern Hemisphere snowcover product. For the study area described above, weekly and monthly snow area totals in units of square kilometers were estimated for the years 1967-2001. Until 1971 however, missing data was present due to poor sensor performance. These estimates were derived as binary data, as for each week a grid box would be considered snowcovered if 50% or more of its area was deemed covered. Linking the weekly value of 0 (not covered) or 1 (covered) with the area of the grid box in question allowed for a snowcover area estimate. Mean weekly and monthly figures were derived for the complete time period to show the annual cycle of snowcover for the region. Snowcover frequency calculations were also computed on both weekly and monthly time scales. The frequency maps show the percentage of time that snowcover was present in a grid box during some given time period. Additional programming was used to convert the snow data into a compatible format for mapping within ArcGIS.

4.3 Correlation Calculation:

The relationship between the snowcover estimates described above and additional climatological variables was explored using correlation statistics. Gridded sea level pressure, surface temperature and precipitation were correlated with European snowcover extent totals on a monthly time scale. Using the SPSS statistical package, a bivariate correlation analysis was performed between the climate variable for each grid point/box and the corresponding monthly value for European snowcover extent. This resulted in a correlation coefficient grid for each climate variable

(pressure, temperature, precipitation) on a monthly basis. Contour maps of the correlation coefficient for each variable were produced to show the spatial distribution of relationships between snowcover extent area and the climatological field in question.

The type of correlation performed was the Pearson Product Moment Correlation (Pearson's correlation). The "r" values calculated represent the degree of linear relationship between the variables being analyzed and have a value between -1 and 1 denoting either a negative or positive association. The equation for calculating Pearson's r is given as:

$$r = \frac{\sum xy - \frac{\sum x \sum y}{N}}{\sqrt{\left(\left(\sum x^2 - \frac{\left(\sum x\right)^2}{N}\right)\left(\sum y^2 - \frac{\left(\sum y\right)^2}{N}\right)\right)}} \qquad (4.1)$$

4.4 Maximum and minimum snowcover analysis:

In order to better understand the climatological context of extreme European snowcover events the most and least abundant snowcover extent seasons were identified using a simple ranking procedure. This was carried out on a month-by-month basis, with the five most extreme years (high and low extent) being identified in each case. Composite plots for 500-hPa geopotential heights, sea level pressure and sea surface temperature were produced using simple averaging of the variables. Results were obtained for the mean fields and anomalies (based on 1971-2000 mean) for each extreme case.

Chapter 5

RESULTS

5.1 Introduction:

The results of the analysis described in the previous chapter are now discussed. A general European snowcover extent climatology, for both snowcover magnitude and spatial distribution is presented. Relationships between snowcover area and other climatic variables are investigated. These variables include surface temperature, precipitation and sea level pressure. Finally, analysis of atmospheric conditions corresponding to extreme snowcover area extents throughout the dataset's history is explored. This includes both extreme maximum and minimum snowcover extents.

5.2 Annual cycle of European snowcover extent:

An investigation of the annual cycle of European snowcover was the initial analysis conducted. This was a necessary task as the majority of large-scale snow studies have discussed only the annual cycle of Eurasian snowcover, which due to factors such as continentality alone, may be misleading when considering the area of Western Europe.

Mean snowcover extent totals were extracted from the Northern Hemisphere product on both a monthly and weekly time scale. Data from 1967 to 2002 were used in calculating the annual cycle. There were a few instances of missing

data that occurred in the years (1967-1971) during summer months. The 35 year mean monthly time series, shown in Figure 5.1, displays great variability in snow area totals over the course of the annual cycle with values ranging from over 8.5 x 10^6 km^2 in January to almost no snowcover throughout the summer months. The lack of snowcover for the summer months points to the nature of the binary data used in area estimation, as only persistent snowcover for an entire grid box results in that box being considered snowcovered for a particular week.

In considering the weekly time series (Figure 5.2), the mean annual cycle is given in more detail. This graphic indicates that the first substantial snowcover appears during weeks 40-45 (beginning of November). Rapid accumulation occurs from weeks 44-50 increasing from under 2 x 10^6 km^2 to over 6 x 10^6 km^2. Snowcover area continues to increase until approximately week 5 (mid-February), when snowcover peaks at just under 9 x 10^6 km^2. From mid-February through June there is consistent decline in snowcover area, with rapid ablation occurring from approximately week 12 (end of March, beginning of April) to week 28.

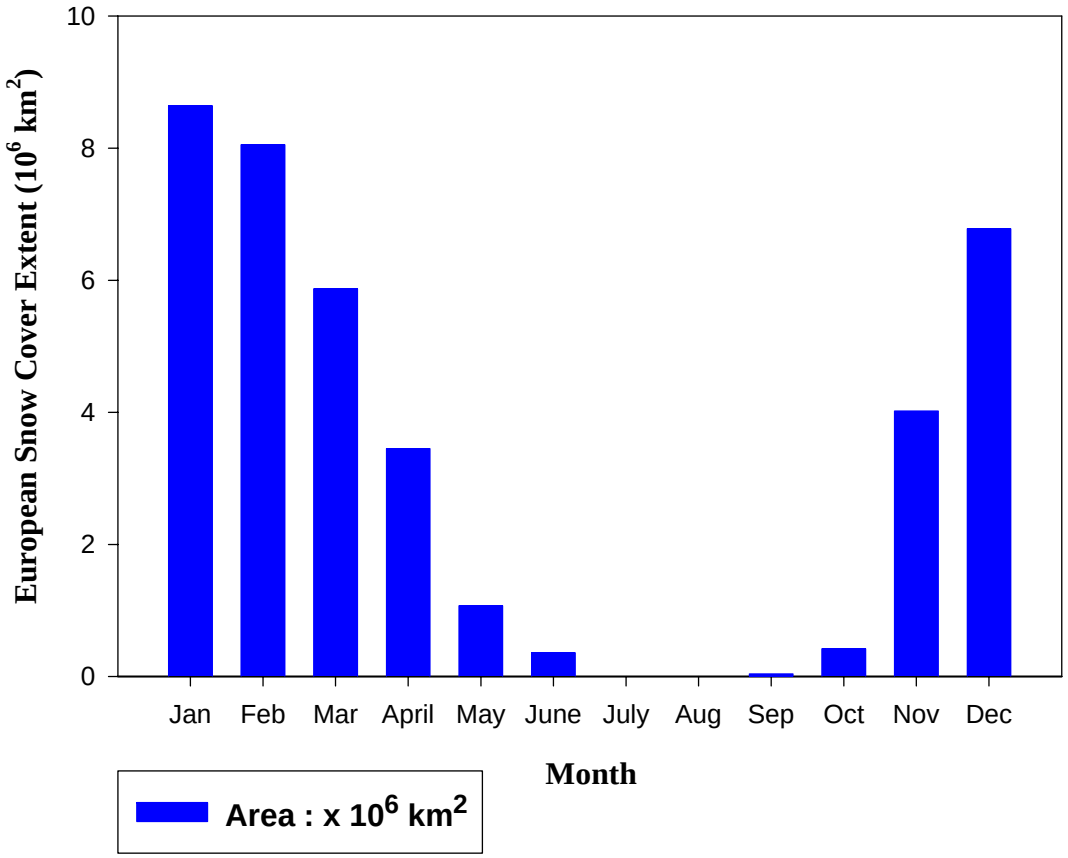

Figure 5.1- Mean monthly European snowcover extent area 1967-2002. Total European land area in study region~ 12 x 10^6 km^2

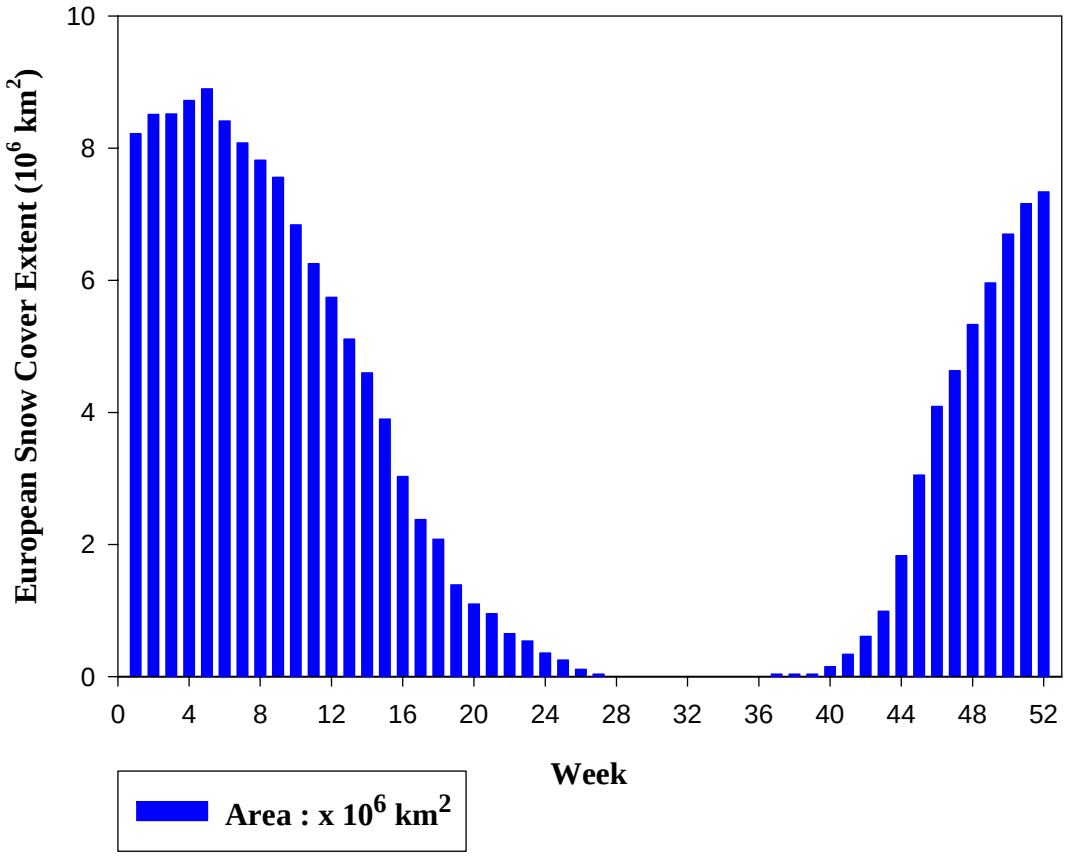

Figure 5.2- Mean weekly European snowcover extent area, 1967-2002. Total European land area in study region~ 12 x 10^6 km^2

5.3 Spatial distribution of mean snowcover extent:

Although mean snowcover extent values are useful for some applications, a spatial representation of those values is a pre-requisite for many others. Figures 5.3-5.8 depict the distribution of mean snowcover extent (based on the period 1967-2002) in Europe for each month during the winter season November to April. These maps represent highly generalized depictions of the snowcover location. If 50% or greater of a grid box is covered and the land mask equals land, the cell's area is included in the snowcover total for that month. All maps were produced using GIS and are in north polar stereographic projection. Land areas are therefore not equal area but due to the scale of the study region in question, latitudinal areal distortion is minimal.

During the early winter season (November) snowcover appears over northern Scandinavia and the Central Russian Uplands (Figure 5.3). Some isolated pockets of snowcover appear over the Alps and the Caucasus region (elevation of 2000-3000ft). By December and into January, snowcover extends south and west into central Europe and throughout higher elevations in Turkey (Figures 5.4-5.5). The greatest areal coverage is evident during January and February when snowcover extends, on average, through western Russia, most of the eastern European countries, the Alps and much of the Balkans regions (Figures 5.5-5.8). Western Europe, especially the coastal extremes remain snow free on average during the winter. This is most likely explained by the maritime influence on the climate of these areas together with the inconsistent and patchy nature of snow receipt throughout these regions. The binary nature of the snow data is not conducive to recording highly changeable or brief snowcover events.

Major ablation takes place during March and April with the snowcover extent retreating steadily northwards (Figures 5.7-5.8). Some isolated areas of snowcover remain over southern Europe, mostly indicative of higher elevations in the Alps and Caucasus's. By April, snow is found on the surface in only the northern Russian Uplands and northern Scandinavia (Figure 5.8). The isolated high elevation snowcovered areas throughout southern Europe have also reduced in size by this point.

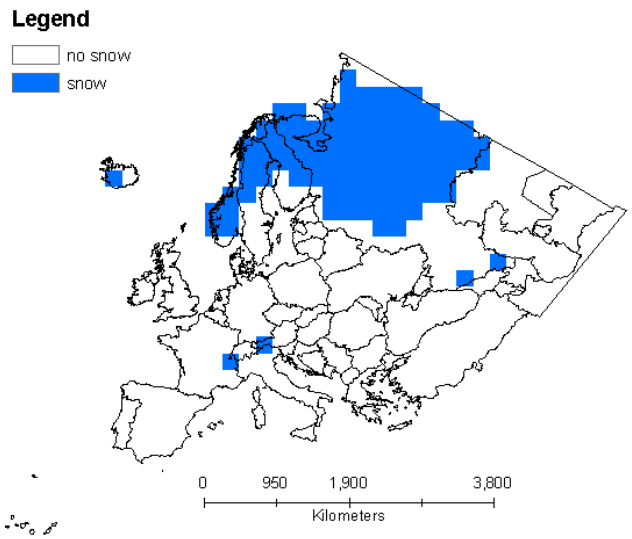

Figure 5.3- November snowcover extent distribution.

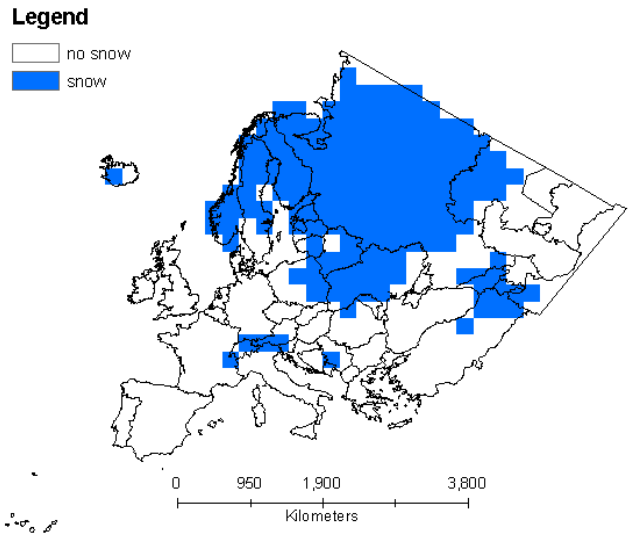

Figure 5.4- December snow extent distribution

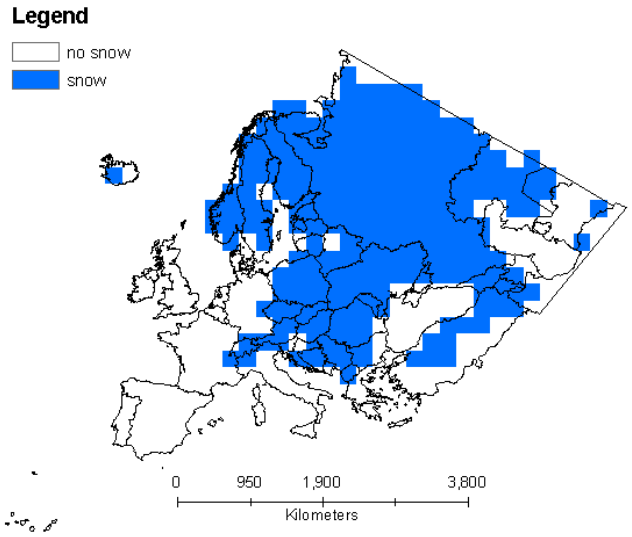

Figure 5.5- January snowcover extent distribution

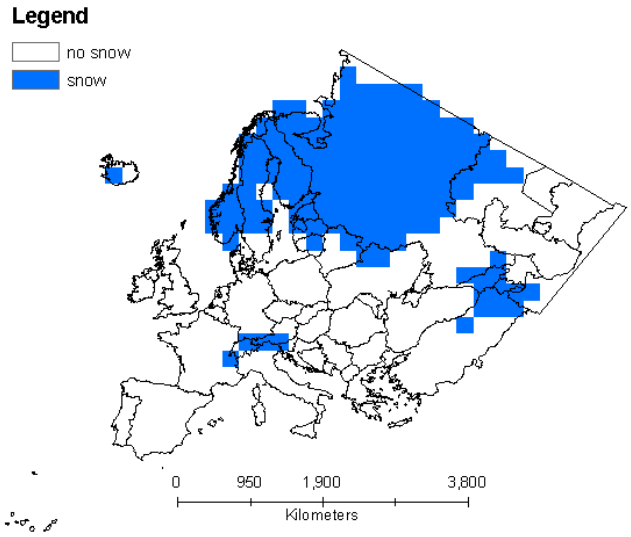

Figure 5.6- February snowcover extent distribution

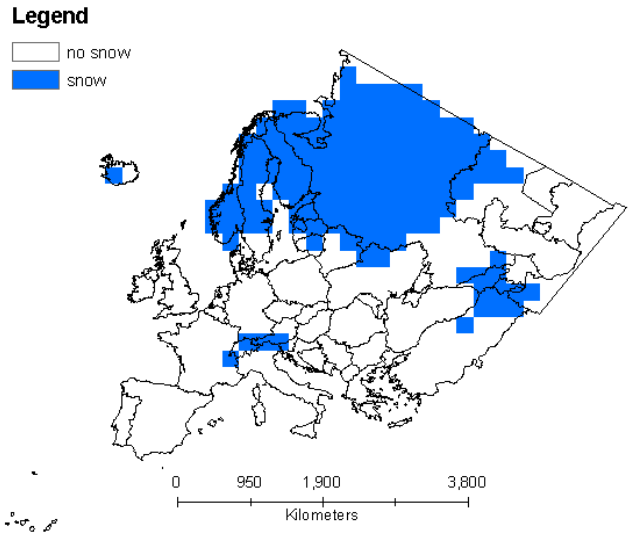

Figure 5.7- March snowcover extent distribution

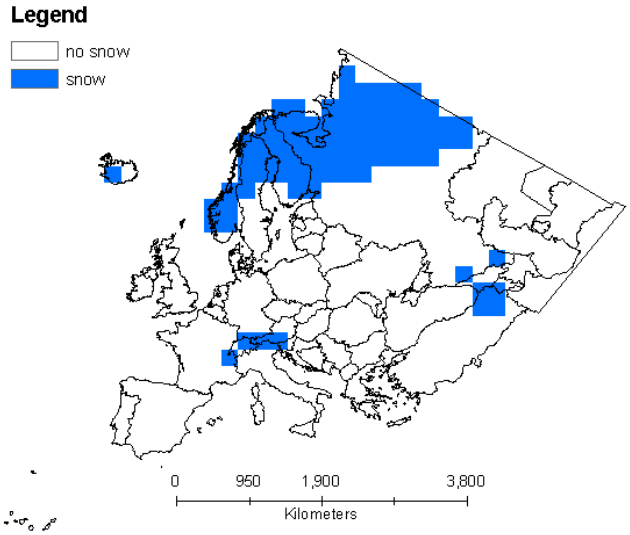

Figure 5.8- April snowcover extent distribution

5.4 Snowcover and other climate variables:

With a greater understanding of the overall spatial and temporal nature of European snowcover extent over the study period, the relationship between snowcover and other climatic variables can be further explored. Climatic variables in this analysis include surface temperature, precipitation and sea-level pressure.

5.4.1 Mean European snowcover area and surface temperature:

Contour maps showing the correlation coefficient (r) between European snowcover area totals and the surface temperature of each grid box were produced for each month during the winter season. These maps were produced using SURFER and are in geographic coordinate system. Correlations between temperature and snowcover were based on the period 1967-2000 and were produced for the months November to April. Areas of negative correlation represent lower temperatures being associated with higher snowcover totals.

During November (Figure 5.9), an area of negative correlation (-0.5) is evident over the Baltic Sea into western Russia. Lower temperatures over this region are associated with higher snowcover totals. The highest correlation values are found in the region with the most ephemeral snowcover during the month. The December map (Figure 5.10) displays a less organized pattern with no significant relationship apparent especially in western Russia and portions of Scandinavia. In January (Figure 5.11), the notable negative correlation area of November has shifted westward over the North Sea and is centered to the south of Scandinavia and to the east of the British Isles. This negative relationship strengthens (-0.7) and grows throughout February (Figure 5.12), extending east and south over the majority of the region. The January

and February maps indicate that large snowcover extents across Europe are normally associated with below normal temperatures over central and Eastern Europe. By March the stronger correlations (-0.7) are limited to the northern and eastern sections of Europe, with the western coast of the continent displaying a weaker relationship. By this time within the annual cycle, most snowcover is limited to these same areas indicating that generally colder conditions favor more extensive snowcover. In April (Figure 5.14), a more meridional pattern is evident in the correlation values as the negative relationship decreases in strength from east to west. Higher continentality of the Eurasian interior leading to longer annual snowcover extent through persistent lower temperatures later into the spring may account for the development of this meridional pattern development.

5.4.2 Mean European snowcover area and precipitation:

Maps similar to those of temperature were produced showing the relationship between the total liquid precipitation within each grid box and European snowcover total for each month during the winter season (November to April). As expected, the relationship between these two variables is less homogenous than for surface temperature, as precipitation in general is a less homogenously distributed variable. Overall, a negative relationship is evident between precipitation and snowcover totals, with larger snowcover areas being associated with lower precipitation values (Figures 5.15-5.20).

Small negative correlations (-0.3) are present over Scandinavia and off the northwestern coast of France during November (Figure 5.15). A smaller area of positive correlation (0.25) is evident in the vicinity of the Caucasus. These results over Europe are indicative of colder and dryer air masses that cover the region when

snowcover is more extensive than the mean extent. Once again, December's pattern is less organized and displays no significant relationship, perhaps due to the transitional nature of this month. In January (Figure 5.17), a negative relationship (-0.45) is apparent over the Russian Uplands and Scandinavia, weakening to the south. A small pocket of positive association is present over northern Italy and the Adriatic Sea. The relationship strengthens during February (Figure 5.18) with stronger (-0.6) negative values present over the greater part of northern Europe. Larger snow extents during this month are usually associated with lower temperatures, typically indicating a drier atmosphere and therefore lower precipitation receipts across northern regions. This association continues to be evident during March (Figure 5.19) and into April (Figure 5.20) as areas with stronger negative correlation values (-0.4 and -0.5 respectively) shift east, where colder temperatures persist later in the winter season, along with snowcover. Again, lower precipitation values may be associated with colder and dryer air masses that help to increase snowcover extent in these areas late in the winter season. Thus, snowcover extent across Europe seems to be primarily temperature dependent. Colder winter temperatures are associated with greater snowcover extents, even though these cold, dry air masses limit total liquid precipitation. This may also indicate that large snowcover extent years have snow mass (water equivalent) values that are relatively small due to decreased total liquid precipitation.

5.4.3 Mean European snowcover area and sea-level pressure:

Sea-level pressure and its relationship to European snowcover was evaluated across the entire North Atlantic sector in order to explore possible influences of large-scale teleconnection patterns. Sea-level pressure data on a 5º

latitude by 10º longitude grid was correlated with the snowcover totals for each month for the period 1967-2000 yielding the following maps of correlation coefficients (r).

November (Figure 5.21) shows a generally weak pattern of correlation over the Atlantic basin between sea-level pressure and snowcover total. Positive r values are present to the east of the British Isles into the North Sea and over much of Scandinavia. The northerly flow associated with positive pressure anomalies could enhance the chance of snowcover development in the region to the east of the higher-than-normal pressure. Similarly, the presence of negative r values located to the south of the Caspian Sea indicate an area of negative pressure anomalies during high snow extent months. These negative pressure anomalies would enhance northerly flow over western Russia and Scandinavia, leading to larger snowcover extents. In December (Figure 5.22), the beginning stages of a weak di-pole pattern is evident, with positive correlations (0.3) over the North Atlantic and northwestern Europe contrasting with negative values (-0.3) over southern Spain and North Africa. This di-pole pattern is indicative of the North Atlantic Oscillation (NAO). The di-pole pattern strengthens during January (Figure 5.23) and February (Figure 5.24) covering much of the North Atlantic Basin. Throughout January, positive correlations on the order of 0.4 are located over northern Scandinavia and extend into the North Atlantic, while negative correlations on the order of -0.45 exists off the coast of Spain and North Africa.

These centers intensify during the month of February and increase to 0.7 and -0.6 respectively. The presence of this di-pole pattern over the North Atlantic sector suggest a strong relationship between European snowcover extent and the strength and phase of the NAO. Positive snowcover/sea-level pressure correlations to the north and negative correlations to the south indicates a link between a negative

NAO phase, characterized by reduced gradient between the Azores High and Icelandic Low, and extensive European snowcover. However, this NAO-like dipole pattern is shifted somewhat to the east of the “mean” NAO location.

The correlation maps for March (Figure 5.25) shows the initial break down of the organized pattern, with both positive and negative values weakening and shifting from common NAO centers of action. The positive relationship to the north moves to the east into the Russian interior while the negative area to the south swings westward into the Atlantic. By April (Figure 5.26) no strong correlation values are present, except for generally high values over central Europe. Like November, high pressure over central Europe during extensive snowcover years would tend to advect cold air across Eastern Europe, leading to more extensive snowcover.

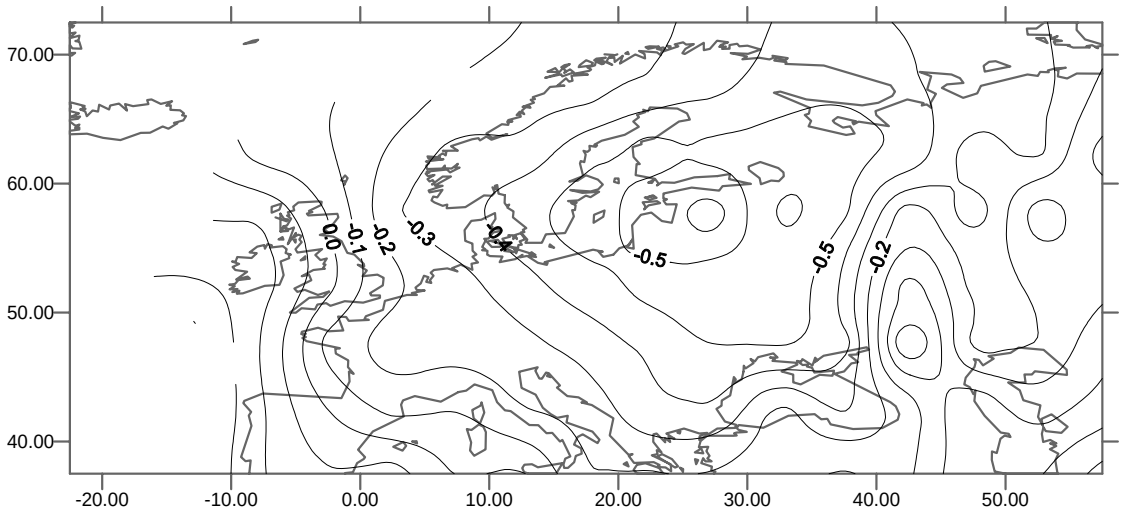

Figure 5.9- November correlation: surface temperature vs. snowcover total

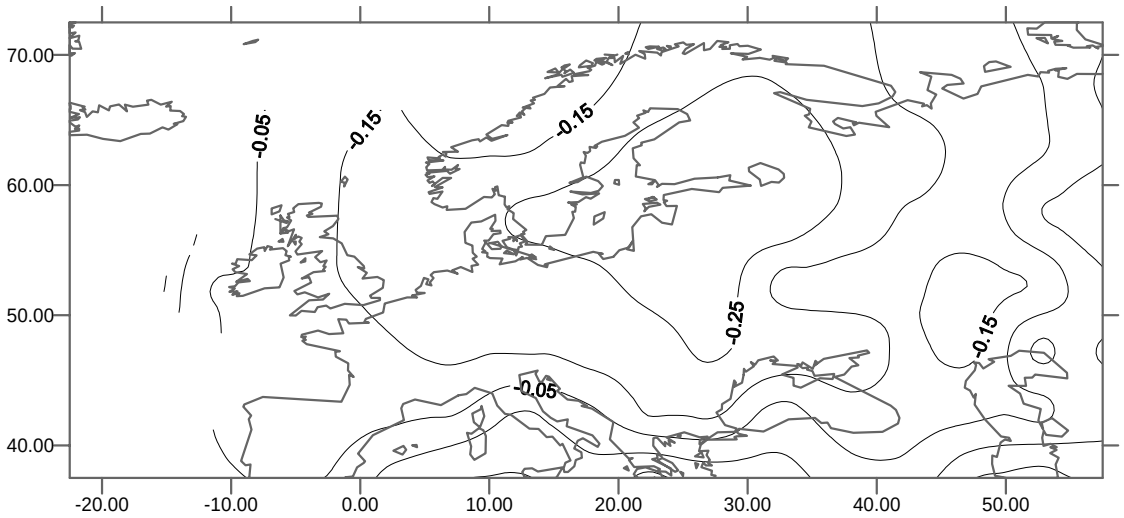

Figure 5.10- December correlation: surface temperature vs. snowcover total

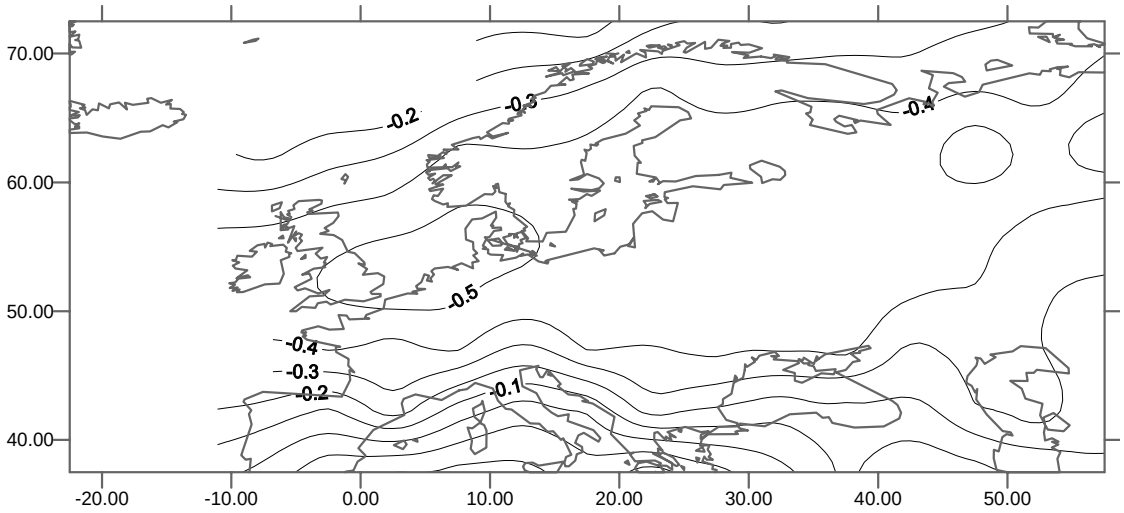

Figure 5.11- January correlation: surface temperature vs. snowcover total

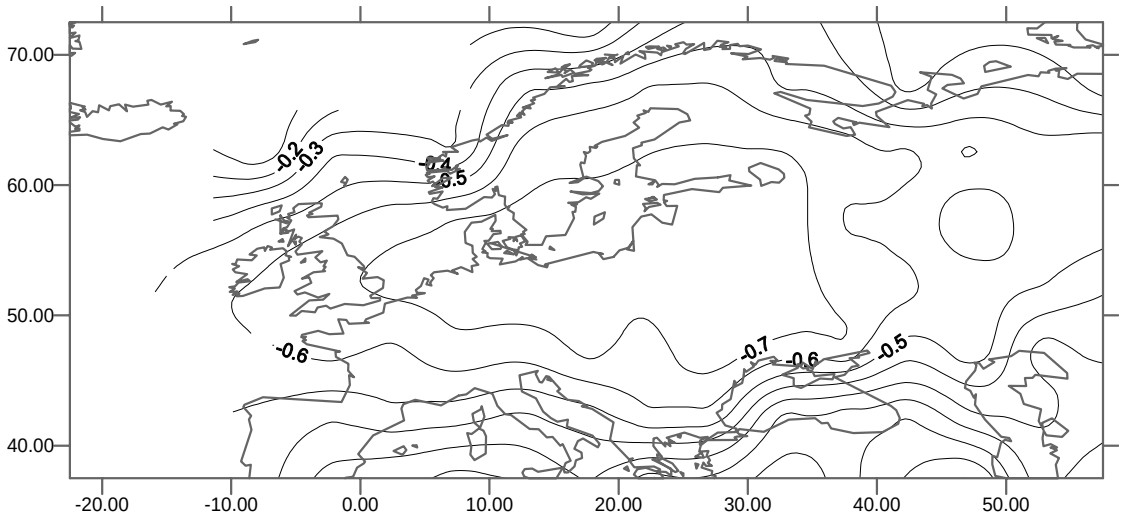

Figure 5.12- February correlation: surface temperature vs. snowcover total

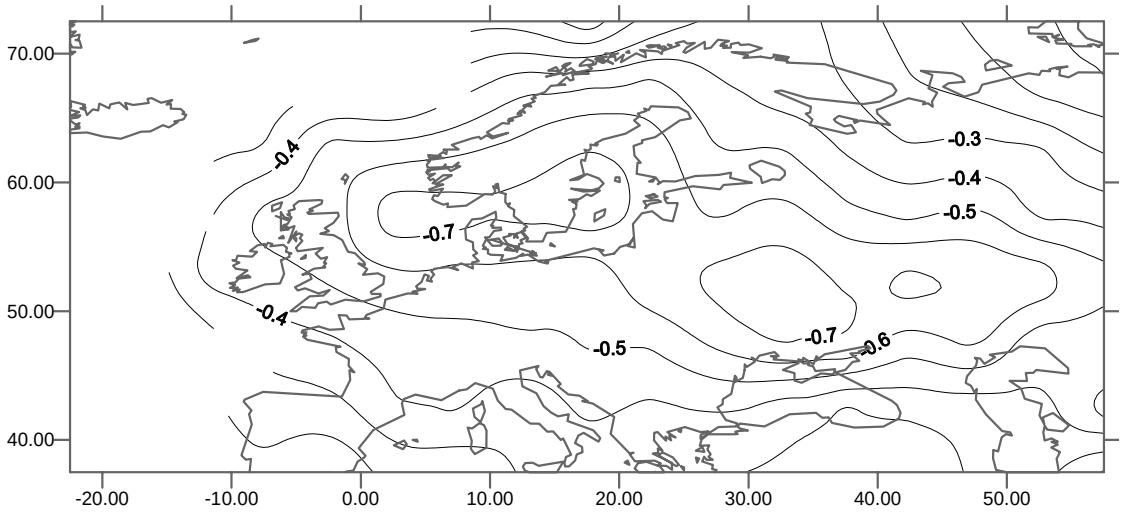

Figure 5.13- March correlation: surface temperature vs. snowcover total

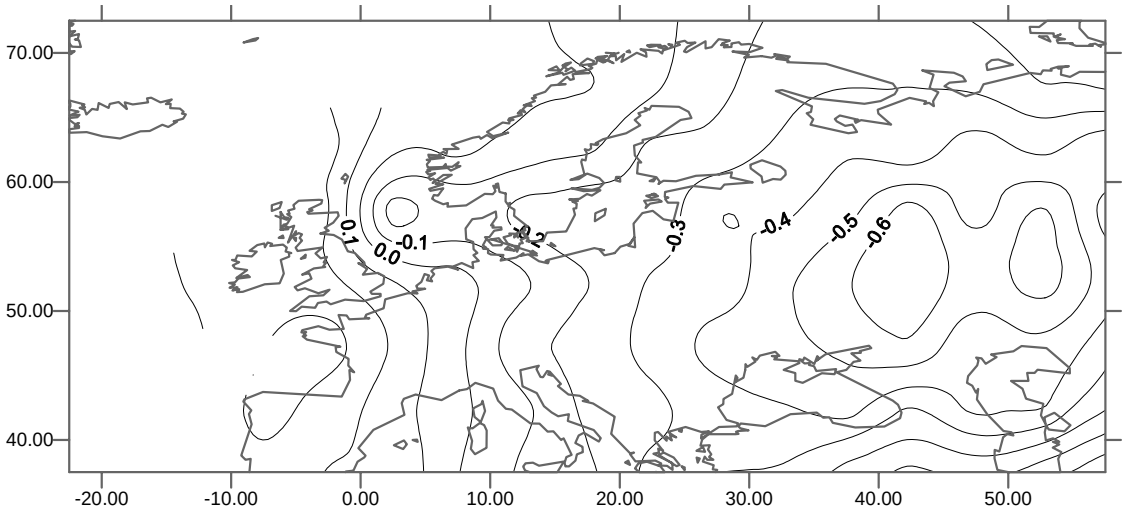

Figure 5.14- April correlation: surface temperature vs. snowcover total

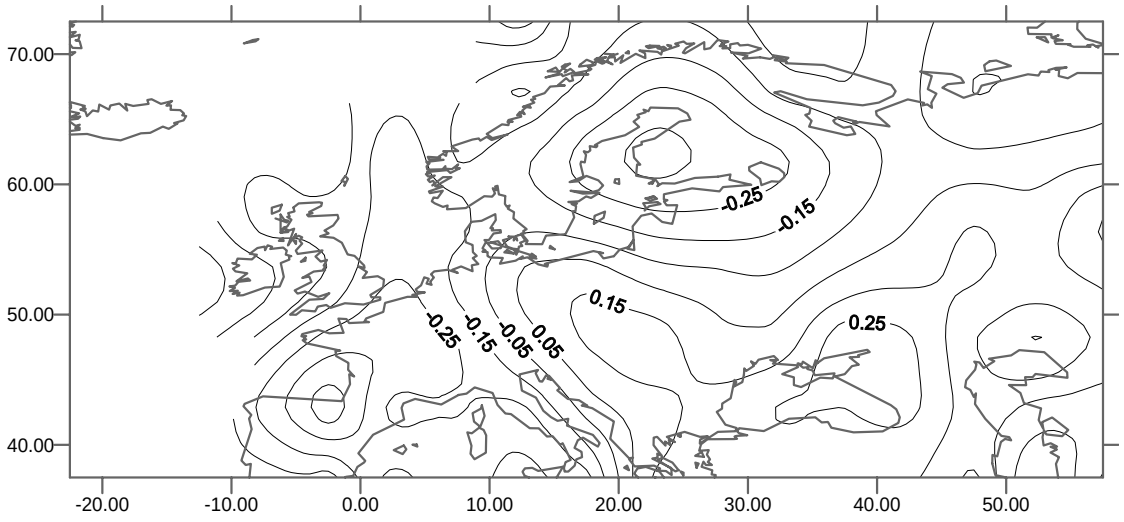

Figure 5.15- November correlation: precipitation vs. snowcover total

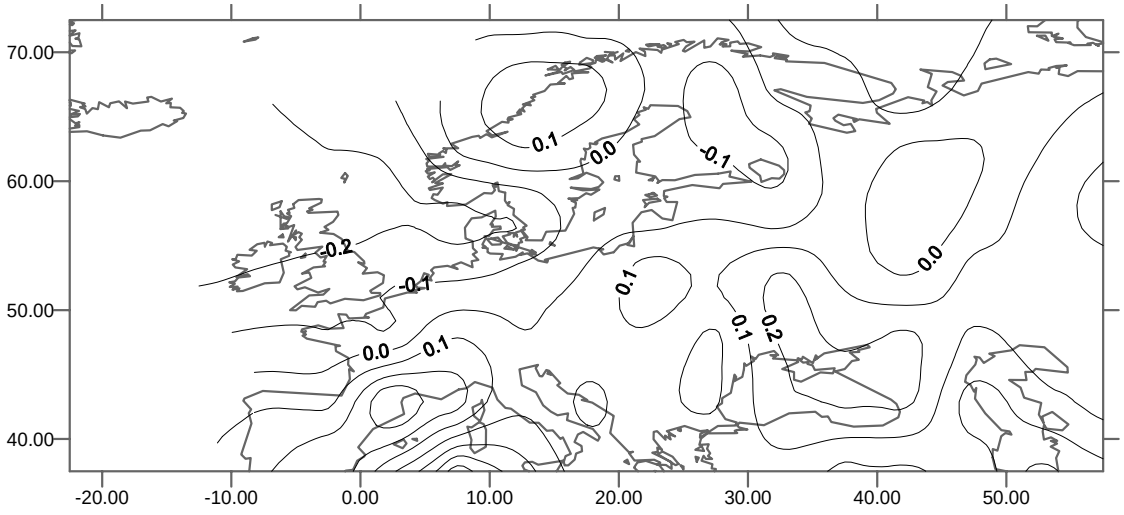

Figure 5.16- December correlation: precipitation vs. snowcover total

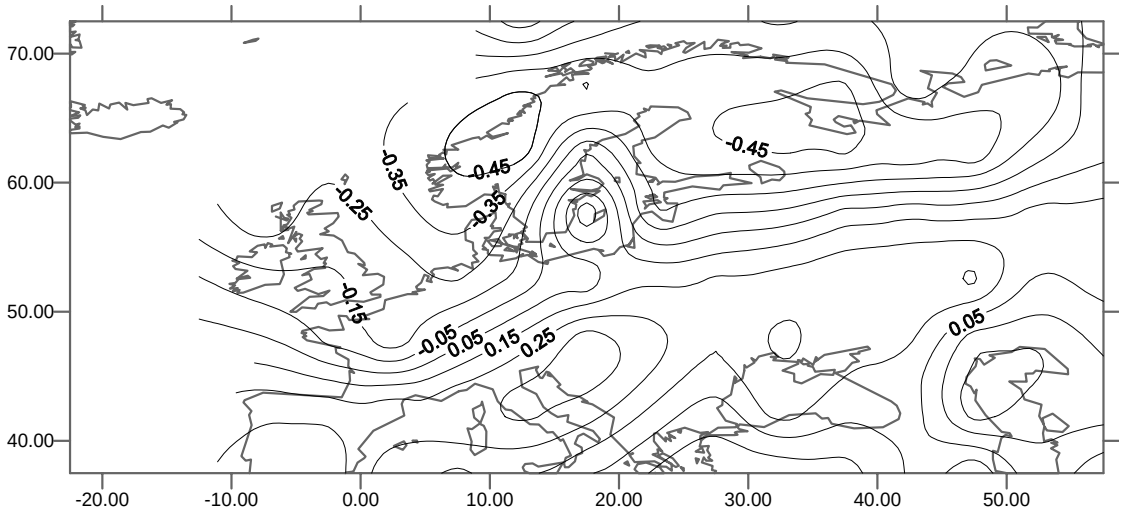

Figure 5.17- January correlation: precipitation vs. snowcover total

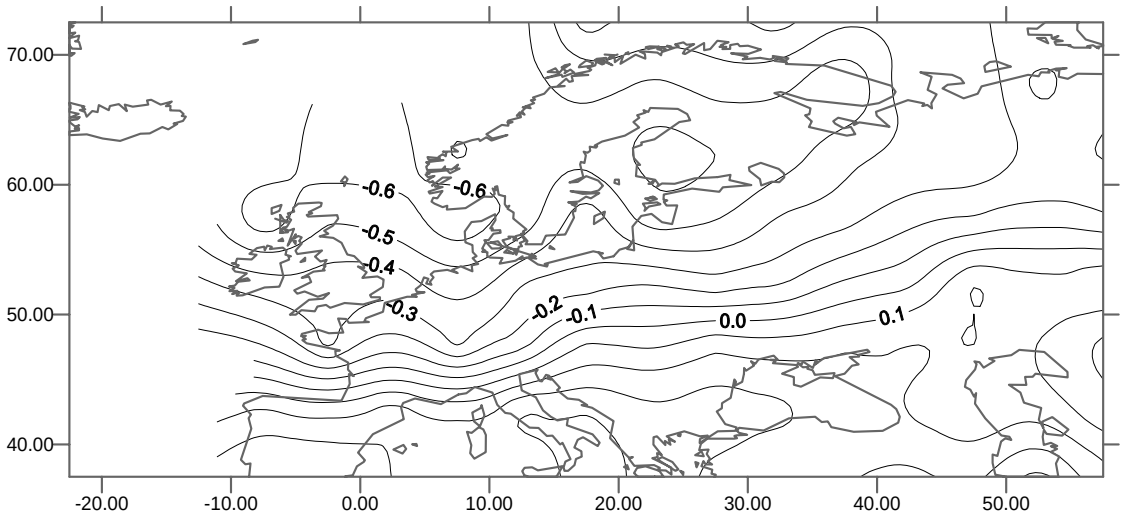

Figure 5.18- February correlation: precipitation vs. snowcover total

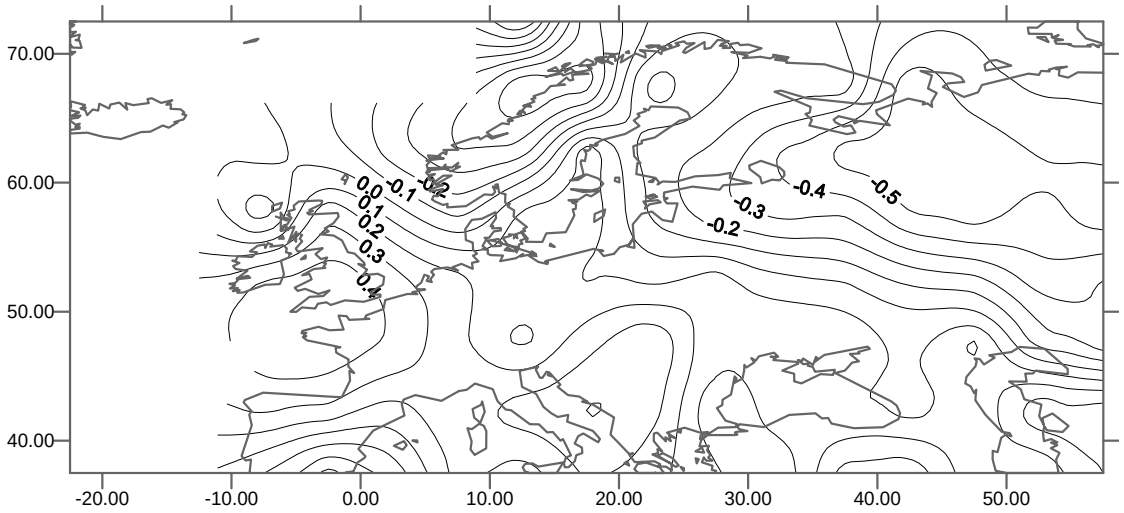

Figure 5.19- March correlation: precipitation vs. snowcover total

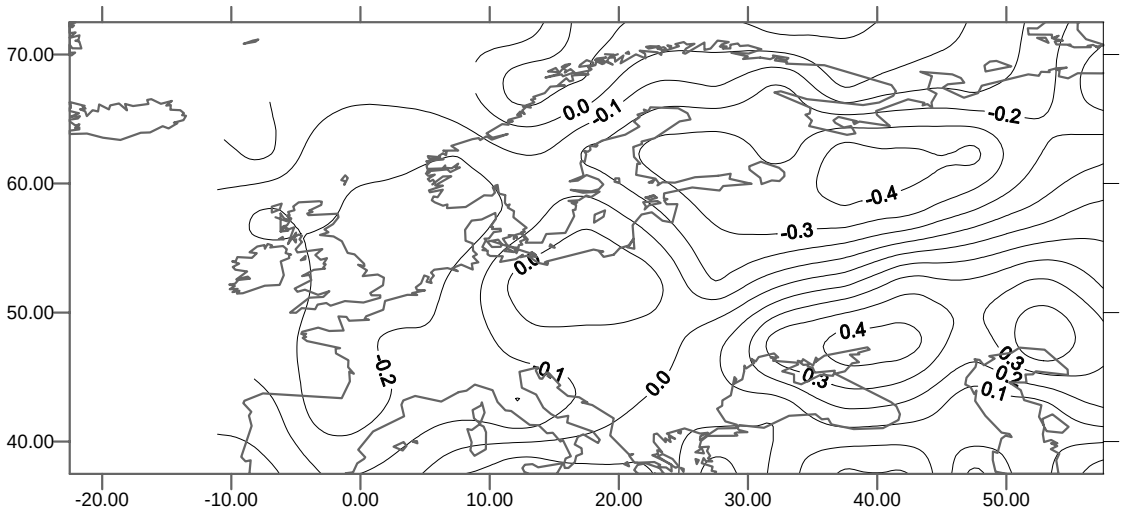

Figure 5.20- April correlation: precipitation vs. snowcover total

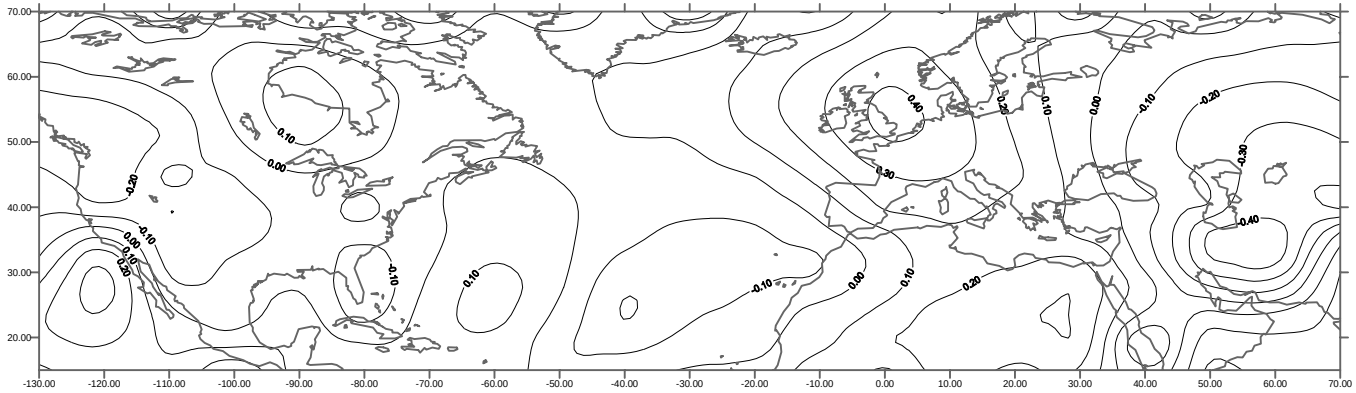

Figure 5.21- November correlation: sea-level pressure vs. snowcover total

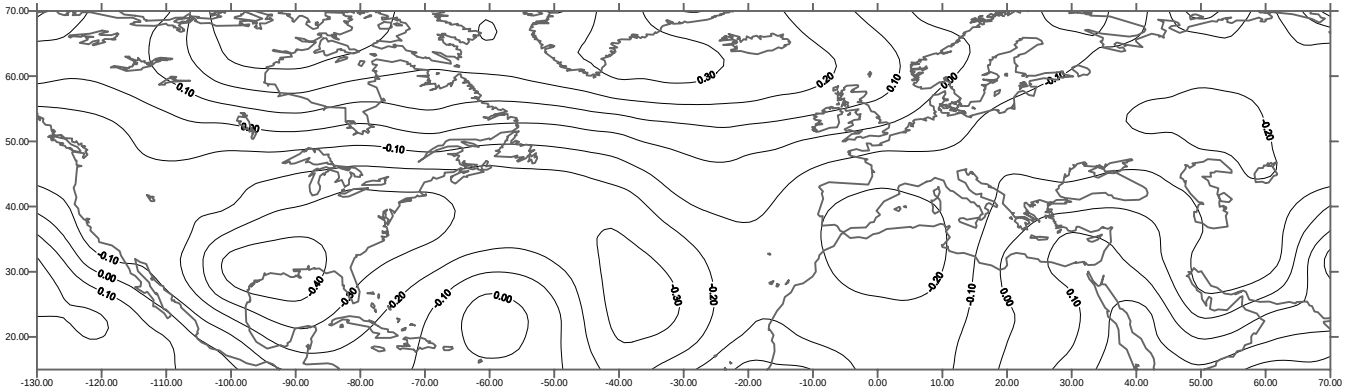

Figure 5.22- December correlation: sea-level pressure vs. snowcover total

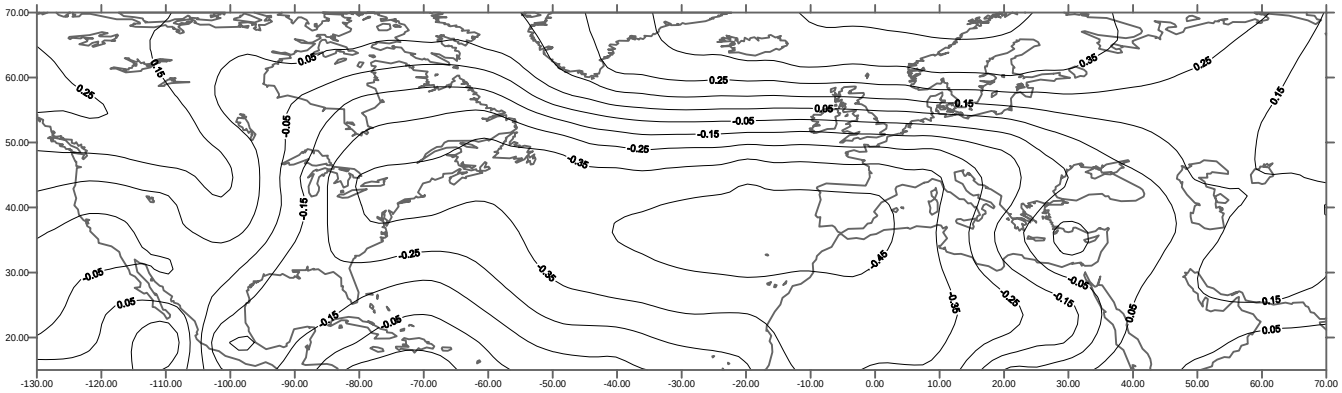

Figure 5.24- January correlation: sea-level pressure vs. snowcover total

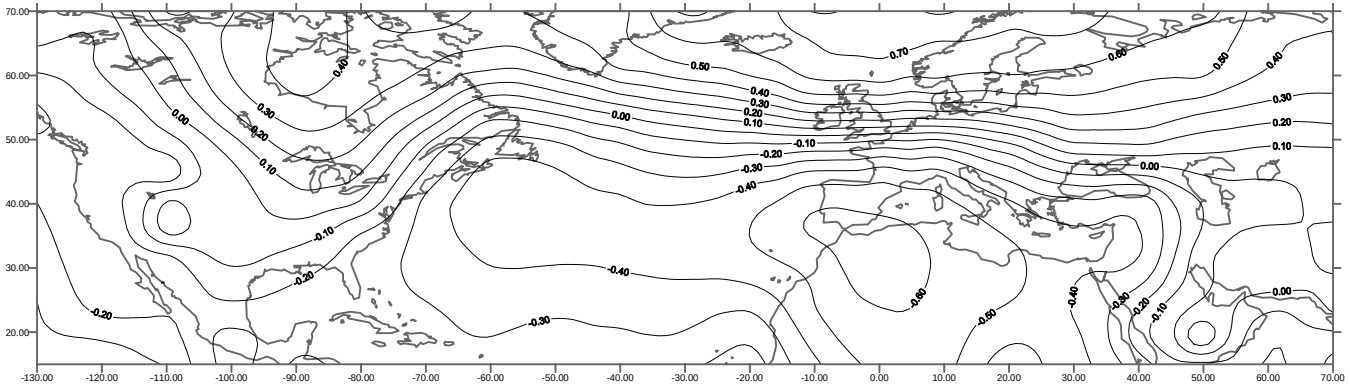

Figure 5.24- February correlation: sea-level pressure vs. snowcover total

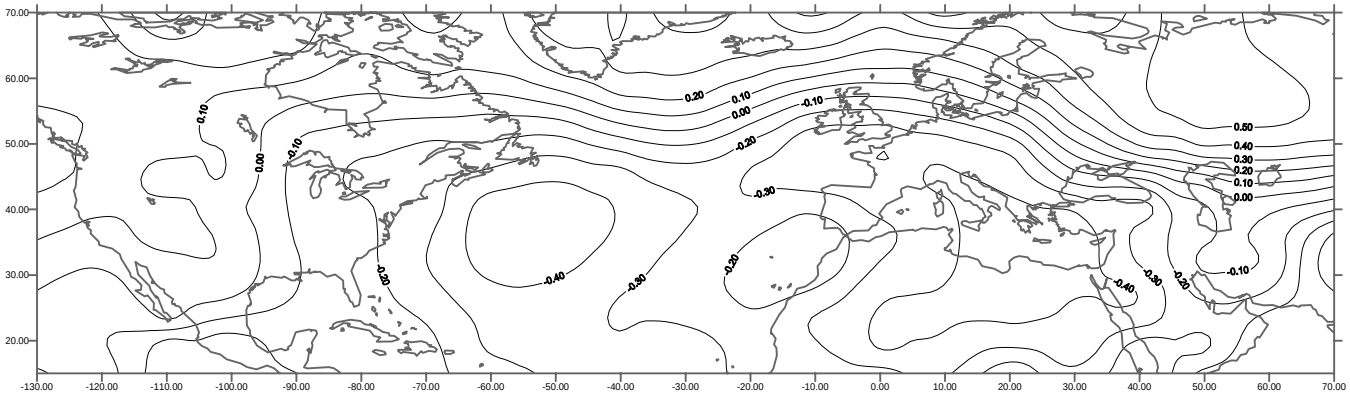

Figure 5.25- March correlation: sea-level pressure vs. snowcover total

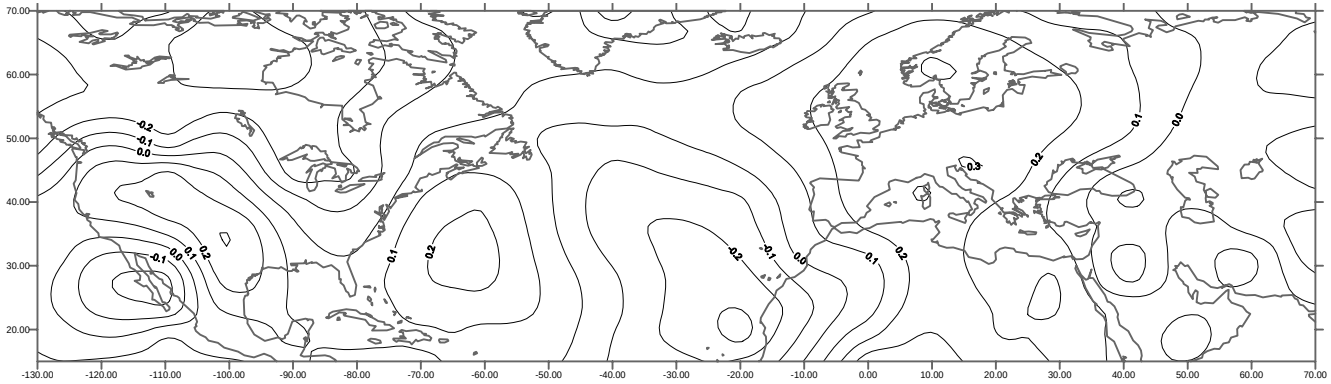

Figure 5.26- April correlation: sea-level pressure vs. snowcover total

5.5 Extreme snowcover area extent analysis:

Extreme snowcover extent years for both maximum and minimum snowcover areas were considered in the next step of this study. The five largest and smallest snowcover extent years were identified for each month. Composite maps of those years of 500-hPa geopotential heights, sea-level pressure and sea surface temperature were created. Monthly composites were produced from the NOAA-CIRES Climate Diagnostics Center, Boulder Colorado (http://www.cdc.noaa.gov/). A mean plot including all five years, and an anomalous plot with departures from a long-term mean specific to each dataset represents conditions during each month's extreme extents.

Tables 5.1 and 5.2 contain the ranked maximum and minimum snowcover years for each month. The order was based on snowcover extent area values calculated for the study region.

Table 5.1- Maximum snowcover area extent years by month.

NOV	DEC	JAN	FEB	MAR	APR
1993	1973	1979	1985	1987	1996
1995	1970	1985	1986	1985	1980
1999	1977	1977	1980	1981	1987
1998	1967	1982	1991	1996	1981
1973	1981	1987	1987	1979	1985

Table 5.2- Minimum snowcover area extent years by month.

NOV	DEC	JAN	FEB	MAR	APR
1975	1984	1981	1995	1990	1975
1974	1980	1991	1990	1989	1973
2000	1986	1994	1989	1993	1972
1990	1979	1999	1981	1995	1992
1967	1996	1975	2000	1992	1988

5.5.1 500-hPa geopotential heights:

Figures 5.27-5.38 depict the distribution of 500-hPa geopotential heights throughout the European sector during maximum and minimum snowcover years, for the winter months November through April. For the large snowcover extent years in November (Figure 5.27), mean geopotential heights are lowest over the extreme North Atlantic and gradually increase to the south. Across northern Europe the approximate height ranges from 5400m over Scandinavia to 5600m across much of continental Europe. As geopotential height is directly related to the thickness of the underlying atmosphere, it is reasonable to associate higher 500-hPa geopotential heights with a warmer underlying atmosphere. Consequently, lower 500-hPa geopotential heights can be associated with a thinner underlying atmosphere and therefore lower temperatures. Anomalous 500-hPa geopotential heights in November (Figure 5.27) represent the mean of the five anomalous years less that of the climatology, where positive and negative areas indicate higher and lower height occurrences respectively, than average. From this composite, a band of lower heights are present over southern Europe, extending and intensifying to the northeast into Eurasia. Positive anomalies exist to the north of this band with the anomalies being in excess of 40m over northern Europe. Thus, a trough-ridge-trough wavetrain extends from northeastern North

America, across the Atlantic to western Russia during maximum snow extent Novembers. The Russian trough would lead to colder temperatures and enhanced snowcover extent in these regions.

November's minimum snowcover extent mean composite map (Figure 5.28) shows a wavetrain with a significant ridge located over western Russia. This ridge would allow advection of warm air to the north, decreasing the likelihood of large, long-lasting snowcover extents in this area, early in the snowcover seasons.

From the December mean composite maps a relatively weak trough-ridge-trough pattern can be identified during maximum snowcover extent years (Figure 5.29), with a ridge over Western Europe and a trough present to the east. This trough would allow cold air outbreaks over Eastern Europe and a better chance for extensive long-lasting December snowcover. No significant anomalies are present over Europe during December for minimum snowcover years (Figure 5.30). However, a weak ridge is evident over northeastern sections of the study area. This ridge likely discourages the presence of snowcover over Eastern Europe in December.

Considerable differences can been seen when considering the January mean 500-hPa height composites (Figures 5.31 & 5.32), as a distinctive dipole pattern is evident during both maximum and minimum snowcover years. The anomaly maps show that maximum snow years have positive anomalies over Greenland and the North Atlantic, while a strong negative band is located to the south extending across much of the mid-Atlantic. During minimum snowcover years in January, a weaker di-pole pattern is evident with negative values to the north and positive to the south. From the described arrangement of height departures, an association between these patterns and corresponding phases of the NAO can be implied. During January's

maximum snowcover years, a decreased pressure gradient between the Icelandic Low and Azores High is suggested due to the presence of positive departures to the north and negative to the south. This corresponds to a negative phase of the NAO, characterized by colder conditions across Northern Europe. Minimum snowcover years in January however, display a reversed pattern with negative height anomalies to the north and positive heights to the south. Association with a positive NAO phase characterized by a steeper pressure gradient between the Icelandic Low and Azores High can be inferred under such conditions, leading to warmer and wetter winters throughout Europe as the flow is more strongly westerly across much of Europe.

In February's maximum mean snowcover extent composite (Figure 5.33), ridging to the north of the U.K. and Ireland is more pronounced than in the January maximum plot and a well developed trough exists over Eastern Europe. Lower mean heights extend south throughout this region, corresponding to lower temperatures conducive to large snowcover extent occurrences. February minimum mean geopotential heights (Figure 5.34) display a zonal pattern with a steady gradient increasing to the south, with higher overall heights present over much of continental Europe. This would suggest a thicker underlying atmosphere in general with higher surface temperatures, corresponding to a lower snowcover extent value. A weaker dipole pattern corresponding to the negative phase of the NAO is present in the February maximum snow extent map (Figure 5.33). Weakened westerly flow across the Atlantic would lead to decreased warm advection across Europe and a cooling of the region, increasing snowcover extent in Western Europe. A reversal of height anomaly patterns is apparent from the February minimum anomaly plot (Figure 5.34), with substantial negative height differences located over Iceland and Greenland while

positive height differences are located over much of the mid-latitudes from eastern North America to western Eurasia. This spatial height distribution corresponds to the positive phase of the NAO, and reversal of the conditions described above for maximum February snowcover months.

During March, 500-hPa geopotential height patterns becomes less strong (Figures 5.35 & 5.36). The previous ridge-trough arrangement during maximum years has returned to that of a more zonal nature (Figure 5.35), while the anomalous heights retain a weakened north/south di-pole. Mean heights during minimum snowcover extent years tend to be higher over the majority of continental Europe, whereas a substantial di-pole pattern of height anomalies persists over the region. This suggests continued association between positive NAO like conditions and minimum snowcover areas late in the winter season. The existence of a significant ridge over continental Europe would advect warm air from the south and penetrate the continental interior, encouraging rapid ablation of ephemeral snowcover.

Finally, when considering the composite patterns present for the month of April, maximum mean heights show a steady decrease in values to the north with negative anomalous heights located over the Central Russian Uplands while positive heights exists over Western Europe (Figure 5.37). A return to a trough-ridge-trough wavetrain is evident for April's maximum snowcover years, extending from the eastern Atlantic across to central Eurasia. Cold air advection from the Arctic prompted by the interior trough could support long-lasting snowcover in this area. April's minimum snowcover extent mean composite (Figure 5.38) displays a slight ridge-trough-ridge pattern over Western Europe into central Russia, possibly aiding in the

advection of warmer air from the Mediterranean region to the continental interior, thus encouraging snowcover extent ablation.

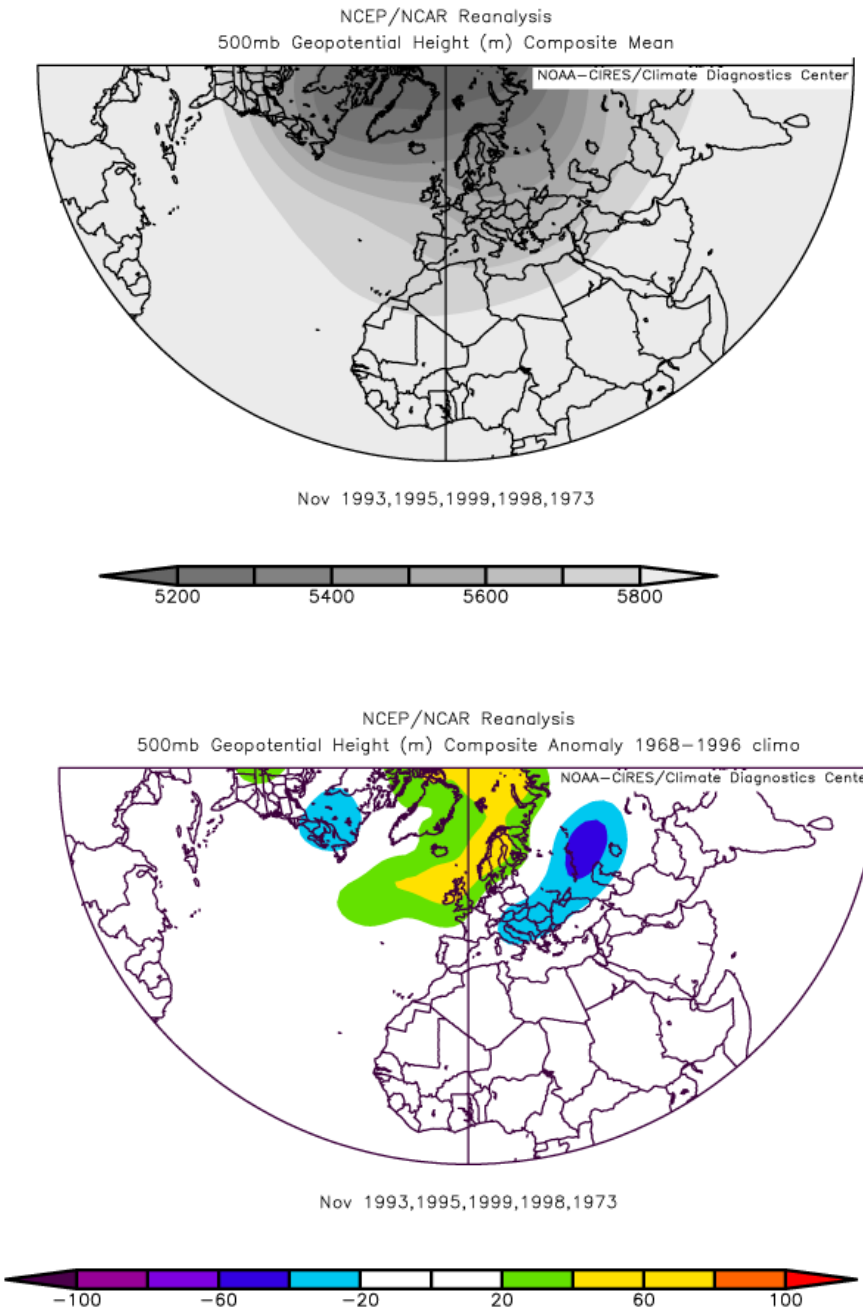

Figure 5.27- November maximum: mean and anomalous 500-hPa geopotential heights.

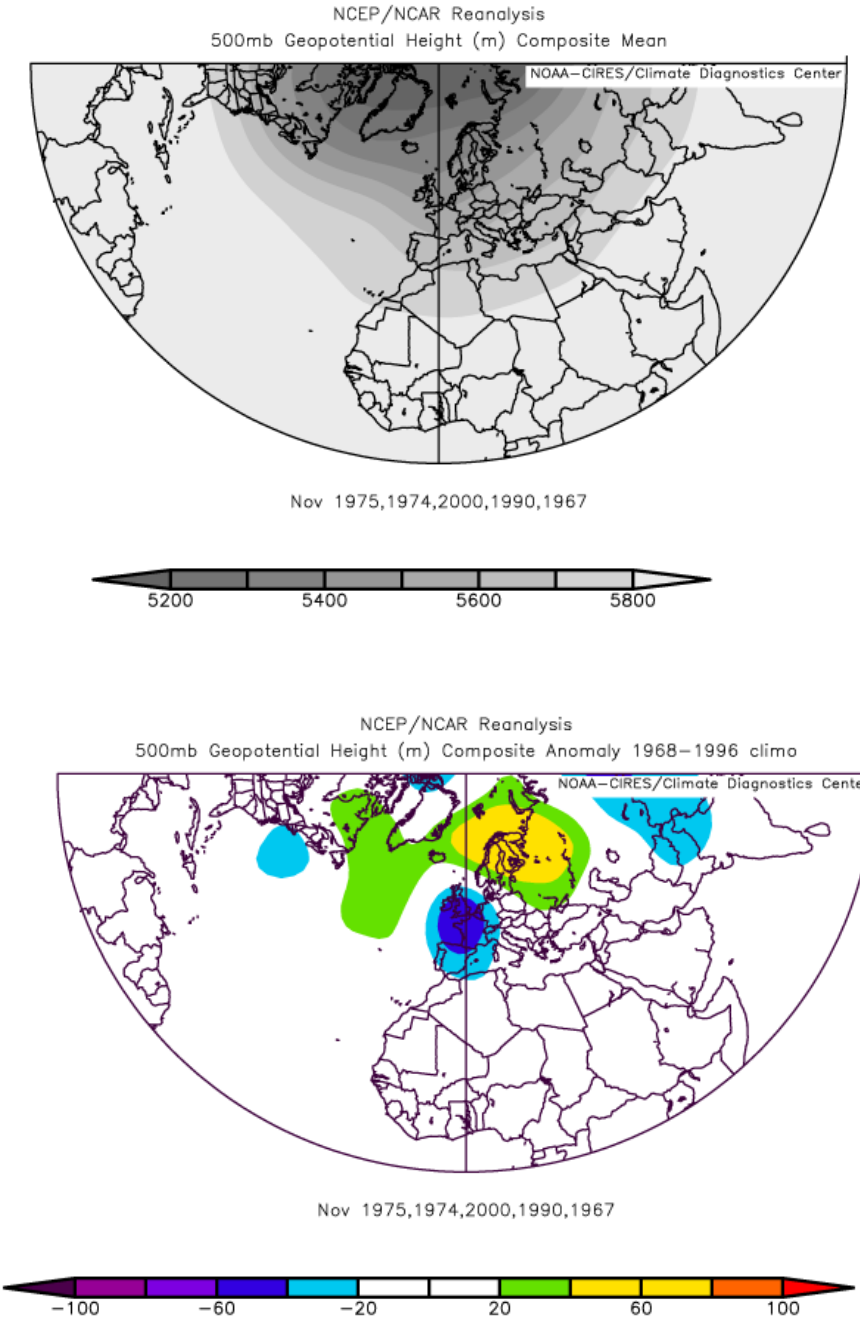

Figure 5.28- November minimum: mean and anomalous 500-hPa geopotential heights.

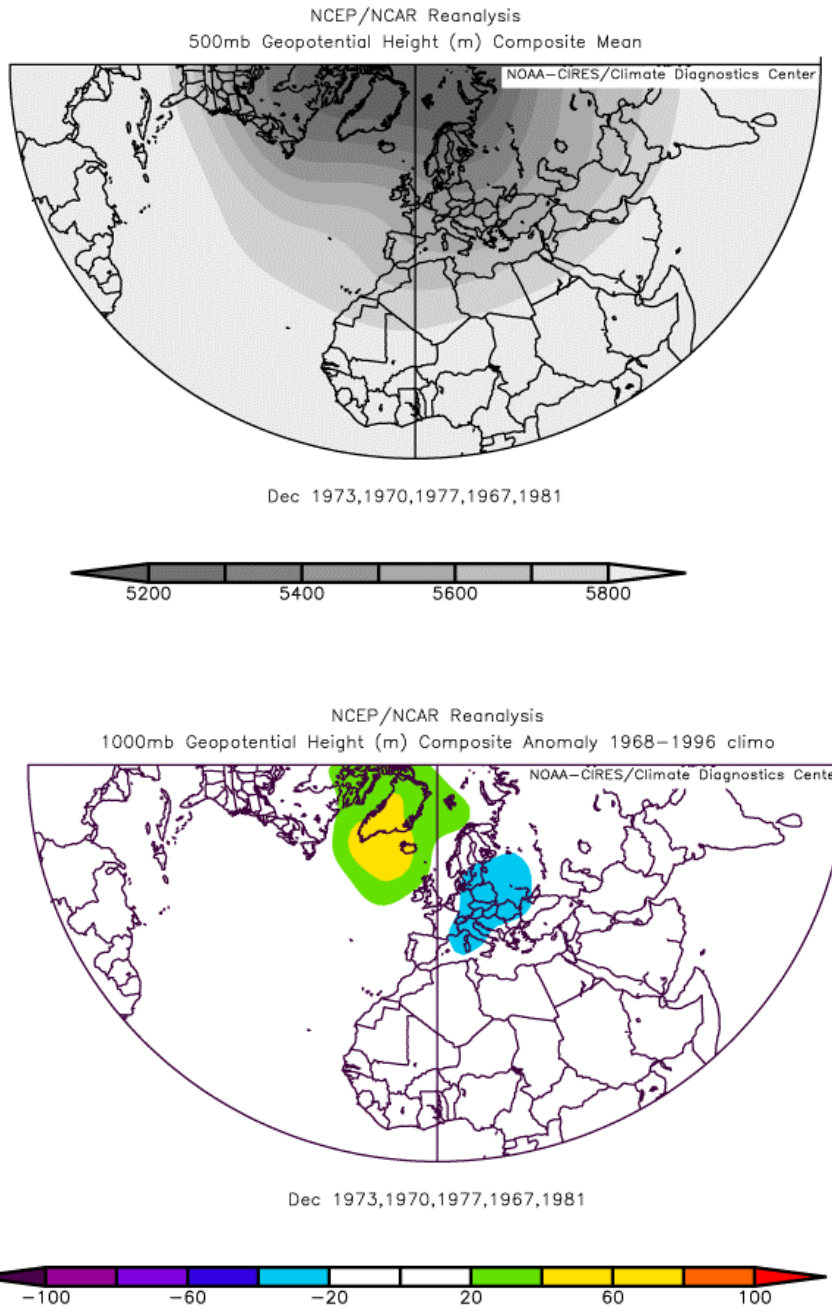

Figure 5.29- December maximum: mean and anomalous 500-hPa geopotential heights.

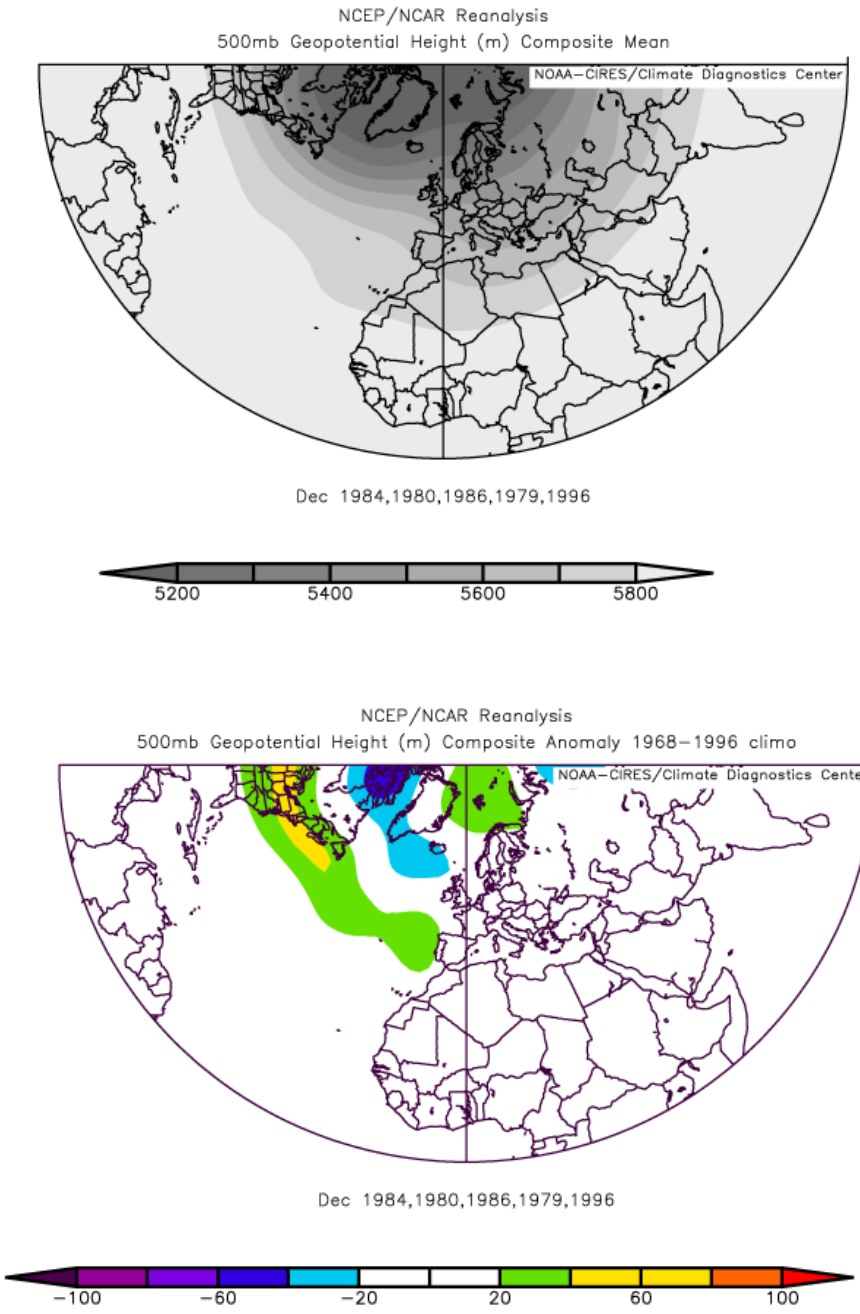

Figure 5.30- December minimum: mean and anomalous 500-hPa geopotential heights.

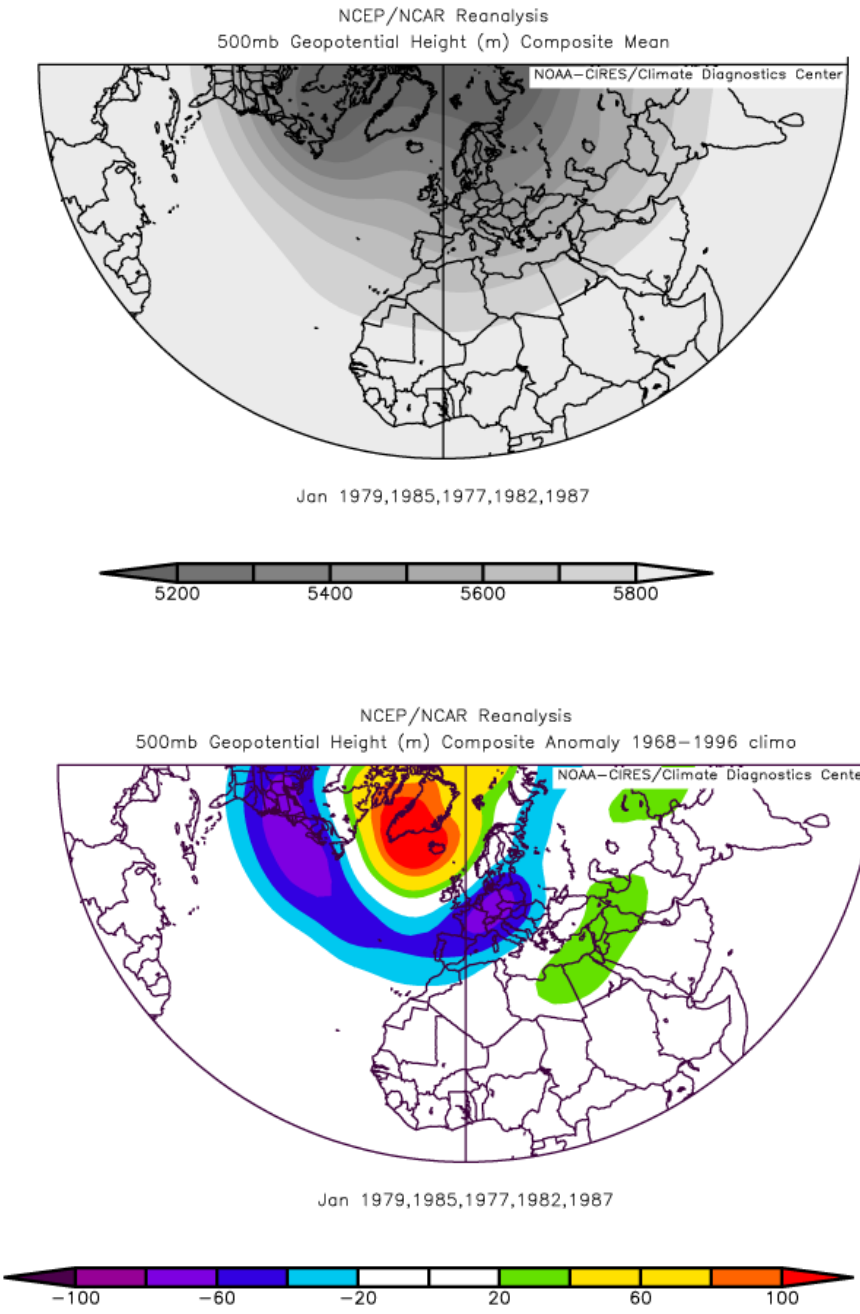

Figure 5.31- January maximum: mean and anomalous 500-hPa geopotential heights.

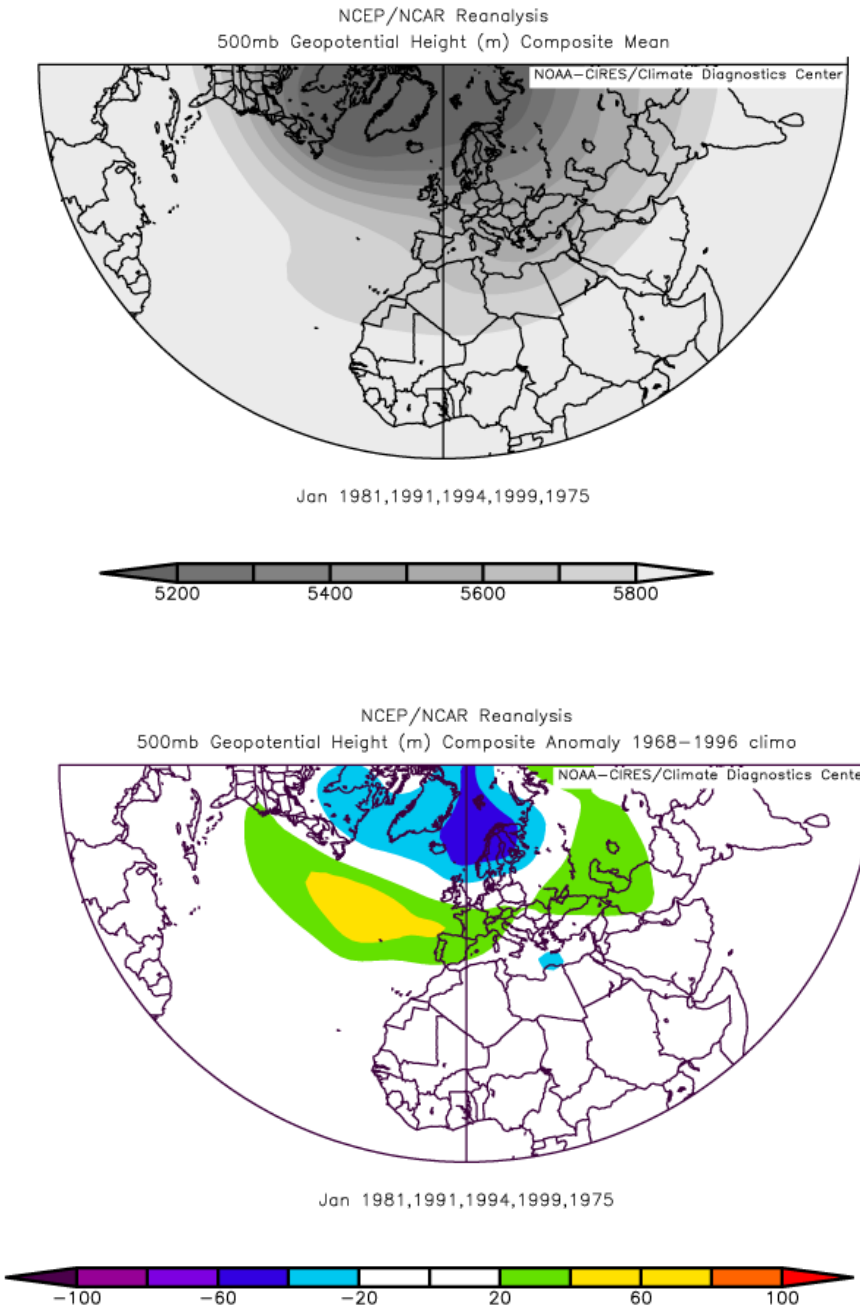

Figure 5.32- January minimum: mean and anomalous 500-hPa geopotential heights.

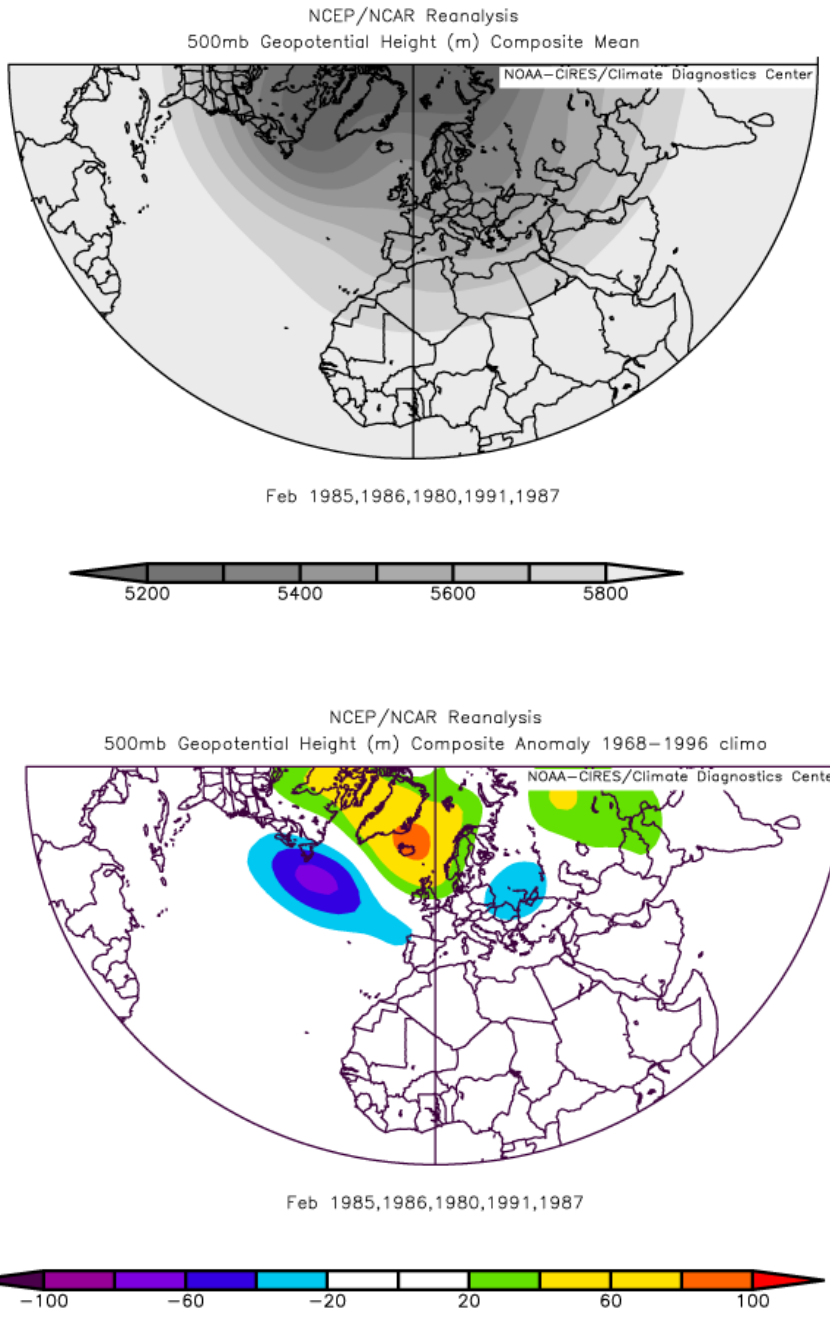

Figure 5.33- February maximum: mean and anomalous 500-hPa geopotential heights.

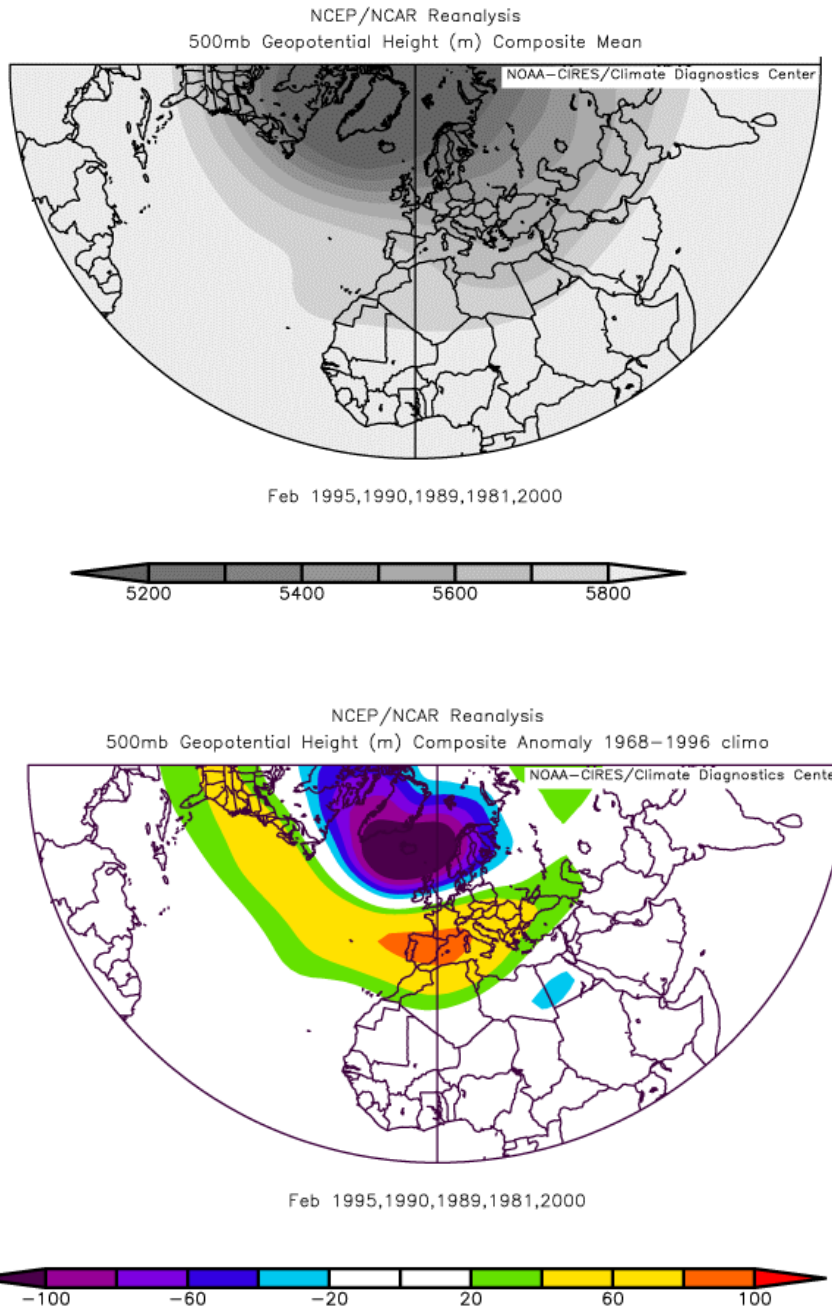

Figure 5.34- February minimum: mean and anomalous 500-hPa geopotential heights.

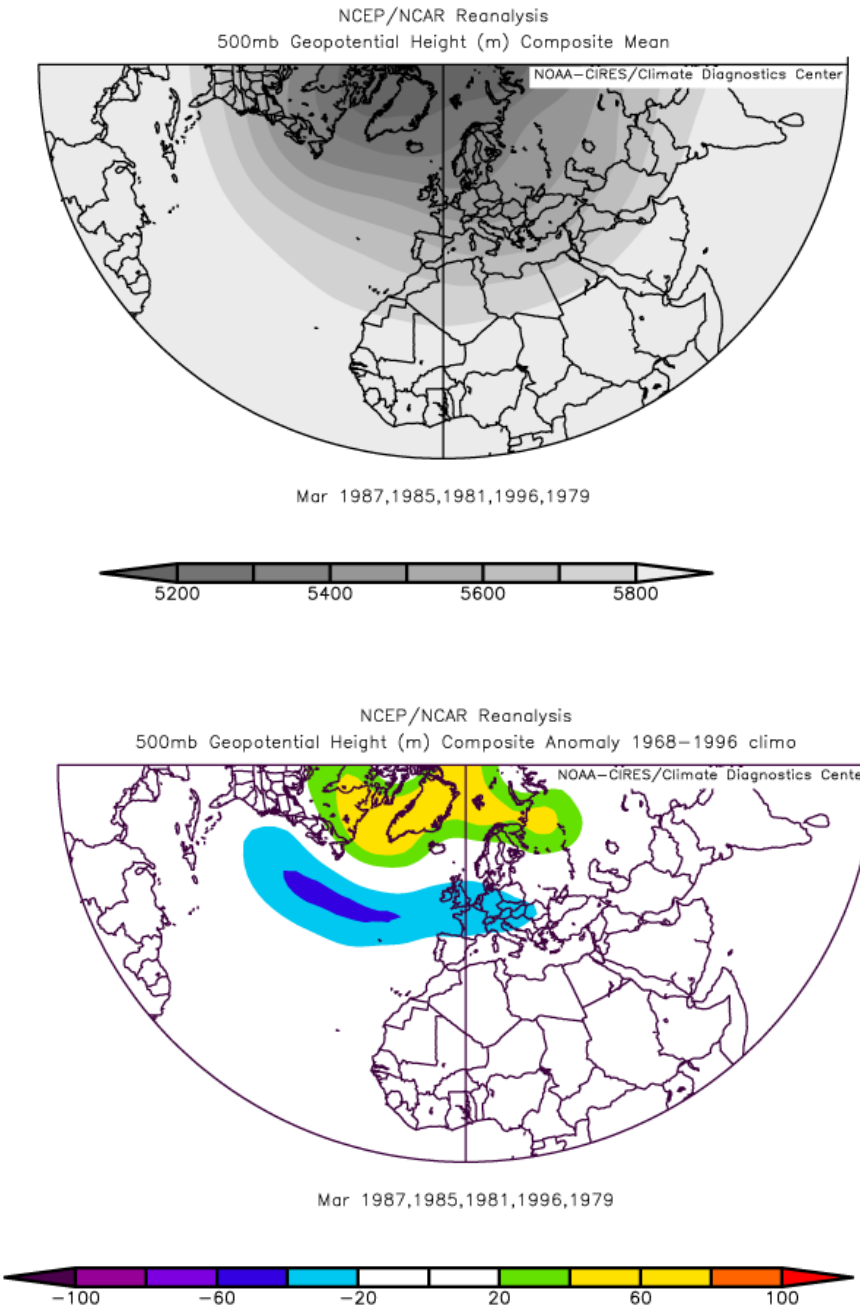

Figure 5.35- March maximum- mean and anomalous 500-hPa geopotential heights.

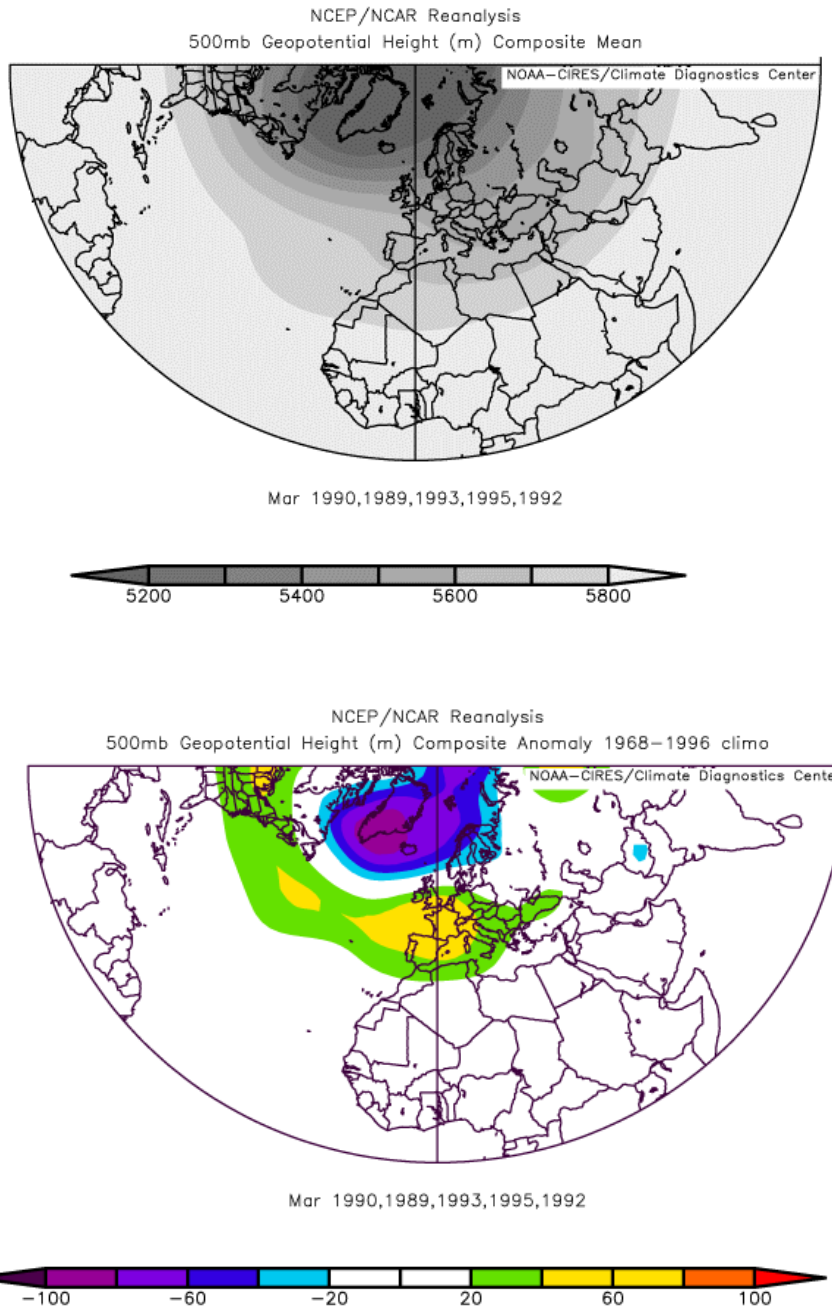

Figure 5.36- March minimum- mean and anomalous 500-hPa geopotential heights.

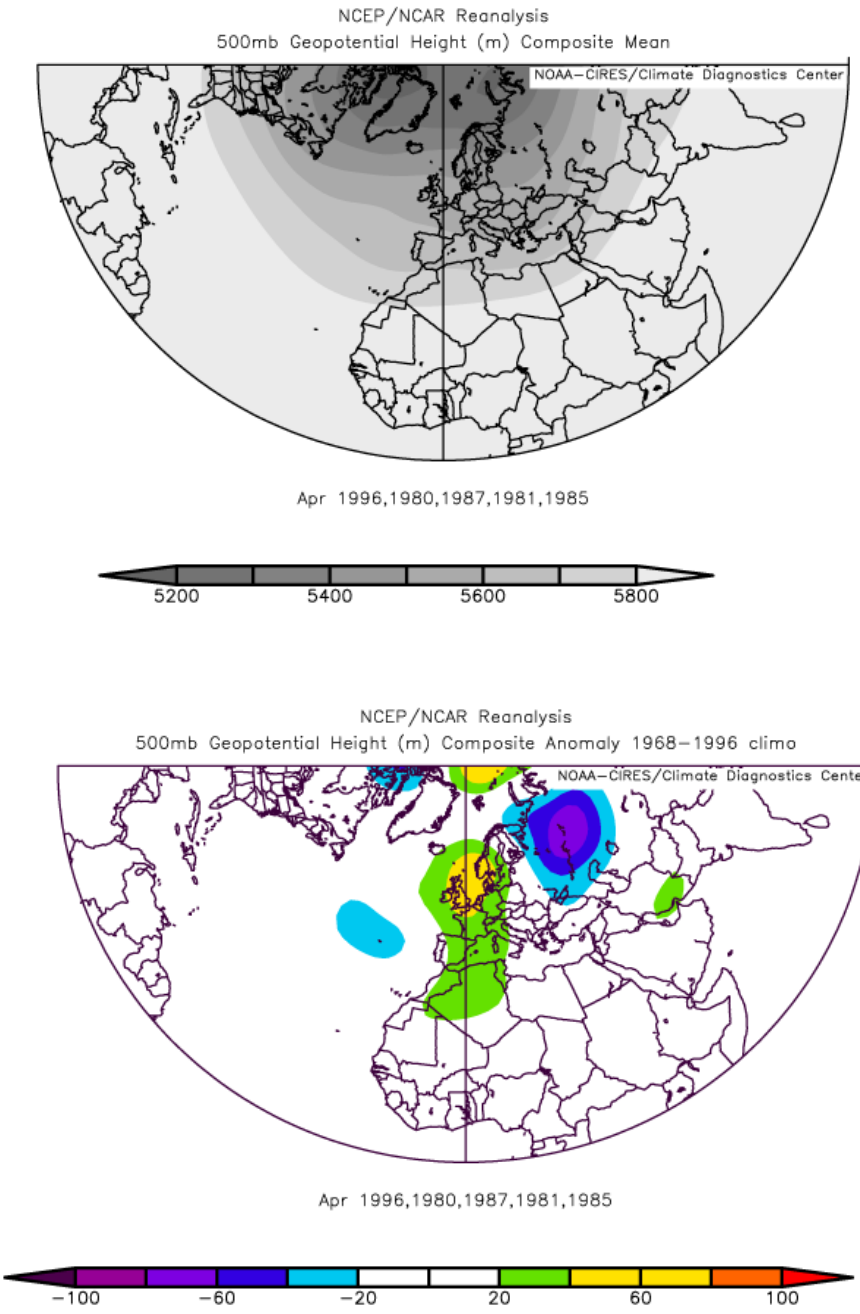

Figure 5.37- April maximum: mean and anomalous 500-hPa geopotential heights.

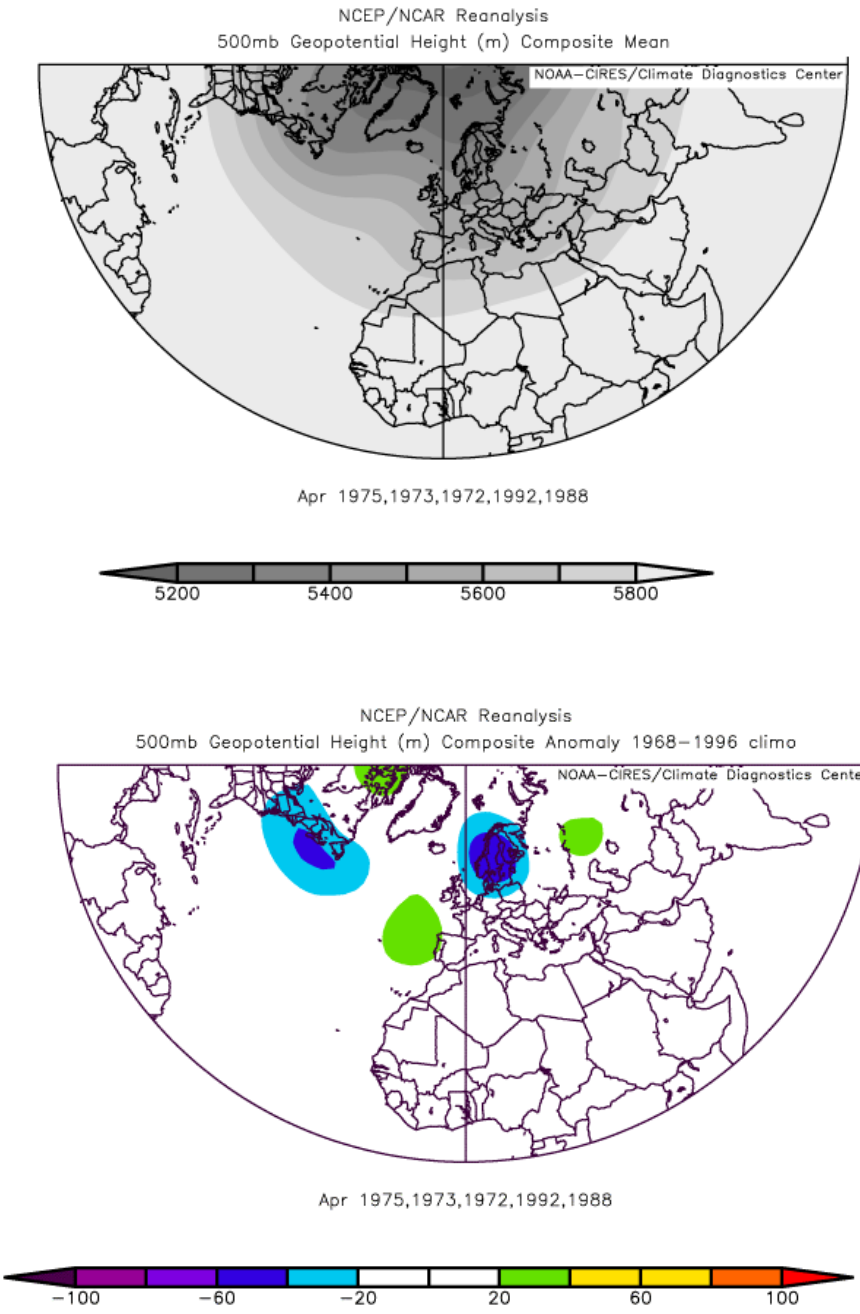

Figure 5.38- April minimum: mean and anomalous 500-hPa geopotential heights.

5.5.2 Sea Level Pressure:

The distribution of sea level pressure during maximum and minimum snowcover extent years was also analyzed. Sea level pressure composites were created for each month using data from both the five largest and five smallest snowcover area years for each month, November through April. The resulting maps are presented in Figures 5.39-5.50.

At the start of the winter season during November and December, no strong associations between sea level pressure distribution and maximum or minimum snowcover extent emerges. During November maximum snowcover years (Figure 5.39), mean sea level pressure is anomalously high over Scandinavia and Northern Europe. This pressure distribution is similar for December during large snowcover extent years (Figure 5.41). Minimum snowcover extent years for both months (Figures 5.40 &5.42) show similar general patterns, however anomalies are even weaker during minimum snowcover years and shifted further eastward. The placement of the high pressure anomalies in maximum extent years would bring anomalous northerly flow across northeastern Europe early in the season leading to more extensive snowcover. The placement during minimum extent years, further to the east, may lead to a more southerly return flow across this region and a smaller snow extent.

A more organized pattern over much of the North Atlantic is evident when considering sea level pressure distribution during January. From the maximum snowcover extent years mean plot (Figure 5.43), a substantial area of lower pressure can be seen over the North Atlantic and into the Arctic while higher pressure is present over Eurasia. A distinctive north/south di-pole arrangement of anomalies can also be seen with positive pressure to the north centered over Iceland and negative values to the south stretching across the Atlantic. This pattern of anomalies is likely

associated with a negative NAO phase, characterized by a weakened pressure gradient between the Azores High and the Icelandic Low, and is associated with a larger snowcover extent. The minimum mean snowcover extent map for January (Figure 5.44) has a similar pattern to that of the maximum years; however as with the 500-hPa geopotential height composites, a reversal of the sign of the anomalies is evident with negative pressure departures to the north and positive to the south.

This relationship continues in February and is apparent from the anomalous composite plots in particular. During maximum snowcover extent years (Figure 5.45), the mean distribution of sea level pressure remains similar to that described for January maximum years. The di-pole pattern is weaker than the previous month for both the positive and negative values. During minimum snowcover extent years (Figure 5.45), the mean pressure distribution is similar to that of January. An intensification of both the positive and negative anomalies is evident resulting in a strong pressure gradient across the North Atlantic. This suggests a possible link to a positive NAO phase, characteristic of warm wet European winters, with reduced snowcover.

During March and April extreme snowcover extent years, no significant sea level pressure distribution is apparent (Figures 5.47 &5.48). The mean composite maps for maximum and minimum years show greater heterogeneity in values while anomalous pressures display weaker departures. March maximum snowcover extent years (Figure 5.47) illustrate a relatively strong pattern, with positive departures over Northern Europe and into the North Atlantic and negative values over the eastern mid-Atlantic. Little to no significant values can be seen by April for either maximum or minimum years.

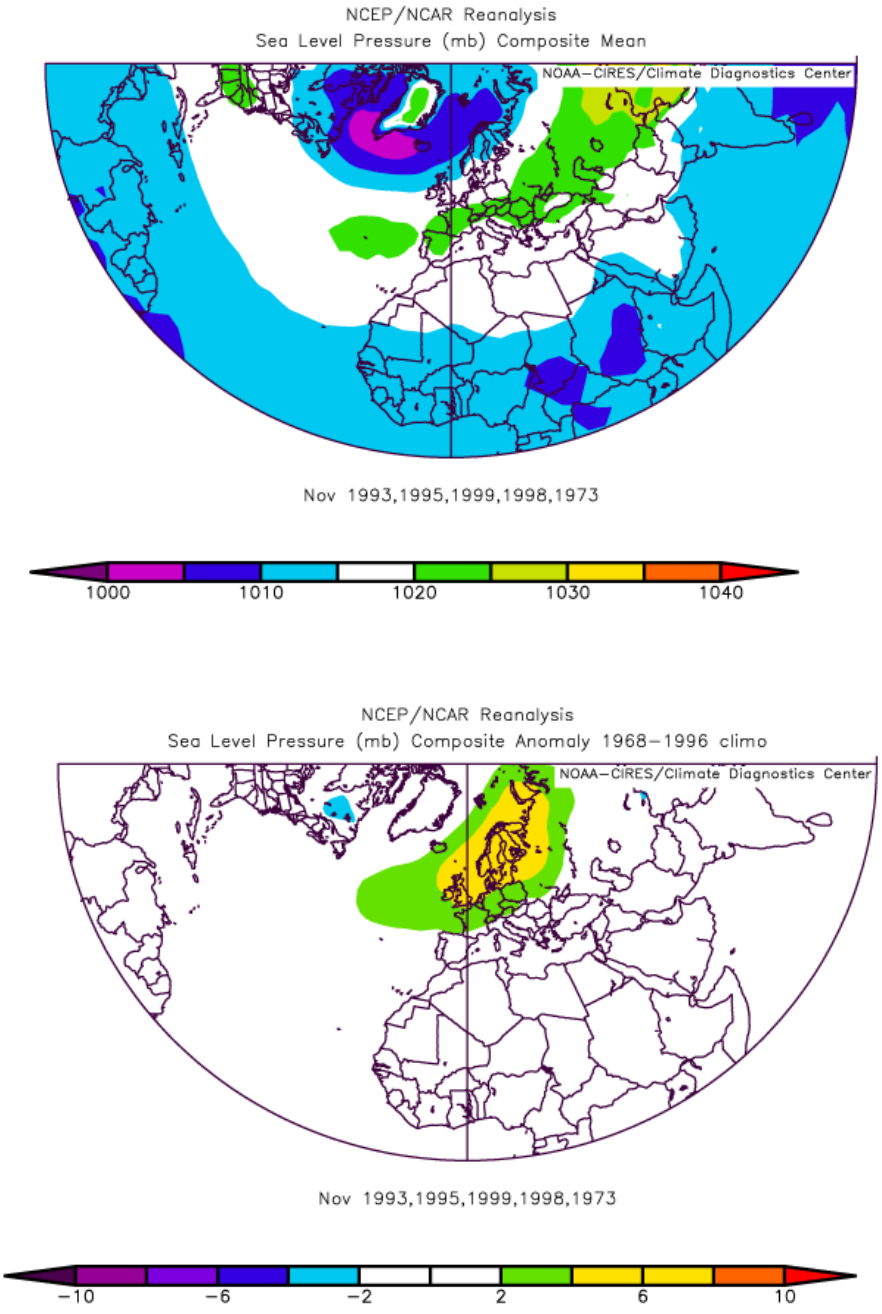

Figure 5.39- November maximum: mean and anomalous sea level pressure.

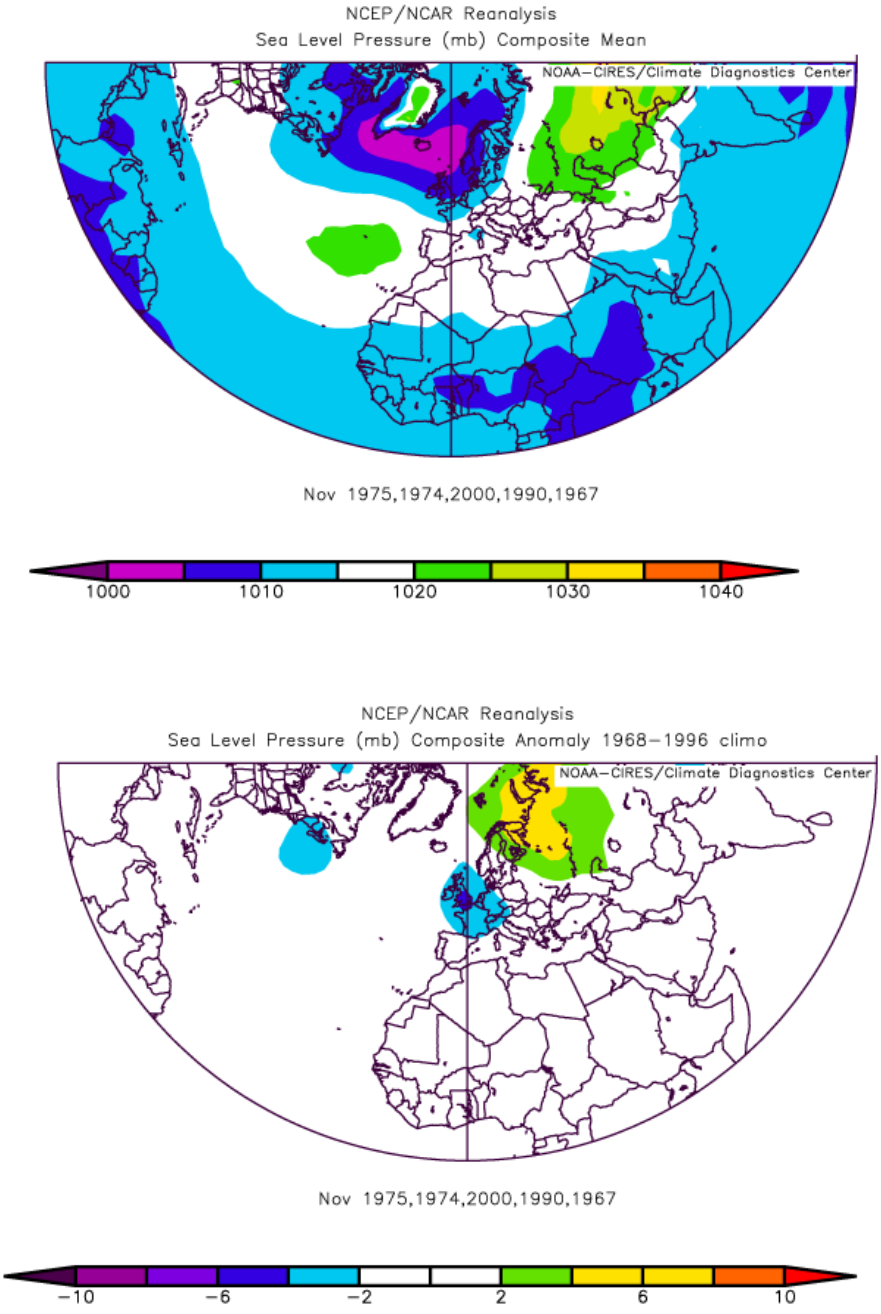

Figure 5.40- November minimum: mean and anomalous sea level pressure.

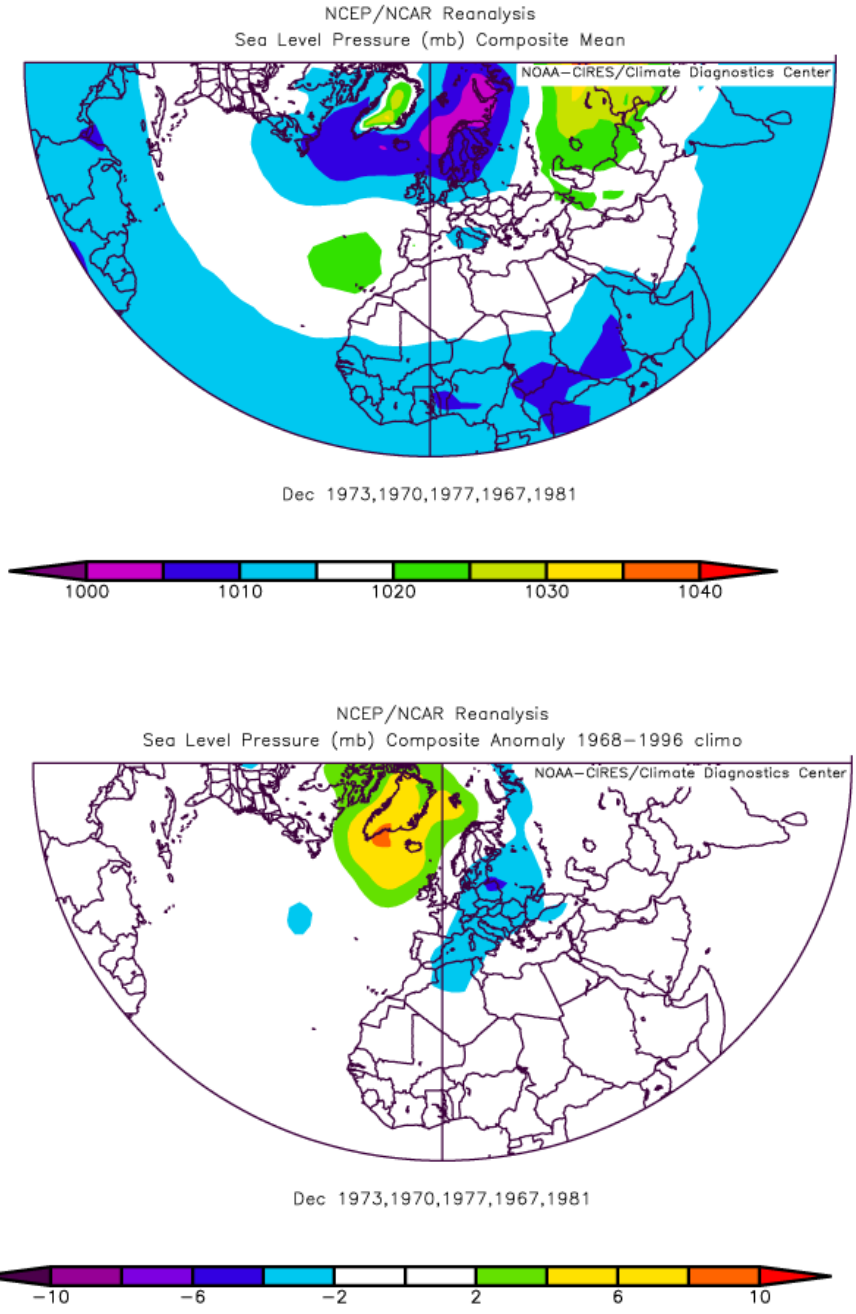

Figure 5.41- December maximum: mean and anomalous sea level pressure.

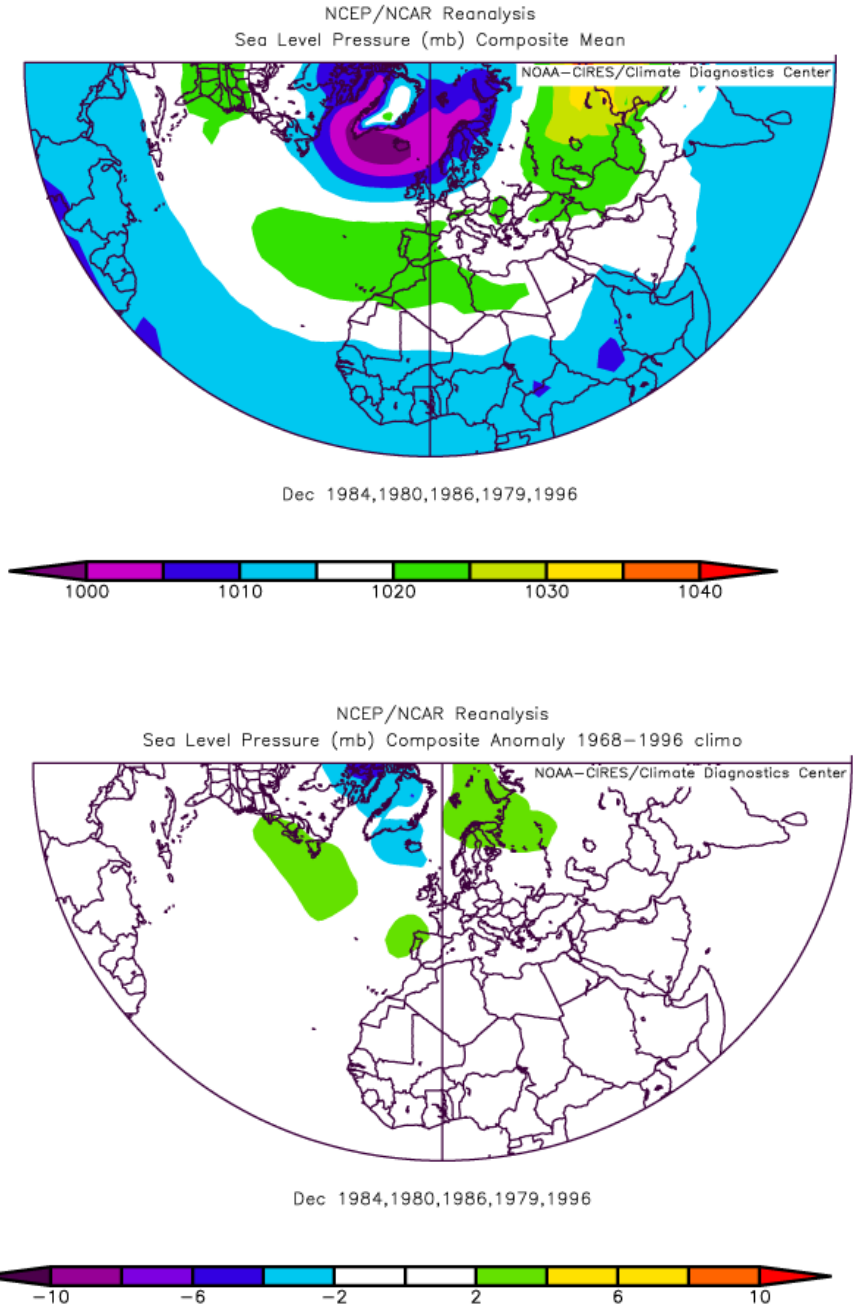

Figure 5.42- December minimum: mean and anomalous sea level pressure.

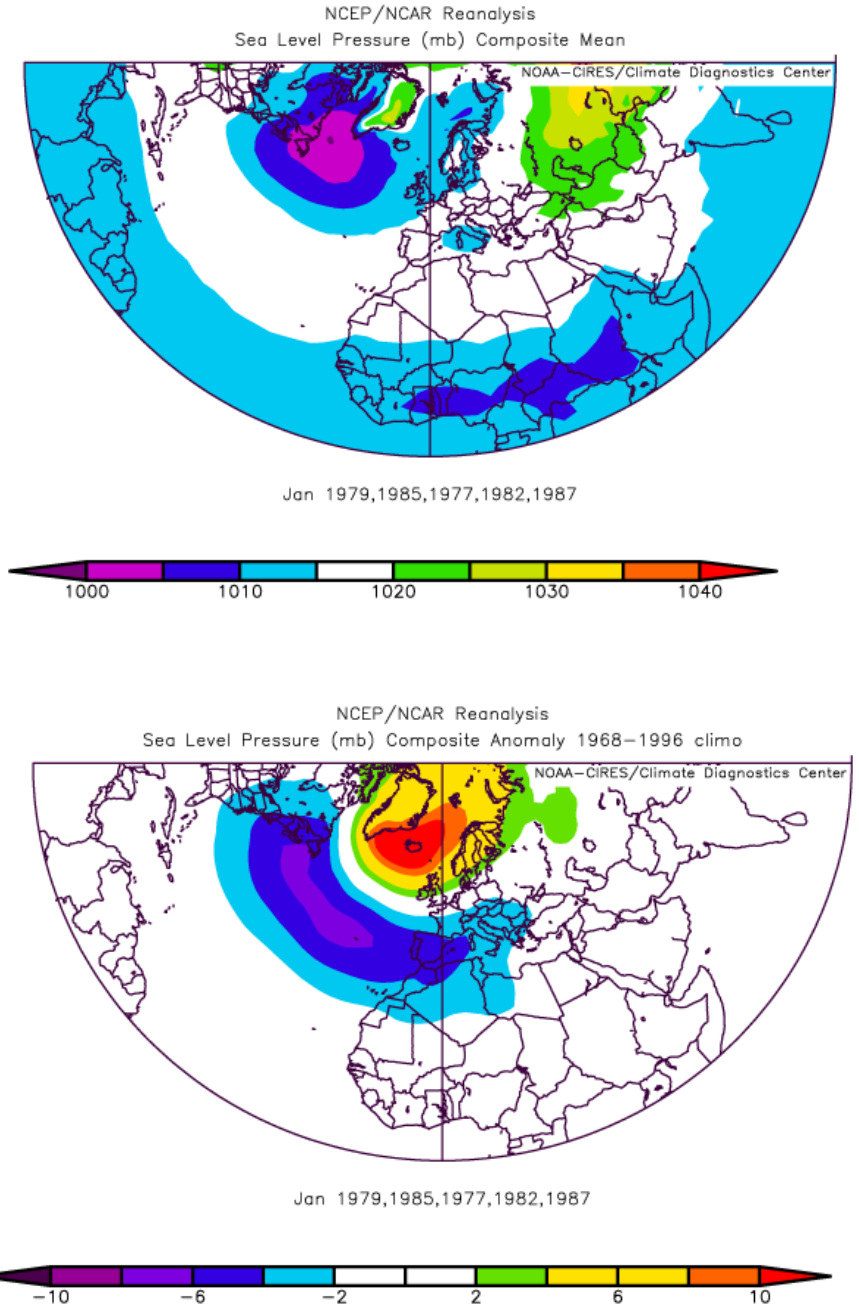

Figure 5.43- January maximum: mean and anomalous sea level pressure.

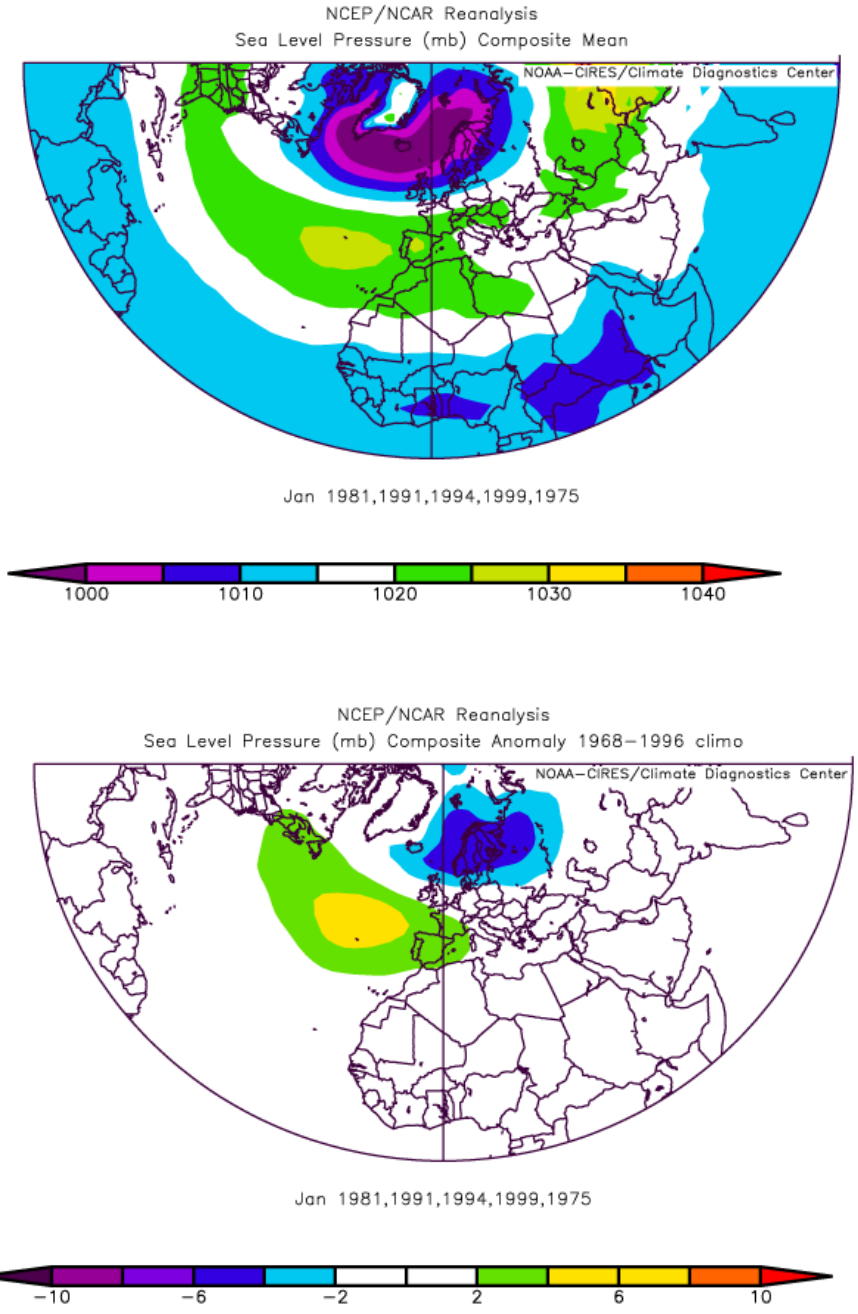

Figure 5.44- January minimum: mean and anomalous sea level pressure.

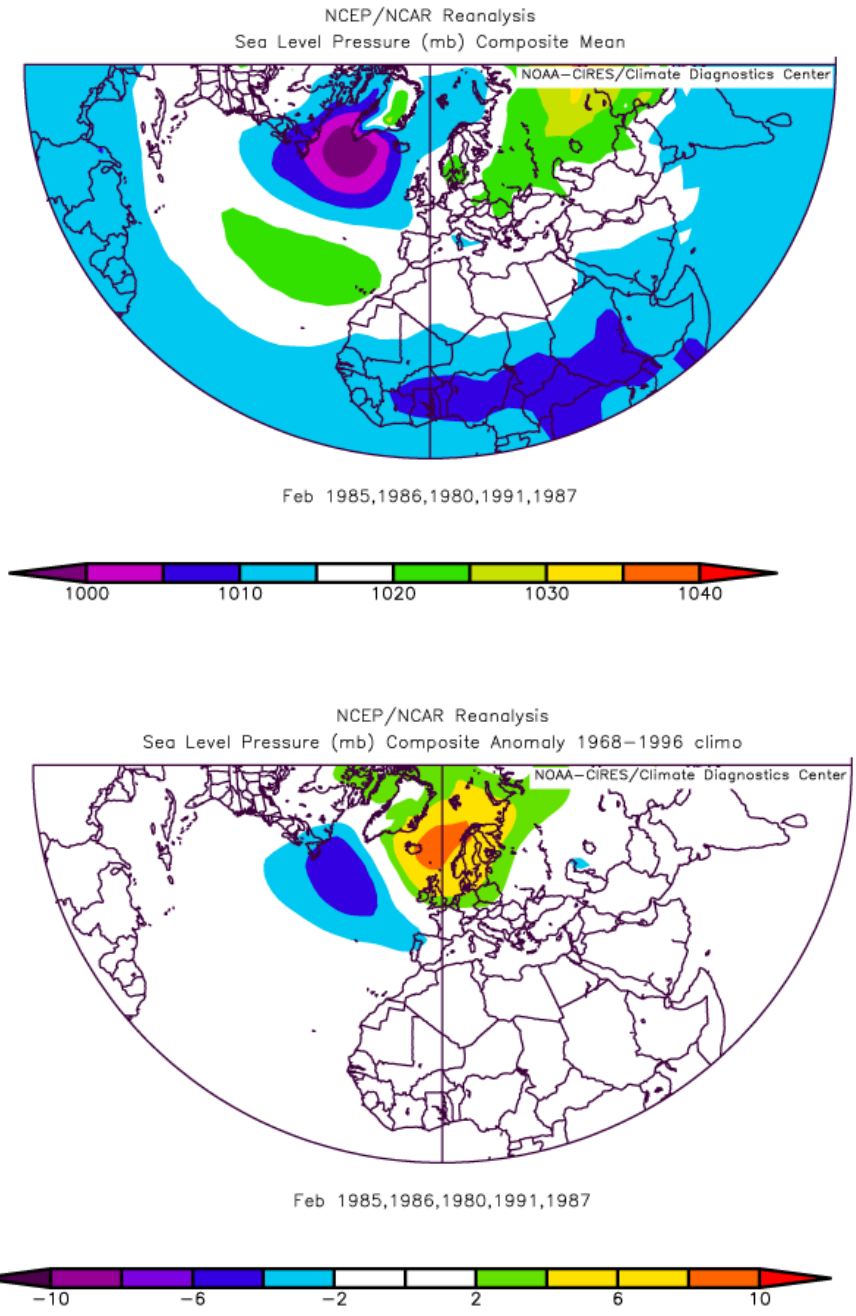

Figure 5.45- February maximum: mean and anomalous sea level pressure.

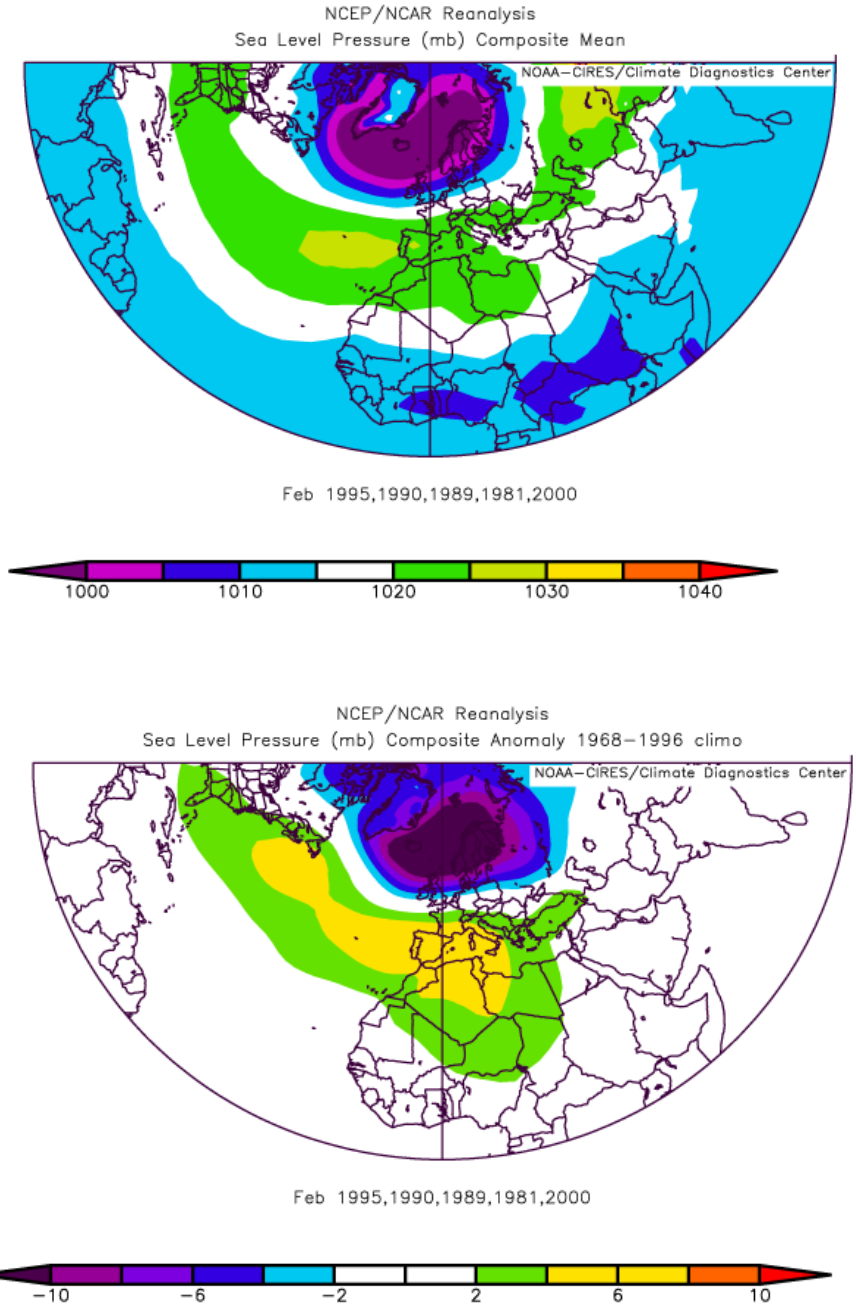

Figure 5.46- February minimum: mean and anomalous sea level pressure.

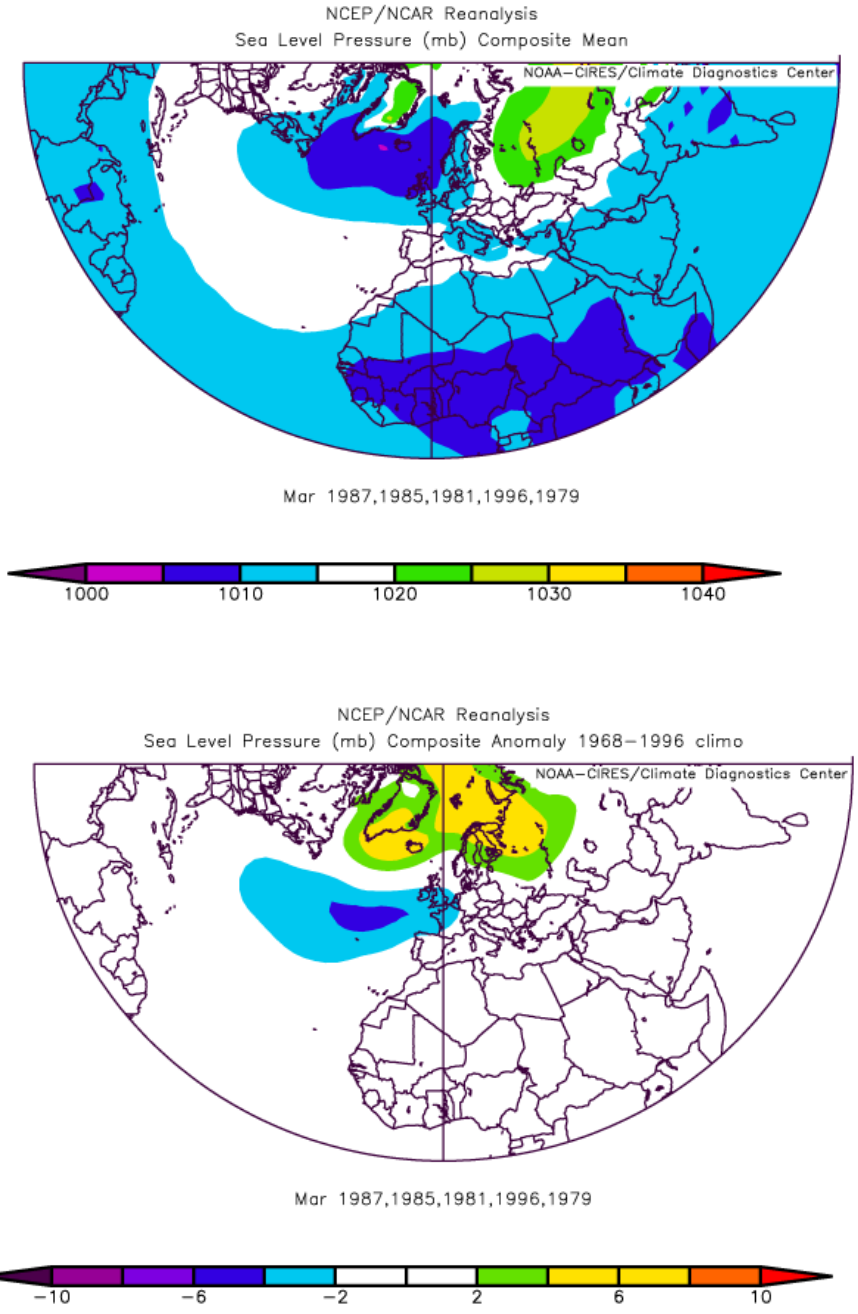

Figure 5.47- March maximum- mean and anomalous sea level pressure.

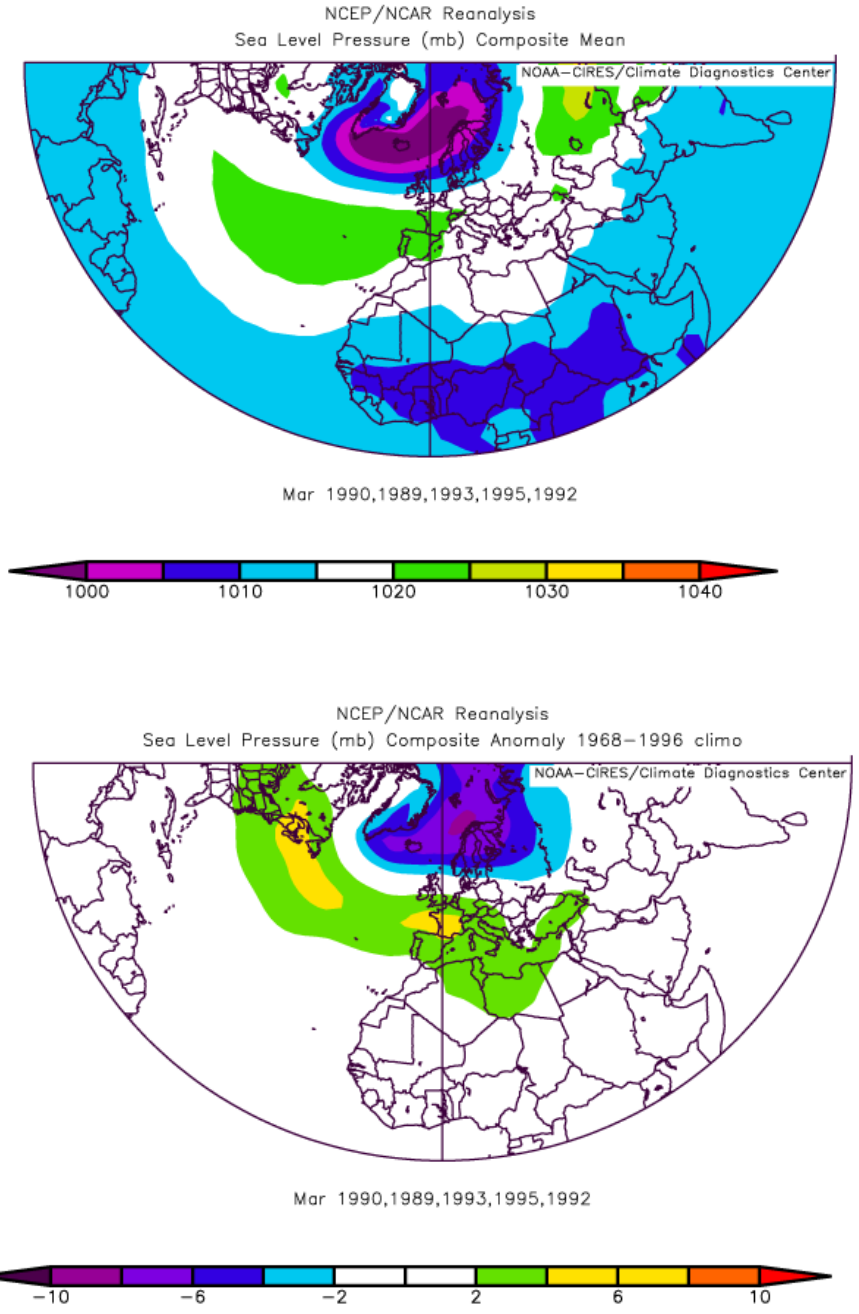

Figure 5.48- March minimum- mean and anomalous sea level pressure.

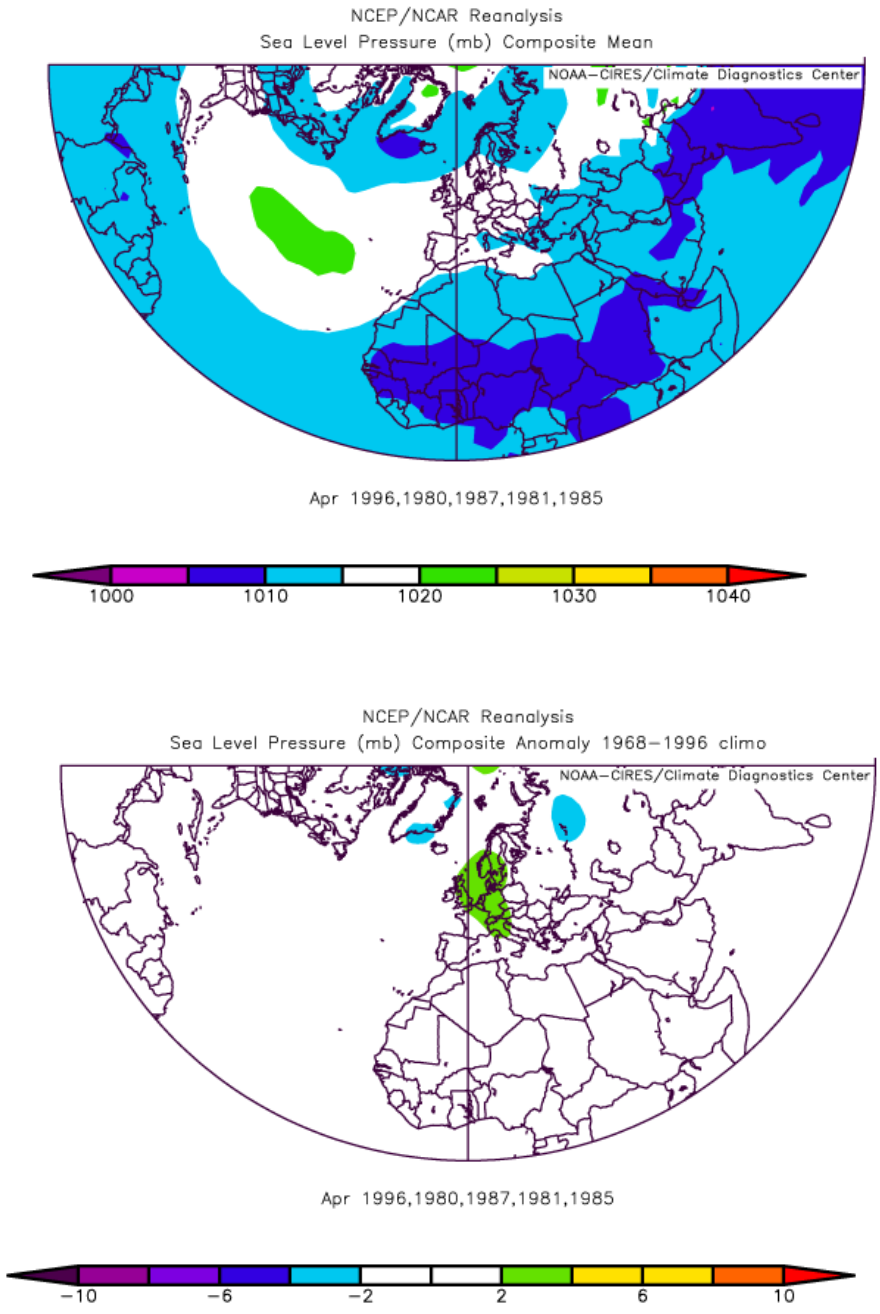

Figure 5.49- April maximum: mean and anomalous sea level pressure.

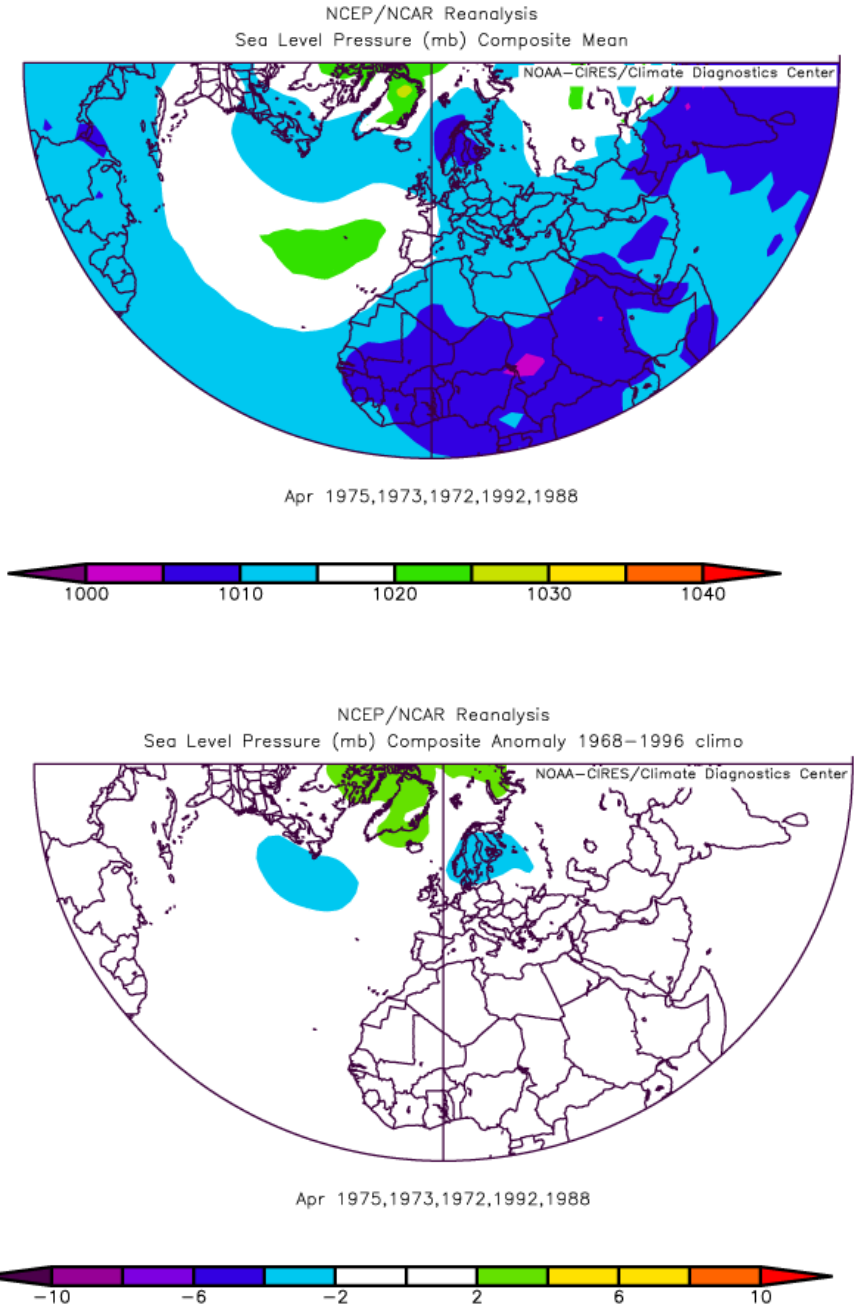

Figure 5.50- April minimum: mean and anomalous sea level pressure.

5.4.3 Sea Surface Temperature:

Figures 5.51-5.62 illustrate the anomalous sea surface temperature distribution during maximum and minimum snowcover extent years. Due to the steady nature of sea surface temperature, analysis of mean temperature distributions for the winter months was not included as little variation in values is evident on a mean month-to-month scale. Anomalous sea surface temperature plots were created for each month for the five largest and five smallest snowcover years, November through April.

During the early winter season including November and December, distribution of temperature anomalies vary. November maximum snowcover extent years (Figure 5.51) display no consistent anomalies, with isolated positive values found across the North Atlantic region. November minimum snowcover extent years (Figure 5.52) have strong positive temperature anomalies off the Scandinavian coast and across the North Atlantic. Weak negative values are evident off much of the coast of Western Europe and North Africa. Stronger positive anomalies are present during December maximum snowcover extent years (Figure 5.53) while no significant departures are evident during this month's minimum snowcover extent years (Figure 5.54). At this point during the region's winter season little snowcover extent is present in Western Europe, especially in coastal areas. For this reason anomalous sea surface temperatures later in the season may be of greater significance and affect snowcover and the length of its extent throughout the study region.

A more homogenous pattern of sea surface temperature anomalies is evident from January's maximum snowcover extent map (Figure 5.55), as below normal sea surface temperatures occur along the northern coast of Europe and

Scandinavia. An isolated area of negative values is also located to the northeast of North America into the Atlantic. The strongest departures on the order of 1ºC however, are located over smaller water bodies including the Baltic, North and Caspian Seas. During minimum snowcover extent years for January (Figure 5.56), the pattern of anomalies is less significant with a substantial area of positive temperatures over the mid-Atlantic region and the Caspian and eastern Mediterranean Seas.

The arrangement of anomalous sea surface temperatures during February maximum years (Figure 5.57) largely resembles that of the previous months with the added strengthening of the negative anomaly located to the east of North America. February minimum snowcover extent years (Figure 5.58) however, display extensive positive temperature departures across the eastern to north Atlantic region and also throughout the North, Baltic and Mediterranean Seas. The presence of such extensive positive temperature anomalies could be a factor contributing to low snowcover extent during the extreme years in question.

During March and into April, the distribution of sea surface temperature anomalies becomes more complex across much of the Atlantic. Some consistent patterns are evident however when considering the maximum versus the minimum snowcover extent maps. March and April maximum snowcover extent years (Figures 5.59 & 5.61), both display negative temperature anomalies along coastal Western Europe and throughout the North, Baltic, Caspian and Mediterranean Seas. Negative values are also evident from both maps across the mid-Atlantic. Positive departure values are present south of Greenland and off the northwestern African coast. The presence of negative sea surface temperature anomalies off the European coast during

large snowcover extent years could suggest that this variable contributes to more persistent snowcover extent throughout the study region.

The pattern is reversed during minimum snowcover extent years with strong positive anomalies across coastal Europe and Scandinavia during March (Figure 5.60) and to a lesser degree in April (Figure 5.62).

These sea surface temperature anomalies are likely related to the strength and phase of the NAO, especially during the mid-and-late winter season. Snowcover, atmospheric and sea surface temperature anomalies are all synergistically associated with each other through a complex set of interactions that represent the coupled ocean-atmosphere system of the North Atlantic.

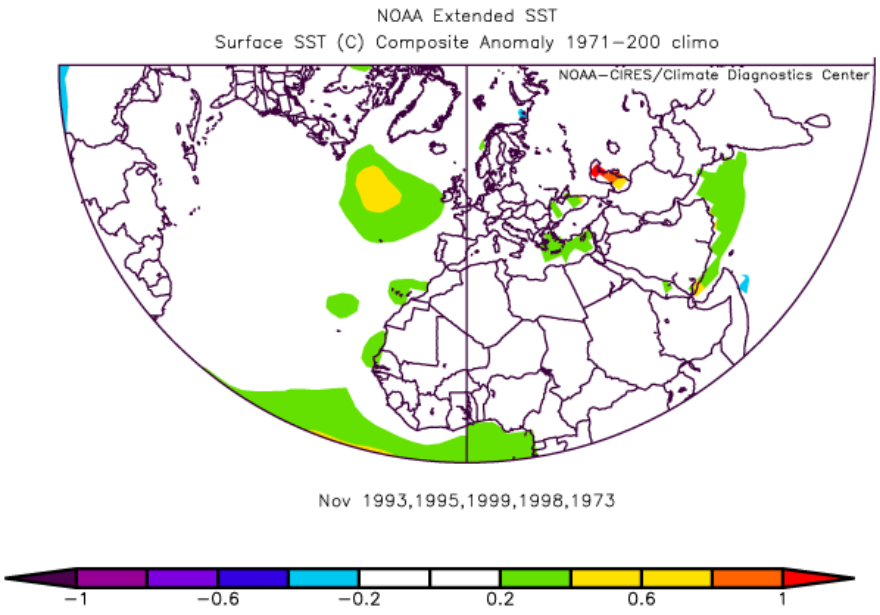

Figure 5.51- November maximum: anomalous sea surface temperature.

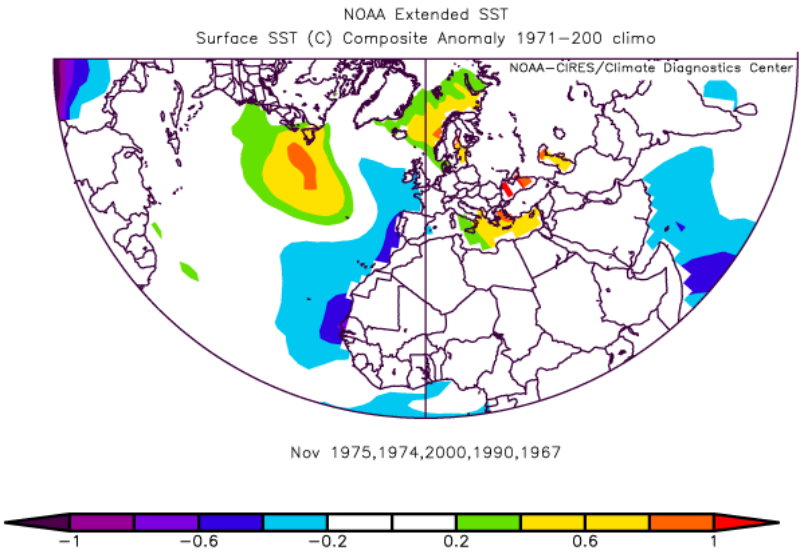

Figure 5.52- November minimum: anomalous sea surface temperature.

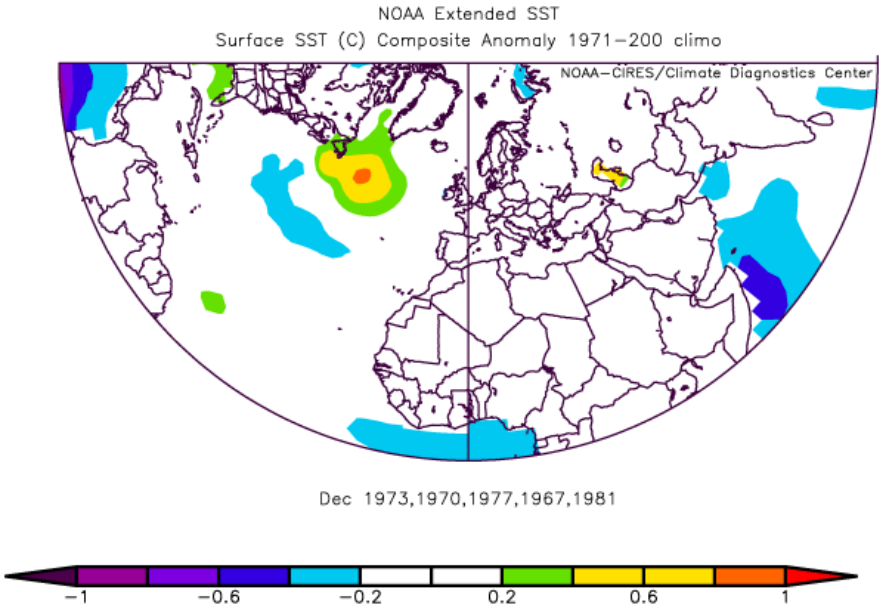

Figure 5.53- December maximum: anomalous sea surface temperature.

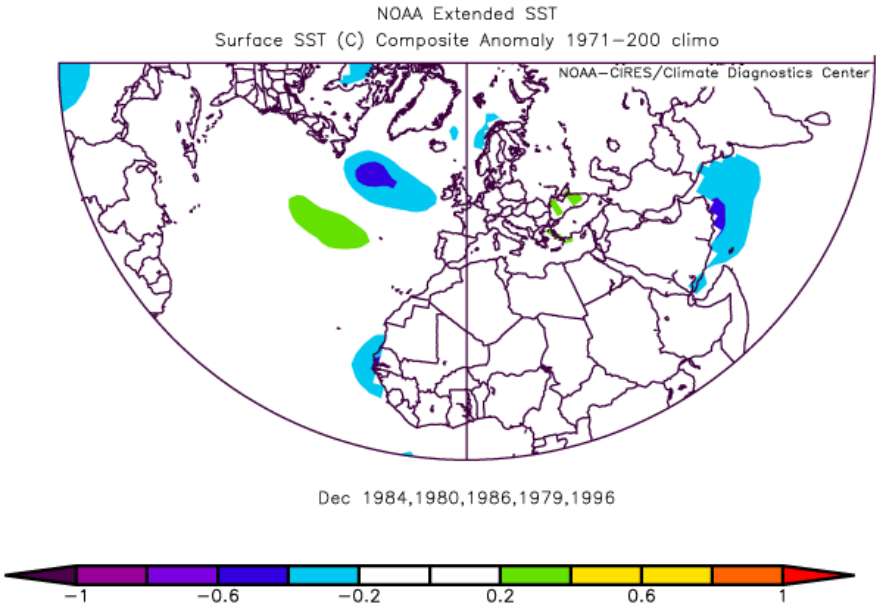

Figure 5.54- December minimum: anomalous sea surface temperature.

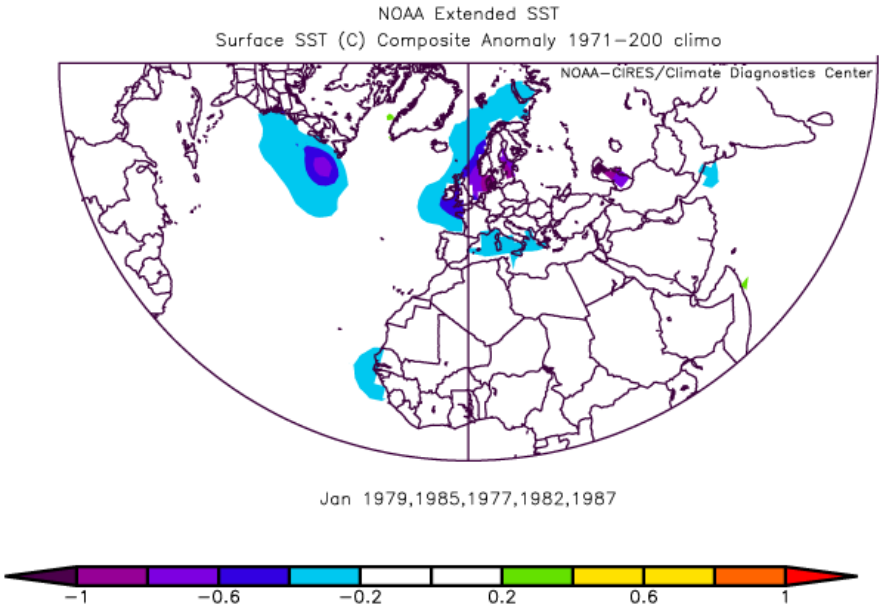

Figure 5.55- January maximum: anomalous sea surface temperature.

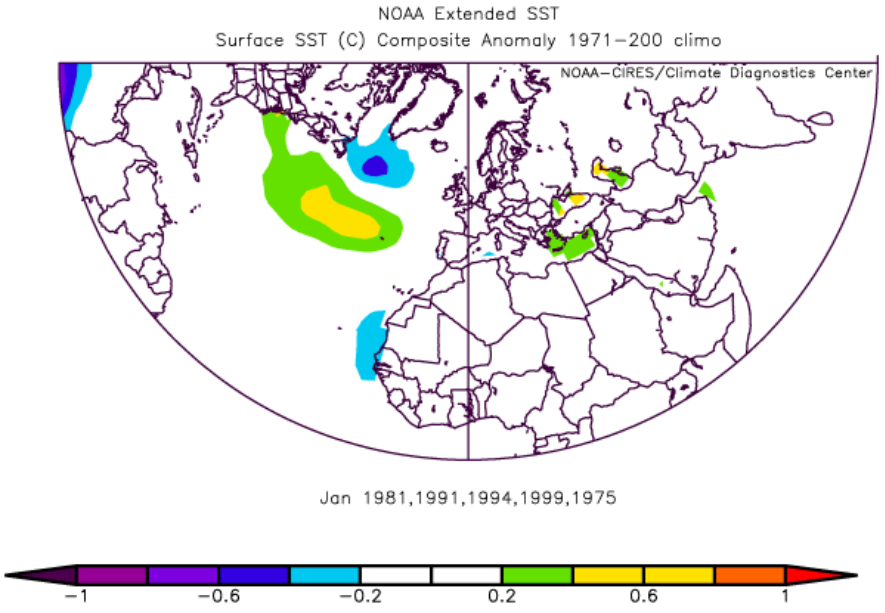

Figure 5.56- January minimum: anomalous sea surface temperature.

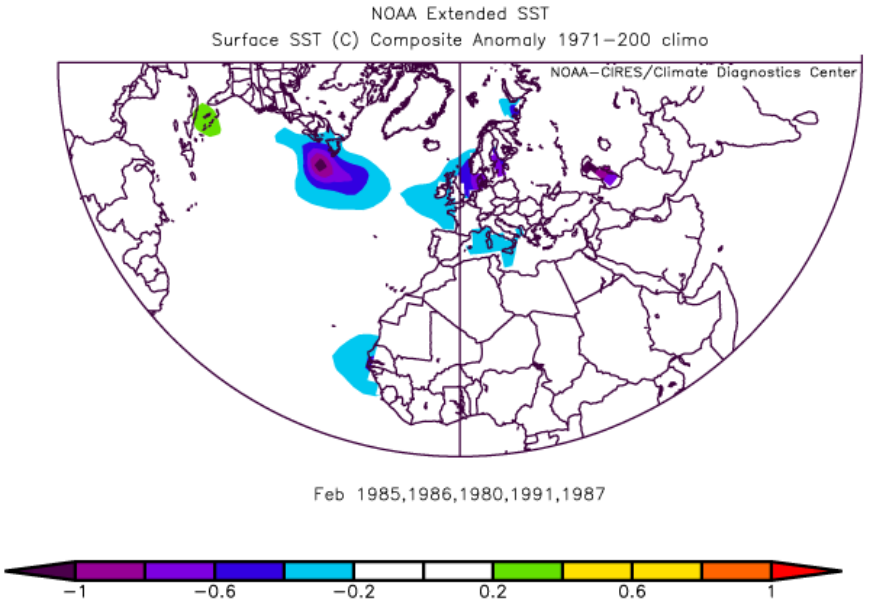

Figure 5.57 - February maximum: anomalous sea surface temperature.

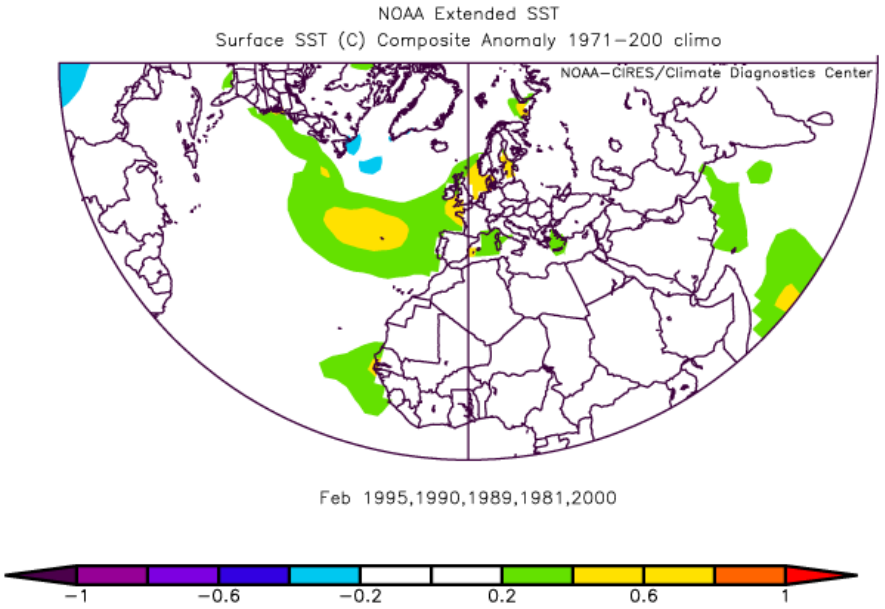

Figure 5.58- February minimum: anomalous sea surface temperature.

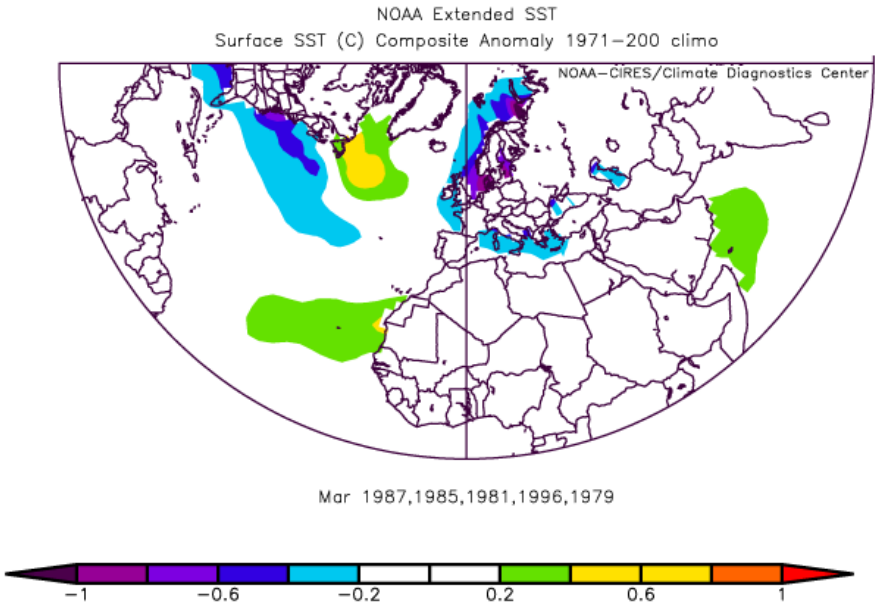

Figure 5.59- March maximum- anomalous sea surface temperature.

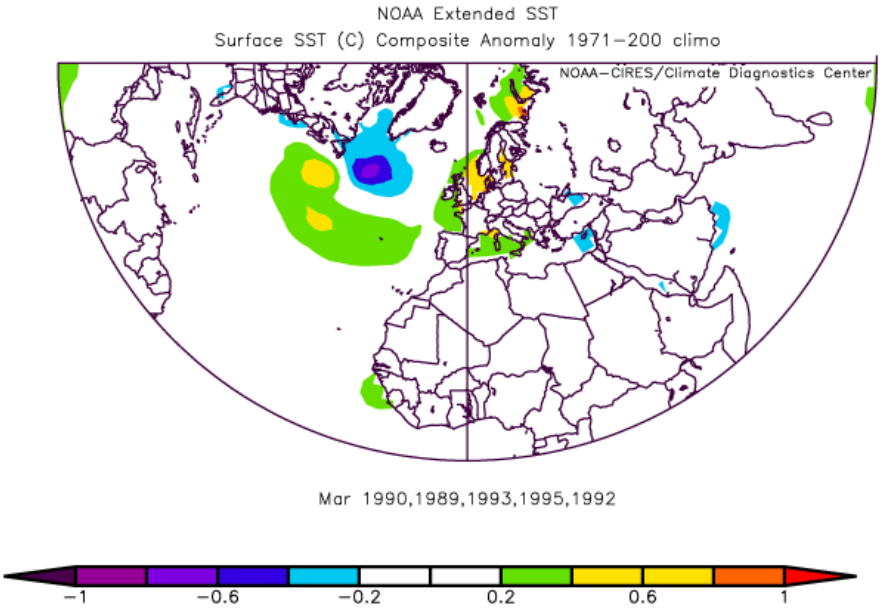

Figure 5.60- March minimum- anomalous sea surface temperature.

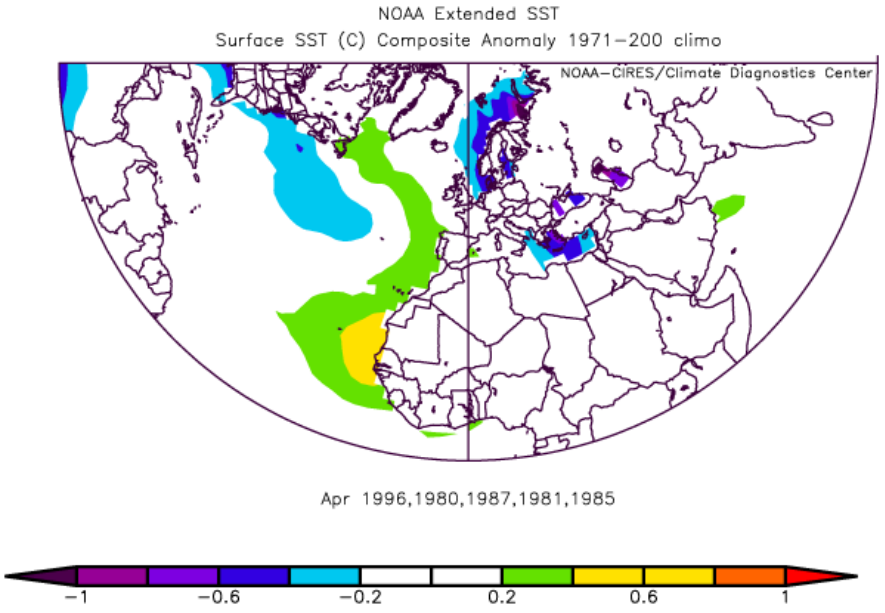

Figure 5.61- April maximum: anomalous sea surface temperature.

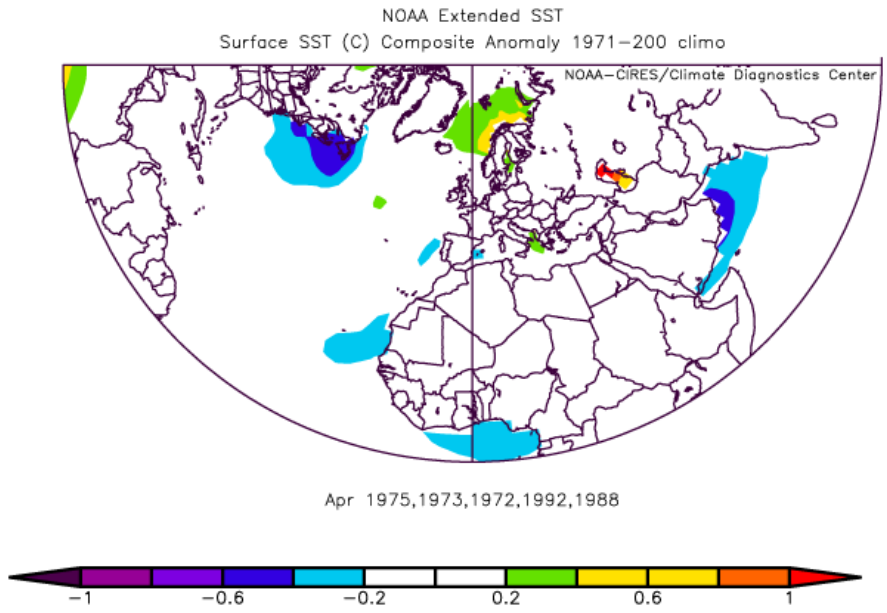

Figure 5.62- April minimum: anomalous sea surface temperature.

Chapter 6

DISCUSSION AND CONCLUSION

6.1 Summary of the annual cycle:

European snowcover variability and extent represents an important component of this region's climate. Analysis addressing the topic of snowcover extent to date has tended to focus on hemispheric or continental scale studies, with the area of Western Europe being routinely considered part of the greater continent, Eurasia. The purpose of this study was to isolate the area of Europe located west of the 60º E meridian and explore this region's snowcover extent record more fully.

From the NOAA Northern Hemisphere snow cover product, data for the region was extracted on both weekly and monthly time scales for the period 1967-2000. Area totals were calculated and the geographic distribution mapped in order to gain an understanding of the annual cycle of snowcover. Great variability within the region's seasonal cycle is found, with snow areas ranging from over 8.5×10^6 km^2 in January to almost no snowcover during summer months. Distribution of snowcover differs across the region; as coverage throughout the north and east is continuous for the majority of winter months, whereas along the coast and to the west, coverage displays greater variability and is ephemeral in nature.

6.2 Snowcover extent and the atmosphere:

Correlation between European snowcover extent totals and other climatic variables were calculated, with the resulting correlation "r" statistic being displayed as contour maps. The relationships between mean monthly snowcover area total and surface temperature, precipitation and sea-level pressure were explored in this way. When considering European snowcover extent and temperature, results indicate that large snowcover areas across the region are associated with below normal surface temperatures over central and Eastern Europe. This is especially evident during January and February, while a meridional correlation pattern develops later in the season implying that colder conditions favor more extensive and persistent snowcover to the east.

A generally negative relationship between precipitation and snowcover is maintained throughout the winter season, with large snowcover extents being associated with lower precipitation values. Colder, dryer air masses would produce lower precipitation values while being more conducive to preserving snow pack in marginal areas. The combined results from both surface temperature and precipitation analysis point towards snowcover extent in Europe being primarily temperature dependent as colder winter temperatures are linked with greater snowcover even though this results in cold and dry air masses and therefore less total precipitation. Therefore, snowcover extent and total snow mass (total water equivalent) may not be directly related to one another.

Sea-level pressure and snowcover correlations demonstrate significant findings, as a considerable link between snowcover area and the NAO is implied. A distinctive and well organized north/south di-pole pattern is present from the correlation analysis of these two variables. During mid-winter (January and February),

large positive values exist over the North Atlantic and throughout northern Europe while negative values are present to the south. The distribution of these values implies a decreased pressure gradient across the North Atlantic region, with a weakened Icelandic Low and Azores High, synonymous with the negative phase of the NAO. With this weakened gradient, fewer storms cross the Atlantic to Western Europe, resulting in more meridional flow, and colder temperatures across much of western and central Europe.

This relationship can be seen again when considering the extreme extent analysis for maximum and minimum snowcover years. Composites of mean and anomalous 500-hPa geopotential heights during winter months illustrate upper level flow patterns conducive to large and small snowcover extent conditions. When considering the maximum snowcover year's composite, trough and ridge location throughout these months could support snowcover development early in the winter season or persistent coverage later in the season through cold air advection. This is illustrated by the presence of a deep trough over central Russia from the November and December maximum snow anomaly composites (Figures 5.27 & 5.29), and is visible again in April (Figure 5.37). During mid-winter months (January and February), evidence of an NAO signal is clearly identifiable as large positive height anomalies are present to the north while negative values exist to the south (Figures 5.31 & 5.33). A reversal of mean and anomaly height patterns emerge during minimum snowcover years, with height departure locations supporting positive NAO phase conditions during mid-winter months. Similarly in both the early and later winter season, sizable ridging over Eastern Europe into western Russia provides

opportunity for warm air advection from the south which could inhibit early season snowcover development and encourage late season rapid snow pack ablation.

Sea-level pressure composite analysis during maximum and minimum extent years once again supports the suggested link between European snowcover and the NAO. Early season pressure distribution shows relatively weak organization of both mean and anomalous sea-level pressure. By January and February however, pressure departures display robust association between NAO negative and positive phases and maximum and minimum extreme snowcover years. The characteristic di-pole pattern weakens during March and by April no association is apparent.

Results from sea surface temperature composite analysis were limited to those based on anomaly values only, as little variation in mean temperature is evident on a month-to-month basis. No significant departures are present during the early winter months. By January and into February anomalies become more consistent, with maximum and minimum composites being associated with negative and positive temperature departures respectively, along the northern European coast and interior water bodies. Late season sea surface temperature anomalies become more complex throughout the region, however persistent negative (positive) departures exist off the coast of Western Europe during March and April during maximum (minimum) snowcover extent years. These departures could support increased cold/warm air advection and assist in either the maintenance or ablation of late season snow extent, especially throughout marginal snowcover regions.

6.3 European snowcover and the NAO:

The relationship between European snowcover and a variety of climatic variables has been explored. This was a necessary step in order to gain a greater

understanding of atmospheric conditions throughout the region and possibly identify factors contributing to variability in snowcover extent. Implications of the relationship between European snowcover and the NAO are a persistent theme emerging from the analysis described above. When this relationship is explored further and NAO indices available from the NOAA Climate Prediction Center (http://www.cpc.ncep.noaa.gov/) are utilized, strong agreement between snowcover area totals during January and February and the corresponding NAO index value is evident. For the duration of this study, years experiencing above average mid-winter (January and February) snowcover extent coincide with negative NAO index values, while below average receipts are concurrent with positive values. This association is accurate in over 80% of all cases. Examples of the three most negative and three most positive NAO years for January and February are displayed in Table 6.1 along with the associated snowcover area anomalies for those months (January and February together). As expected, significantly above average snow extent areas occurred during negative NAO years while well below average extents existed during positive NAO years.

Table 6.1- Three largest and smallest NAO years and associated snowcover area anomalies for January and February (x 10^6 km^2).

Negative NAO Cases:			Positive NAO Cases:		
Year	**NAO**	**Snow Anomaly**	**Year**	**NAO**	**Snow Anomaly**
1969	-1.33	+1.07	**1989**	1.70	-4.19
1977	-0.77	+0.17	**1990**	1.30	-4.61
1985	-0.63	+5.94	**1995**	1.10	-3.45

6.4 Future Research:

This study has comprehensively investigated the topic of European snowcover as measured by the NOAA Northern Hemisphere snowcover product and demonstrated the distinctive nature of its annual cycle, separate to that of the Eurasian record. Factors governing variability in snow extent throughout the study region include availability of moisture and atmospheric circulation across the North Atlantic, but of primary importance is winter temperature.

As the dataset used in this study matures, greater understanding of European snowcover variability and extent will be apparent. This project was limited to a 33-year period of record that is too brief from which to draw any substantial conclusions about decadal tendencies of snowcover throughout the region.

Strong association between snowcover in Europe and the NAO emerged repeatedly, which suggests significant links between this area's snowcover extent and large-scale circulation in the North Atlantic. Due to this strong relationship, especially during January and February, reconstruction of European snowcover extent using NAO indices could be possible. With the extension of the NAO index back to 1821 (Jones et al. 1997), the relationship between snowcover in Europe and this teleconnection could provide new insight into the historical record of snow extent in this region, and as a significant tool in climate change assessment in general.

Further study involving the possible relationship between snowcover extent in eastern North America and subsequent European snowcover extent could prove significant. Preliminary modeling studies by Klingaman (2005) suggest a linkage between eastern North American snowcover and the NAO during mid-winter months. Further modeling and observational experiments of these relationships would

help in understanding the complex air, ocean, land interactions across the North Atlantic.

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