Attribution of Seasonal and Regional Changes in Arctic Moisture Convergence

NATASA SKIFIC
Department of Atmospheric Sciences, Rutgers, The State University of New Jersey, New Brunswick, New Jersey

JENNIFER A. FRANCIS
Institute of Marine and Coastal Sciences, Rutgers, The State University of New Jersey, New Brunswick, New Jersey

JOHN J. CASSANO
Department of Atmospheric and Oceanic Sciences, University of Colorado, Boulder, Colorado

(Manuscript received 5 September 2008, in final form 23 April 2009)

ABSTRACT

Spatial and temporal changes in high-latitude moisture convergence simulated by the National Center for Atmospheric Research Community Climate System Model, version 3 (CCSM3) are investigated. Moisture convergence is calculated using the aerological method with model fields of specific humidity and winds spanning the periods from 1960 to 1999 and 2070 to 2089. The twenty-first century incorporates the A2 scenario from the Special Report on Emissions Scenarios. The model’s realism in reproducing the twentieth-century moisture convergence is evaluated by comparison with values derived from the 40-yr ECMWF Re-Analysis (ERA-40). In the area north of 75°N, the simulated moisture convergence is similar to observations during summer, but it is larger in winter, spring, and autumn. The model also underestimates (overestimates) the mean annual moisture convergence in the eastern (western) Arctic. Late twenty-first century annual, seasonal, and regional changes are determined by applying a self-organizing map technique to the model’s sea level pressure fields to identify dominant atmospheric circulation regimes and their corresponding moisture convergence fields. Changes in moisture convergence from the twentieth to the twenty-first century result primarily from thermodynamic effects (~70%), albeit shifts in the frequency of dominant circulation patterns exert a relatively large influence on future changes in the eastern Arctic. Increased moisture convergence in the central Arctic (North Atlantic) stems mainly from thermodynamic changes in summer (winter). Changes in the strength and location of poleward moisture gradients are most likely responsible for projected variations in moisture transport, which are in turn a consequence of increasing anthropogenic greenhouse gas emissions as prescribed by the A2 scenario.

1. Introduction

One of the keys to diagnosing the Arctic’s complex climate system and predicting its future trajectory is understanding the processes that drive the hydrologic cycle of high latitudes. Observations and some modeling experiments indicate that the Arctic’s freshwater cycle is not only sensitive to global climate change, but also that the high-latitude regional changes in hydrology will affect the global climate (e.g., Manabe et al. 1991; Manabe and Stouffer 1994, 1995, 1997; Min et al. 2008). These studies suggest that the enhanced warming in the Arctic—owing to positive feedbacks involving snow, ice, water vapor, and clouds—may decrease the salinity of high-latitude oceans, both through increased runoff and ice melt, and enhance high-latitude precipitation. The oceanic thermohaline circulation may then weaken, which would eventually affect global temperatures. Lawrence and Slater (2005) find that increased temperature and unfrozen moisture in the Arctic soil will result in a northward expansion of shrubs and boreal forests, leading to a reduction in surface albedo (Betts 2000; Chapin et al. 2005) and further melt. Links between Arctic hydrology and human-induced environmental change have been demonstrated in a number of studies (e.g., ACIA 2005).
Net precipitation is a particularly valuable measure for assessing Arctic change because it combines both precipitation and evaporation. Its determination in high latitudes, however, is often hampered by the low density of observing stations, harsh Arctic conditions that frequently lead to station failure, errors in gauge catchment of solid precipitation (Yang 1999; Yang and Ohata 2001; Cherry et al. 2007), and varying measurement techniques (Mekis and Hogg 1999). The so-called aerological approach used in this study circumvents these problems. Moisture convergence is computed from wind and precipitable water profiles as the change in the advection of vertically integrated water vapor, and it has been shown to be a good approximation of net precipitation in the Arctic (Serreze et al. 2005, 2006).

Changes in the net precipitation in high latitudes were investigated by Cassano et al. (2007), who used forecast values of precipitation and evaporation from an ensemble of 15 GCMs. They found that over 75% of the projected increase in net precipitation is due to changes in thermodynamic processes. Emori and Brown (2005) explored projections for extreme precipitation and also found that changing dynamics plays a secondary role to thermodynamics in high latitudes. Finnis et al. (2007) analyzed precipitation in a five-member ensemble from the National Center for Atmospheric Research (NCAR) Community Climate System Model, version 3 (CCSM3) in the twenty-first century and concluded that global changes in thermodynamics would lead to large precipitation increases over high latitudes. These studies focused on the Arctic region as a whole using the “middle of the road” Special Report on Emission Scenarios (SRES) A1B scenario for greenhouse gas emissions (Nakicenovic and Swart 2000). However, according to Rahmstorf et al. (2007), this projection underestimates actual emission rates. In this study we instead use the A2 scenario, or one of the “worst case scenarios,” which now appears to be most similar to the observed trends. We further augment previous studies by focusing on net precipitation \((P - E)\) derived from the more reliable aerological approach, by comparing and contrasting changes in \(P - E\) during each season, and by analyzing regional differences in these projected changes. The self-organizing maps (SOM) approach applied by Cassano et al. (2007) is used in this study to identify predominant mechanisms for the changes. This work also extends the investigation by Skific et al. (2009), which explains the SOM technique in detail as well as its application to the diagnosis of horizontal moisture transport into the Arctic across 70°N.

Climate models provide the best available tool to help understand processes of past variability and project future change. The CCSM3 is a state-of-the-art GCM that realistically simulates the Arctic atmospheric circulation and hydrologic cycle (Cassano et al. 2006, 2007; Chapman and Walsh 2007). A brief summary of the model properties and recent improvements is provided in section 2. Daily fields of moisture convergence are derived from daily model output, and the realism is evaluated by comparing the annual- and seasonal-mean fields with those calculated from the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40). These results appear in section 3. Section 4 briefly describes the application of the SOM method devised by Kohonen (2001) to CCSM3 and ERA-40 sea level pressure (SLP) fields to create a matrix of characteristic SLP patterns and also describes how these circulation regimes are related to net precipitation. The SOM technique is selected for this analysis because it reduces large datasets into representative, fundamental clusters organized in a matrix of 2D fields—geographic patterns in this case—that are expressed in a visual and intuitive rendering. In section 5 we apply an approach devised by Cassano et al. (2007) to attribute the projected change in moisture convergence to factors related primarily to dynamics, thermodynamics, and a combination of the two. Finally we contrast annual and seasonal changes in various regions of the Arctic.

2. Data sources and methods

a. Datasets

The model output used in this study includes six-hourly, multilevel fields of specific humidity, as well as zonal and meridional winds from a single run of the NCAR CCSM version 3.0. Fields were obtained from the Program for Climate Model Diagnostics and Inter-comparison (PCMDI) at the Lawrence Livermore National Laboratory. The atmospheric module of this version of CCSM3 has 26 vertical levels, a top at 2.2 hPa, 13 layers below 200 hPa, and a horizontal resolution of \(\sim 1.4^\circ\). The twentieth-century experiment (20C3M) includes the direct effect of sulfates (Smith et al. 2001, 2005) and also incorporates ozone (Kiehl et al. 1999) and solar (Lean et al. 2002) forcing. The model includes observed concentrations of \(\text{CO}_2\), \(\text{CH}_4\), \(\text{N}_2\text{O}\), and CFCs, and effects of volcanic eruptions are parameterized (Ammann et al. 2003). The twenty-first century simulation is forced by the SRES A2 scenario after 1990 to the end of the twenty-first century, by which time the carbon dioxide concentrations reach 850 ppm.

The original 6-hourly PCMDI data were interpolated from the hybrid sigma-pressure vertical coordinates to pressure coordinates and reduced in size by subsampling the region north of 60°N and to daily resolution (1200 UTC only). Horizontal moisture transport was calculated for
five tropospheric layers (1000–850, 850–700, 700–500, 500–400, and 400–300 hPa), as moisture is sparse above 300 hPa. The time slices used in this study span periods of 1960–99 in the twentieth century and 2070–89 from the SRES A2 scenario. The latter period is chosen to be consistent with results from the Arctic Climate Assessment Report (ACIA 2005; see www.acia.uaf.edu) to represent the mature greenhouse state (Serreze and Francis 2006).

Sea level pressure fields are also extracted for the same regionally and seasonally, under the assumption that the basic physics of the model are correct in responding to the forcing dictated by the A2 SRES scenario.

Daily output from the ERA-40 reanalysis (Uppala et al. 2005) was used to validate the model's performance for the twentieth century. Profiles of zonal and meridional winds and specific humidity as well as SLP fields were interpolated to the same grid as CCSM3. The aerological method was applied to derive the horizontal moisture convergence. The absolute accuracy of wind and moisture profiles is not known owing to a dearth of independent rawinsonde data, but the assimilation of a variety of conventional and satellite information is expected to produce fields of state variables that are realistic (Cullather et al. 2000; Serreze et al. 2005, 2006).

b. Self-organizing maps

A self-organizing map (SOM) algorithm is a neural network technique that attempts to reduce the dimensions of a large dataset by organizing it into a two-dimensional array or a matrix (Kohonen 2001). The dataset used for the SOM analysis in this study consists of a time series of 2D fields of SLP over the Arctic from both ERA-40 and CCSM3. The SOM algorithm organizes the daily fields into clusters of similar maps by identifying SLP patterns that represent the range present in the original dataset. The moisture convergence results from the net transport of precipitable water into or out of a column and is equivalent to net precipitation when assessed over a period of 60°C.

Although the measure of similarity between the data and the reference vector is linear, the iterative training procedure allows the SOM to account for the nonlinear data distributions, as the distances between nodes can vary depending on the significance of differences between them (Hewitson and Crane 2002). The nonlinear approximation of the data space is therefore a great advantage of the method compared to some other approaches (Reusch et al. 2005). For further detail, see Skific et al. (2009) and Cassano et al. (2007).

3. Comparison of ERA-40 and CCSM3 moisture convergence fields

The moisture convergence results from the net transport of precipitable water into or out of a column and is equivalent to net precipitation when assessed over a
period of several months. It is computed using the “aerological” approach (Serreze and Barry 2005) as

\[ \mathbf{V} \cdot (Q_k \mathbf{V}_k), \]

where \( Q_k \) is the precipitable water in a layer defined as

\[ Q_k = \frac{1}{g} \int_{p_1}^{p_2} q \, dp, \]

and \( \mathbf{V}_k \) is the wind velocity in layer \( k \). Cloud liquid water storage and moisture transport across the tropopause are neglected, as they are usually small factors in the column moisture budget in polar conditions (Groves and Francis 2002). Total moisture convergence in the tropospheric column is derived by summing the convergence in all layers.

The long-term, annual-mean moisture convergence derived from ERA-40 and CCSM3 during the twentieth century is presented in Fig. 1. Overall the model result is similar to that derived from ERA-40, although some regional differences are evident. Values along the east coast of Greenland and around Iceland, as well as over the south coast of Alaska, are higher in ERA-40 than in CCSM3, partially due to the lower spatial resolution of the model. The long-term mean values of moisture convergence from the model and observations for the twentieth century in the various regions shown in Fig. 2 are given in Table 1. Values from the model that are significantly higher or lower than those from ERA-40 at a 95% confidence level are highlighted in bold italic. In general the model underestimates moisture convergence in the eastern Arctic (Atlantic sector, Barents and Kara Seas) relative to the reanalysis, but significantly overestimates it in the western Arctic (Laptev, East Siberian, Chukchi, and Beaufort Seas). In the Laptev and East Siberian Seas, the model moisture convergence is about 18% and 39% higher, and differences become more pronounced in the Chukchi and Beaufort Seas, where the model values are double those in ERA-40. These results are consistent with conclusions by Finnis et al. (2009a,b), who found that modeled Mackenzie River basin cyclones are too intense, too persistent, and/or occur too frequently.

A comparison of the modeled and reanalysis moisture convergence fields by season is presented in Fig. 3. The negative values in the Barents Sea and south of Svalbard that appear in both the CCSM3 and ERA-40 during nonsummer seasons are associated with large evaporation rates owing to a strong temperature contrast between open water and the cold, dry air above. Maximum (minimum) moisture convergence in most areas occurs during summer (winter), while the regions east of Greenland and along southern Alaska have a cold-season maximum and warm-season minimum. The summer maximum over the central Arctic is related to cyclones penetrating deeper into the Arctic Ocean (Serreze and Barry 2005). Negative values of moisture convergence over Eurasia in summer result from evaporation exceeding precipitation. Drying of the land surface during summer

![Fig. 1. Long-term annual-mean moisture convergence (cm month\(^{-1}\)) for the twentieth century from (a) ERA-40 and (b) CCSM3.](image-url)
leads to greater warming than over sea ice where temperatures are confined to the melting point. These contrasts increase baroclinicity in the summer Arctic, which is usually also enhanced by steep coastal orography (Serreze and Barry 2005). These conditions favor cyclogenesis over northeastern Eurasia and Alaska/Yukon. Northward-migrating depressions often generate precipitation in the central Arctic during summer. Another pathway of summer cyclones is from the relative weak North Atlantic storm track (Reed and Kunkel 1960). Areas near Iceland and east of Greenland experience maximum moisture convergence in the autumn and winter in conjunction with the well-defined storm track.

Table 2 summarizes the twentieth-century seasonal and regional differences in moisture convergence between ERA-40 and CCSM3. Model values of summer moisture convergence over the central Arctic are similar to those from ERA-40. In the autumn, winter, and spring seasons, however, the model moisture convergence over the central Arctic exceeds that from ERA-40 by 15%, 32%, and 59%, respectively. In the North Atlantic, moisture convergence from the model is most similar to that from ERA-40 in spring, when CCSM3 values are lower by 18%. Differences are more pronounced in the autumn, winter, and summer when modeled moisture convergence is lower than reanalysis values by 39%, 39%, and 29%, respectively. In the Barents Sea, differences between the model and the reanalysis are most pronounced and statistically significant at the 95% confidence level in winter (spring), when moisture convergence in the model is lower (higher) than the reanalysis by 0.77 (0.68) cm month$^{-1}$. They are most similar in summer. In the Kara Sea the model is lower by about 23% in summer and autumn, while in spring the model exceeds the reanalysis value by about 14%. Differences are the smallest in the winter. In the Laptev, East Siberian, Chukchi, and Beaufort Seas, the model is most similar to that of the reanalysis in the summer months. In the western Arctic, the model generally overestimates moisture convergence in all seasons, with largest differences (about 1.5 cm month$^{-1}$) in the

![Fig. 2. Arctic regions analyzed in this study. The central Arctic is defined as the area north of 75°N.](image)

<table>
<thead>
<tr>
<th>Region</th>
<th>ERA-40 (cm month$^{-1}$)</th>
<th>CCSM3 (cm month$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Arctic</td>
<td>1.76</td>
<td>2.06</td>
</tr>
<tr>
<td>North Atlantic</td>
<td>3.81</td>
<td><strong>2.59</strong></td>
</tr>
<tr>
<td>Barents Sea</td>
<td>1.34</td>
<td>1.30</td>
</tr>
<tr>
<td>Kara Sea</td>
<td>2.41</td>
<td>2.17</td>
</tr>
<tr>
<td>Laptev Sea</td>
<td>1.56</td>
<td>1.84</td>
</tr>
<tr>
<td>East Siberian Sea</td>
<td>1.42</td>
<td><strong>1.97</strong></td>
</tr>
<tr>
<td>Chukchi Sea</td>
<td>1.15</td>
<td><strong>2.42</strong></td>
</tr>
<tr>
<td>Beaufort Sea</td>
<td>1.28</td>
<td><strong>2.41</strong></td>
</tr>
</tbody>
</table>
autumn and winter in the Chukchi and Beaufort Seas. These results for the Pacific sector are consistent with findings by Finnis et al. (2009a,b), who found that the CCSM3 oversimulates cyclogenesis in the Mackenzie Basin during autumn, winter, and spring, leading to an overestimation of precipitation in that area. In addition, Alexander et al. (2006) suggests that the resolution of topography plays a crucial role in simulating lee cyclogenesis in the model, which may explain the large discrepancy in the lee of the Rocky Mountains. We also note that differences may arise owing to the comparison of two single realizations of the system, one modeled and one from the real world, and that long-term cycles of natural variability may be out of phase in the two realizations. These apparent shortcomings in the model’s simulation of moisture convergence do not detract from this study’s validity, as the model physics are generally realistic, and our goal is to elucidate the character and fundamental causes of projected changes in the hydrologic cycle of the Arctic atmosphere in a future forced by credible increases in greenhouse gases.

4. Links between moisture convergence and circulation patterns: A SOM approach

The SOM method described in section 2 is applied to the daily SLP anomalies from a combination of both ERA-40 and CCSM3 output for all time periods. Anomaly fields are created by subtracting the domain-averaged SLP for each daily map from the value at each grid point on that day. As argued by Cassano et al. (2007), these anomalies are a better representation of the circulation patterns, as eliminating the daily mean focuses the pattern classification procedure on pressure

FIG. 3. Seasonal-mean moisture convergence (cm month$^{-1}$) for the twentieth century during spring (MAM), summer (JJA), autumn (SON), and winter (DJF) from the (a) ERA-40 and (b) CCSM3.
gradients, which define circulation features. Areas of elevation higher than 500 m are removed from the fields because pressure reduction to sea level in the areas of high elevation can lead to unrealistic patterns.

Figure 4 shows the self-organizing map of SLP anomalies north of 60°N, hereafter called the “master SOM.” This is the same as that presented in Skific et al. (2009) and is provided here for convenient reference. The

![Fig. 3. (Continued)](image)

**TABLE 2.** Seasonal-mean moisture convergence (cm month$^{-1}$) in various regions in the Arctic from ERA-40 and CCSM3 during the late twentieth century. Model values significantly larger or smaller than that of ERA-40 at the 95% confidence level are indicated with bold italic.
matrix of maps represents the dominant circulation regimes in which the atmosphere tends to reside according to the datasets used to create it. Patterns with a strong Icelandic low and moderate-to-strong Aleutian low, accompanied by high pressure over the northern Eurasian continent, are found in the bottom right. Maps in the upper right are characterized by pronounced low pressure in the Atlantic sector extending into the Barents Sea, while the western central Arctic, continental regions, and the Pacific sector are dominated by high pressure. These patterns correspond to a moderate or strong Beaufort high in winter. In the bottom left corner of the map are conditions with low pressure in the central Arctic and high pressure over northwestern Eurasia. Toward the upper-left corner the low is centered near the Kara and Laptev Seas, while high pressure is located over the northeast American continent. The patterns in the middle of the SOM are dominated by high pressure over the central Arctic.

The frequency of occurrence (FO) for twentieth-century SLP anomaly patterns in CCSM3 (1960–99) are presented in the top panel of Fig. 5. Frequencies of occurrence are defined as the percent of days that map into a particular cluster out of the total number of daily fields. Black solid (dashed) contours show values of the FO that are significantly higher (lower) than an expected value for a random binomial distribution (i.e., 2.86%) with a confidence level of at least 95% [or more details see Cassano et al. (2007)]. Because this statistical test does not account for the effects of serial correlation in the daily SLP fields and, thus, likely overestimates the degrees of freedom, we determine an approximation for the effective degrees of freedom by dividing the number of samples of the two datasets by 7. This value is determined from the serial correlation of the SLP time series, which indicates that the atmosphere tends to reside in a circulation regime for about one week. This procedure decreases the degrees of freedom, thus establishing a higher threshold for achieving a level of significance.

The features evident in the top panel of Fig. 5 show that the bordering clusters occur more frequently, while those positioned in the middle of the matrix, representing transitional circulation patterns between the most dominant regimes, are less common. Skific et al. (2009) compared twentieth-century FOs of the CCSM3 single run to those from ERA-40 and found that the modeled fields occupy clusters with high pressure in the central Arctic less frequently, while clusters with pronounced low pressure in the Atlantic region (on the right of the SOM) are occupied more frequently than in ERA-40. This results in the model’s mean sea level pressure of the twentieth century being lower in the central Arctic and Atlantic sector compared to the re-analysis, while pressure in northern Eurasia and the northeastern American continent is higher.

The FOs of winter [December–February (DJF)] and summer [June–August (JJA)] patterns in the twentieth-century CCSM3 are shown in the middle and bottom panels of Fig. 5. The most common winter patterns are on the right side of the master SOM, while circulation patterns on the left side are more characteristic of summer conditions.

The master SOM can be used to identify which days belong to each cluster in the matrix. Maps of other variables corresponding to the days in each cluster can then be analyzed as well, allowing patterns of other related parameters to be identified. Figure 6 presents a mapping of moisture convergence onto the master SOM. Red shading corresponds to positive values, that is, precipitation exceeds evaporation, which usually
FIG. 6. Moisture convergence fields (cm month$^{-1}$) from the CCSM3 twentieth century corresponding to SLP clusters in Fig. 5.
occurs east of low pressure systems and west of high pressure systems. Blue shading corresponds to moisture divergence, that is, where evaporation exceeds precipitation. Patterns in the lower-right corner of Fig. 6, corresponding to strong Icelandic and Aleutian lows in winter, bring more precipitation in the Atlantic and Pacific sectors as well as to northwestern Europe and Canada. Moisture convergence for upper-right patterns is associated with low pressure in the Atlantic sector and high pressure over the central Arctic. An area of negative moisture convergence in the Atlantic sector is related to high evaporation in cold, dry Arctic air driven by low pressure in the Kara and Barents Seas. Patterns in the lower-left corner feature high pressure over northwestern Eurasia and low pressure over the central Arctic, which generates positive (negative) moisture convergence in the North Atlantic (northwestern Eurasia).

5. Future changes in moisture transport for various regions of the Arctic

a. Demonstration of SOM technique for pan-Arctic domain

In this section we use the SOM approach to identify changes in the model’s simulation of moisture convergence in the late twenty-first century relative to the twentieth century and identify the causes of these changes. Even though the CCSM3 simulation for the twentieth century differs from the ERA-40 in some aspects, the projected future changes in the model output forced by the credible conditions described by the A2 scenario are instructive for understanding the mechanisms driving the changes.

There are two ways that a temporal change can be quantified using the SOM. One is a difference in the frequency with which each of the nodes is occupied by individual daily fields. Physically this can be interpreted as a change in the atmosphere’s preference for a particular weather pattern. The other way is through a change in the variable averaged over all the daily maps that belong to a particular cluster. For example, the mean water vapor content for a cluster of similar pressure patterns may increase in the future, resulting in the cluster-mean value for water vapor increasing even though the pressure patterns themselves do not change significantly.

This rationale is the basis of a procedure developed by Cassano et al. (2007) that separates the contributions from changing atmospheric dynamics, as represented by changes in the FOs; thermodynamics, as estimated by the change in the cluster-mean variable of interest; or a combination of the two.

The factors contributing to the total temporal change in a variable $x$ across a region can be expressed mathematically as

$$ x_{\text{future}} = \sum_{i=1}^{N} (f_i x_i + \Delta f_i \Delta x_i + \Delta f_i \Delta x_i). $$

where $i$ is the node (1 to $N = 35$ in this study), $x_i$ is the cluster-averaged variable in the initial time period, and $f_i$ is the FO of cluster $i$ during the initial period. The first term represents the mean value of a variable in a cluster weighted by its FO during the initial time period; the other three terms define contributions to the change between the initial and later period. The second term, $\Delta f_i x_i$, relates the changes in $x$ owing to a shift in the FO of a particular circulation regime or cluster, that is, a change caused primarily by varying dynamics. The third term, $f_i \Delta x_i$, describes the contribution due to changes in the cluster-averaged variable that occurs for a fixed circulation regime and is referred to as the thermodynamic factor. The final term, $\Delta f_i \Delta x_i$, is the combined dynamic-thermodynamic factor, which describes the contribution by changes in the FO acting on changes in the cluster-averaged variable. The differentiation between these factors may be indistinct in some cases—the attribution presented in this study is meant to be an indication of the character and magnitude of the causes of change projected by the model, not a quantitative prediction of contributions. Assuming the basic model physics are correct in their response to the A2 SRES forcing, we submit that the explanations for projected change by the end of the twenty-first century are a valuable tool for understanding system behavior in the mature greenhouse world.

This section briefly summarizes part of the study by Skific et al. (2009) as background for the further analysis of regional and seasonal projections. Change in the FO of sea level pressure anomalies (i.e., $\Delta f_i$) from the twentieth to the late twenty-first century is shown in Fig. 7. Black solid (dashed) lines identify areas where differences in the FO are significantly higher (lower) with a confidence level greater than 95%. Patterns on the left of the master SOM in Fig. 4 (low pressure over the central Arctic), as well as those in the upper-right (high pressure across the western Arctic with low pressure in the eastern Arctic and North Atlantic), are projected to become more frequent. The clusters in the middle, featuring high pressure in the central Arctic, decrease. Overall, these changes suggest that in the greenhouse-gas-forced future, the pressure in the central Arctic will decrease overall, and the SOM reveals which SLP patterns are responsible for the change. Skific et al. (2009) find that this model realization exhibits an Arctic-mean pressure decrease of about 1.8 hPa in the late twenty-first century relative to the twentieth century.
The cluster-averaged moisture convergence \([x_i]\) in Eq. (1) for the pan-Arctic region (area north of 60\(^\circ\)N) for the twentieth century is shown in Fig. 8. Circulation patterns in the lower-right (pronounced Icelandic and Aleutian low pressure) and lower-left corner (low pressure across the central Arctic) favor higher moisture convergence in the pan-Arctic region, while it is lower for clusters in the middle of the SOM with high pressure across the central Arctic.

Figure 9 shows \(\Delta x_i\), the change in the cluster-averaged moisture convergence from the twentieth to the late twenty-first century. This change is positive for each circulation pattern of the SOM, indicating that the thermodynamic term \(f \Delta x_i\) (Fig. 5 multiplied by Fig. 9) is positive for all nodes (middle panel of Fig. 10), totaling 67 mm yr\(^{-1}\). Physically a thermodynamic change may result from a change in horizontal moisture gradients.

The three individual factors are compared in Fig. 10. The dynamic term on top (derived by multiplying values in Fig. 7 with Fig. 8) is positive for the circulation patterns to the left and to the right of the SOM and negative for the clusters in the middle. Its total value summed over all clusters is about 2.8 mm yr\(^{-1}\). Physically the dynamical factor arises from a change in the FO of each cluster. The contribution from the combined factor (Fig. 10, bottom) is relatively very small. The total increase in moisture convergence for the pan-Arctic region (north of 60\(^\circ\)N), derived by summing the contributions by all three terms, is about 70 mm yr\(^{-1}\) with the thermodynamic term accounting for 95% of the total increase. In the next section, we apply this principle to derive and compare changes in moisture convergence for particular regions of the Arctic.

b. Attribution of regional changes

The moisture convergence in eight regions of the Arctic (Fig. 2) are calculated for each daily map within a cluster and presented in Fig. 11. These contours represent \(x_i\) in Eq. (1) and indicate which patterns in the master SOM are responsible for maxima and minima in moisture convergence occurring in each region.

The moisture convergence in the central Arctic and North Atlantic is largest for clusters in the lower-right
section of the master SOM (strong Icelandic low) and in the lower-left (low pressure in the central Arctic and high pressure in northwestern Eurasia). The Kara and Barents Seas have a higher moisture convergence for patterns on the right, which are characterized by low pressure in the Atlantic sector extending northward and eastward into the coastal seas of the eastern Arctic, while high pressure is generally located over northern Eurasia and across the western Arctic. Clusters in the upper- and middle-left sides of the SOM favor higher net precipitation in the Laptev, East Siberian, Chukchi, and Beaufort Seas. These patterns feature low pressure over these areas along with high pressure in northeast Canada. The Beaufort and Chukchi Seas also have higher moisture convergence values when there is a strong Aleutian low (lower middle and right of the SOM). Low pressure in the Atlantic (clusters on the right) generally has little influence on the moisture convergence in the western Arctic regions.

Regional changes in the cluster-averaged moisture convergence $\Delta \xi$ from the twentieth to the late twenty-first century are shown in Fig. 12. Because the sign of the change in the thermodynamic term is determined by the sign of $\Delta x$, it is obvious that this term contributes significantly to the total overall change in most regions. Although the pan-Arctic change is positive across the SOM, the regional values decrease in some clusters. These reductions account for the negative thermodynamic changes in the Barents and Kara Seas. The fourth term in Eq. (1) describes the portion of total change arising from combined dynamic and thermodynamic effects. In a physical sense, this could arise from a change in a thermodynamic variable, such as atmospheric moisture content, that results from a particular circulation regime occurring more or less frequently and the corresponding influence on surface evaporation.

Figure 13 presents the total changes in moisture convergence from the twentieth to the late twenty-first century, as well as the individual contributions by the dynamic, thermodynamic, and combined terms in various regions of the Arctic. In all areas except the Barents and Kara Seas total moisture convergence is projected to increase, primarily owing to the thermodynamic term. The other two terms are substantially smaller, except in the Barents/Kara Seas where the dynamic term is approximately equal and opposite to the thermodynamic term. The North Atlantic experiences the largest increase of about $55 \text{ mm yr}^{-1} (18\%)$, although large spatial variations are evident (Fig. 14). For example, while values in the area south of Svalbard and east of Greenland decrease, they increase in the Norwegian Sea by over $200 \text{ mm month}^{-1}$. A negative sign in the thermodynamic term in the Kara and Barents Seas indicates that evaporation exceeds precipitation, most likely because of substantial regional atmospheric warming, which would lead to decreased poleward gradients in temperature and humidity and reduced moisture advection into a region. This could also be related to extensive loss of sea ice in these two regions, which exposes large areas of open water, leading to increased evaporation. A positive dynamic term results from an increase in the FO of the SOM clusters featuring a strong Icelandic low, which would likely increase the precipitation events in the eastern Arctic. The negative contribution from the dynamic term in the Laptev, East Siberian, Chukchi, and Beaufort Seas can be explained by the decreased FO of clusters that produce strong moisture convergence in these regions (Figs. 7 and 11), that is, the upper-middle, upper-left, and lower-right side of the SOMs.

c. Seasonal changes

Changes in the FO of the SLP anomalies from the twentieth to the late twenty-first centuries and for each season are presented in Fig. 15. The FO of circulation patterns on the left side of the master SOM, featuring
dominant low pressure over the central Arctic, are projected to increase in all seasons, particularly in summer and fall. Patterns in the upper-right corner, characterized by low (high) pressure anomalies in the North Atlantic (western Arctic), occur more frequently in spring and winter. Clusters in the middle, featuring high pressure over the Arctic, become less common in the late twenty-first century, particularly in summer.

Changes in moisture convergence in the CCSM3 from the twentieth to the late twenty-first centuries for each season are shown in Fig. 16. Histograms on the left (right) are for the central Arctic (North Atlantic). Contributions to the total seasonal change from the dynamics, thermodynamics, and combined terms in Eq. (1) are also shown. In both regions, moisture convergence increases in all seasons, with largest changes in summer in the central Arctic (57% of total) and winter in the North Atlantic (44%). This is consistent with the changes in northward moisture transport across 70°N reported by Skific et al. (2009). In the central Arctic, the large summer
and spring increases, accounting for 87% of the total, are contributed almost exclusively by the thermodynamic term owing to an increase in the poleward moisture gradient. The North Atlantic sector receives the most precipitation in winter when the gradients are strong and the winter storm track associated with the Icelandic low is pronounced. The thermodynamic term makes the largest contribution in this region as well, particularly in winter (89% of winter change) and spring (115%), although the dynamic term plays an important role in summer (85%) and fall (38%). These results suggest that the increased moisture convergence in the North Atlantic is not due to more frequent occurrences of the Icelandic low pattern but rather to changes in the moisture content of the atmosphere, which leads to changes in the moisture convergence forced by a particular circulation.

**Fig. 12.** Differences in the regional cluster-averaged moisture convergence (cm month$^{-1}$) from the twentieth to the late twenty-first century in CCSM3.
Precipitating weather systems feed on the moisture that already exists in the atmosphere, mostly through convergence of moisture in the lower and middle troposphere in the vicinity of these disturbances (Stephens and Ellis 2008). Therefore, it is expected that the seasons in which they are most vigorous, or most effective in precipitating, are seasons in which the increase in moisture convergence is most pronounced. This explains the largest increases in moisture convergence in the central Arctic (North Atlantic) that occur in summer (winter). The small contribution by thermodynamics in summer, in stark contrast to the central Arctic, likely arises as the lower troposphere warms enough in the future to reduce the relative humidity, so instead of forming clouds locally the moisture may be advected northward into the central Arctic where it would contribute to the thermodynamic effect in that region. Moreover, as summer sea ice declines, the planetary boundary layer deepens (Schweiger et al. 2008), allowing moisture to penetrate higher into the polar atmosphere where winds tend to be stronger. It is also likely that the portion of precipitation in the North Atlantic derived from evaporation would increase by the end of the twenty-first century. More frequent occurrence of storms could also increase evaporation by intensifying surface mixing, which could contribute to a negative combined term.

**FIG. 13.** Annual-mean changes in regional moisture convergence (mm yr\(^{-1}\)) in the CCSM3 from the twentieth to the late twenty-first century. Contributions to the total change (blue) are also displayed: dynamic (gray), thermodynamic (red), and combined term (yellow).
6. Summary and conclusions

Better understanding of future global climate change will require not only improved model simulations, but also a more system-oriented, interdisciplinary approach. The hydrologic cycle of the Arctic, as well as its connections with lower latitudes, constitutes an important facet of the global climate system that affects the oceans, terrestrial vegetation, marine productivity, and society—truly a cross-cutting element. In this study we demonstrate that, if today’s trends in greenhouse gas emissions continue, the Arctic hydrologic cycle will undergo large changes, and these changes will vary by region, season, and attribution.

By the late twenty-first century of the SRES A2 scenario, a simulation by the CCSM3 projects that annual-mean moisture convergence into the Arctic, or equivalently net precipitation, will increase by about 20% (70 mm yr$^{-1}$), over 95% of which is attributed to changes in thermodynamic factors such as increased precipitable water and a strengthening of the poleward moisture gradient. While the thermodynamic term is positive across

![Fig. 14. Difference in annual-mean moisture convergence (cm month$^{-1}$) from the twentieth to the late twenty-first century in CCSM3.](image)

![Fig. 15. Seasonal differences in frequency of occurrence of SLP anomalies from the twentieth to the late twenty-first century in CCSM3. Black solid (dashed) lines indicate differences that are significantly higher (lower) at the 95% confidence level.](image)
all nodes of the SOM, the contribution from changes in the dynamic term is primarily from patterns featuring pronounced low pressure in the North Atlantic and those with low pressure over the central Arctic. The patterns responsible for change in each region, however, vary considerably. In the Beaufort Sea, for example, the clusters with low pressure in the North Pacific are the primary drivers, while in the nearby Chukchi Sea those with low pressure in the western Arctic are mostly responsible. In six of the eight regions studied, the thermodynamic term accounts for the overwhelming majority of the total change. Exceptions are the Barents and Kara Seas, where a small decrease in moisture convergence is projected owing to negative contributions from the thermodynamic and combined terms, offset by a positive dynamic term.

Our analysis of attribution by season reveals large differences in each region, which elucidate the causes for projected changes in annual-mean values. Net precipitation in the central Arctic increases by about 40 mm yr$^{-1}$ (16%). The change in all seasons is positive, with the largest occurring in summer (57%), followed by spring, autumn, and winter. The thermodynamic term is clearly the primary driver. In addition to this increase in net precipitation, it is expected that continued warming will lead to a more frequent occurrence of rain rather than...

FIG. 16. (top) Total annual and seasonal changes in moisture convergence (mm yr$^{-1}$) from the twentieth to the late twenty-first century in CCSM3 for the central Arctic and North Atlantic regions. (bottom four rows) Contributions to seasonal changes from dynamic, thermodynamic, and combined terms are shown as indicated.
snow, particularly during summer. Increased water vapor in the atmosphere will also enhance the emission of longwave radiation to the surface (Francis and Hunter 2007). Both of these effects constitute positive feedbacks to the system that will augment Arctic warming and the loss of sea ice, permafrost, and low-elevation land ice.

Net precipitation in the North Atlantic region is projected to increase substantially (about 18%), but it exhibits a very different seasonal behavior. The largest increase occurs in nonsummer months, with winter accounting for about 44% of the annual-mean change. Thermodynamic effects are again the primary contribution, but changing dynamics play a larger role than in the central Arctic, particularly in summer and autumn. The CCSM3 projects an increased frequency of patterns characterized by a strong Icelandic low, which tends to enhance precipitation in the North Atlantic region. While the net precipitation change in summer is relatively small, the increased evaporation owing to sea ice loss will likely result in enhanced northward moisture advection, contributing to an increase in the thermodynamic term over the central Arctic.

The Arctic is characterized by a variety of climate interactions and feedbacks resulting from a sensitive balance between the atmosphere, ocean, cryosphere, and biosphere. State-of-the-art global climate models project an increase in precipitation over high latitudes through the twenty-first century (Solomon et al. 2007), which will almost certainly have substantial effects on the balance among components in the system. In this study we investigate the regional and seasonal variations in moisture convergence over the Arctic according to one of these models and attribute the changes to factors related to thermodynamics and dynamics. It is clear from this simulation forced by realistically increasing greenhouse gases and other anthropogenic effects that the Arctic hydrological regime will change in the future and that related feedbacks are most likely positive. Further research will illuminate the impacts of these changes on other components of the Arctic and global systems.

Acknowledgments. We acknowledge and appreciate the technical support of Gary Strand from the National Center for Atmospheric Research for providing the CCSM3 daily output used in this study. Comments and valuable technical information were also provided by Eli Hunter in the Institute of Marine and Coastal Sciences at Rutgers University. We are grateful for the very constructive suggestions by the anonymous reviewers. Special thanks go to Jaakko Peltonen in the Department of Computer and Information Science at Helsinki University of Technology for his helpful advice in applying the self-organizing maps algorithm. This work is funded by the National Science Foundation, NSF ARC-0455262.

REFERENCES


