Summer Arctic Atmospheric Circulation Response to Spring Eurasian Snow Cover and Its Possible Linkage to Accelerated Sea Ice Decrease

SHINJI MATSUMURA

Faculty of Environmental Earth Science, Hokkaido University, Sapporo, Japan

XIANGDONG ZHANG

International Arctic Research Center, and Department of Atmospheric Sciences, University of Alaska Fairbanks, Fairbanks, Alaska

KOJI YAMAZAKI

National Institute of Polar Research, Tokyo, and Faculty of Environmental Earth Science, Hokkaido University, Sapporo, Japan

(Manuscript received 9 September 2013, in final form 28 May 2014)

ABSTRACT

Anticyclonic circulation has intensified over the Arctic Ocean in summer during recent decades. However, the underlying mechanism is, as yet, not well understood. Here, it is shown that earlier spring Eurasian snowmelt leads to anomalously negative sea level pressure (SLP) over Eurasia and positive SLP over the Arctic, which has strong projection on the negative phase of the northern annular mode (NAM) in summer through the wave–mean flow interaction. Specifically, earlier spring snowmelt over Eurasia leads to a warmer land surface, because of reduced surface albedo. The warmed surface amplifies stationary Rossby waves, leading to a deceleration of the subpolar jet. As a consequence, rising motion is enhanced over the land, and compensating subsidence and adiabatic heating occur in the Arctic troposphere, forming the negative NAM. The intensified anticyclonic circulation has played a contributing role in accelerating the sea ice decline observed during the last two decades. The results here provide important information for improving seasonal prediction of summer sea ice cover.

1. Introduction

Summer Arctic sea ice extent (SIE) has declined rapidly during recent decades (e.g., Serreze et al. 2007; Comiso et al. 2008), while spring Eurasian snow cover extent (SCE) has decreased over the past several decades (e.g., Groisman et al. 2006; Brown et al. 2010; Derksen and Brown, 2012). In seasonality, the Eurasian subarctic becomes snow free in early summer, while the Arctic Ocean remains continually covered by a large area of sea ice until late summer. This lagged seasonal cycle between snow and sea ice is expected to result in an increased thermal contrast across the Arctic coastline before sea ice reaches its annual minimum. The surface thermal contrast across the Arctic coastline would therefore vary with interannual fluctuations of snow and sea ice covers. When earlier snowmelt occurs, surface albedo and soil water content will decrease, leading to a more rapid surface warming in spring, which could persist even further into the following summer (Matsumura et al. 2010; Matsumura and Yamazaki 2012). All of these changes in snow cover and resultant alterations of thermal contrast are expected to impact overlying hemispheric or local atmospheric circulation.

However, the mechanism by which the altered thermal contrast resulting from altered spring snow cover could exert across-season impacts on summer Arctic atmospheric circulation has not been clearly understood. In addition, recent studies suggest that changed atmospheric circulation could significantly contribute to amplified Arctic warming and associated accelerated sea ice decrease via increased poleward transport of atmospheric heat and moisture (e.g., Graversen et al. 2008; Zhang

Corresponding author address: Shinji Matsumura, Faculty of Environmental Earth Science, Hokkaido University, Kita 10 Nishi 5, Sapporo, 060-0810, Japan.
E-mail: matsusnj@ees.hokudai.ac.jp

DOI: 10.1175/JCLI-D-13-00549.1

et al. 2008, 2013). However, the mechanisms responsible for the atmospheric circulation change remain to be elucidated, particularly from the spring, when Eurasian snow begins to melt throughout the late summer when sea ice reaches its minimum. To address these questions, we have analyzed the impact of spring Eurasian snow anomalies upon summer Arctic atmospheric circulation and, in turn, upon sea ice.

2. Data and methods

We used a number of data resources, including the National Centers for Environmental Prediction–U.S. Department of Energy Atmospheric Model Intercomparison Project II reanalysis (NCEP-2) (Kanamitsu et al. 2002). Northern Hemisphere (NH) SIE was acquired from the National Snow and Ice Data Center (Fetterer et al. 2002). Eurasian SCE is the monthly snow cover fraction information derived at Rutgers University (Robinson et al. 1993).

Substantial Arctic multiyear ice has been lost since the late 1980s (Maslanik et al. 2007). As a consequence, dramatically thinned sea ice and shrunk snow became vulnerable to atmospheric circulation forcing and the Arctic climate shifted to a new state. We therefore conducted this study focusing on the last two decades (1988–2011). Long-term changes in surface radiative forcing and the atmospheric circulation may play a major contributing role in sea ice and snow declining trend. In this study, however, we only focus on seasonal connections between anomalous spring snow cover and summer sea ice via altered seasonal evolution the atmospheric circulation, which will be revealed by using the detrended data. We used September SIE to represent summer sea ice, because the sea ice reaches an annual minimum in September, and June SCE to represent spring snow cover, because its anomalies can more effectively measure earlier or later spring snowmelt in each year (Matsumura and Yamazaki 2012). The same analysis using April and May SCE anomalies exhibits highly consistent results, excluding potential biases caused by using different definition of the snow index. Note that signs in the following regression analysis are reversed to emphasize earlier snowmelt or sea ice reduction.

3. Results

We first analyzed surface thermal conditions and atmospheric circulation prior to and following the occurrence of anomalous June SCEs (Fig. 1). The regression analysis indicates that earlier spring snowmelt, represented by negative Eurasian SCE anomaly in June, is associated with strong positive temperature anomalies in March–May over the Eurasian and North American high latitudes and negative temperature anomalies over Greenland and the Far East (Fig. 1a). This surface air temperature pattern is consistent with that induced by positive phase of the North Atlantic Oscillation (NAO) (Xie et al. 1999) or northern annular mode (NAM) (Thompson and Wallace 2000), which is characterized by negative geopotential height anomalies over the Arctic and positive anomalies over the lower latitudes (Fig. 1b). Operational monitoring of the NAM index also confirms the positive values during early spring in the earlier spring snowmelt years (not shown). The positively polarized NAO/NAM enhances horizontal temperature advection to Eurasian continent (Xie et al. 1999; Thompson and Wallace 2000), As a result, Eurasian land surface warms and earlier spring snowmelt occurs (Bojariu and Gimeno 2003). This earlier snowmelt further contributes to surface warming via reduced surface albedo throughout the late spring (Déry and Brown 2007; Matsumura et al. 2010).

In summer (June–August), however, regression analysis indicates that strongly positive geopotential height anomalies over the central Arctic and Greenland, as well as negative anomalies throughout the high latitudes of Eurasia and North America, occur in association with the negative Eurasian SCE anomaly in June (Fig. 1c). This geopotential height anomaly pattern demonstrates a strong projection on a negative NAM phase. Because there is almost no climatological snow cover remaining over the Eurasian study area in July and August, Fig. 1c really represents the response of the atmospheric circulation to June SCE anomalies. In addition to the time-lag regression above, the comparison between Figs. 1a and 1c indicates a good correspondence between summer negative height anomalies and spring surface warming over northern landmasses. This may indicate an across-season linkage, suggesting that the spring land surface warming that is induced by earlier snowmelt contributes to summer atmospheric circulation variability.

Now, we will check any possible linkage between the atmospheric circulation and sea ice in summer. Associated with the negative anomaly of September SIE, anticyclonic circulation anomalies emerge over the Arctic and Greenland (Fig. 1d), similar to what Ogi and Wallace (2007) identified. Simultaneously, negative height anomalies occur throughout the high latitudes of Eurasia and North America. This September sea ice–associated circulation pattern shares common features with that induced by June Eurasian SCE anomalies. This suggests that September sea ice variability could be linked to spring snowmelt through the atmospheric circulation.

As discussed above, the geopotential height anomaly pattern changes sign from spring to summer, indicating

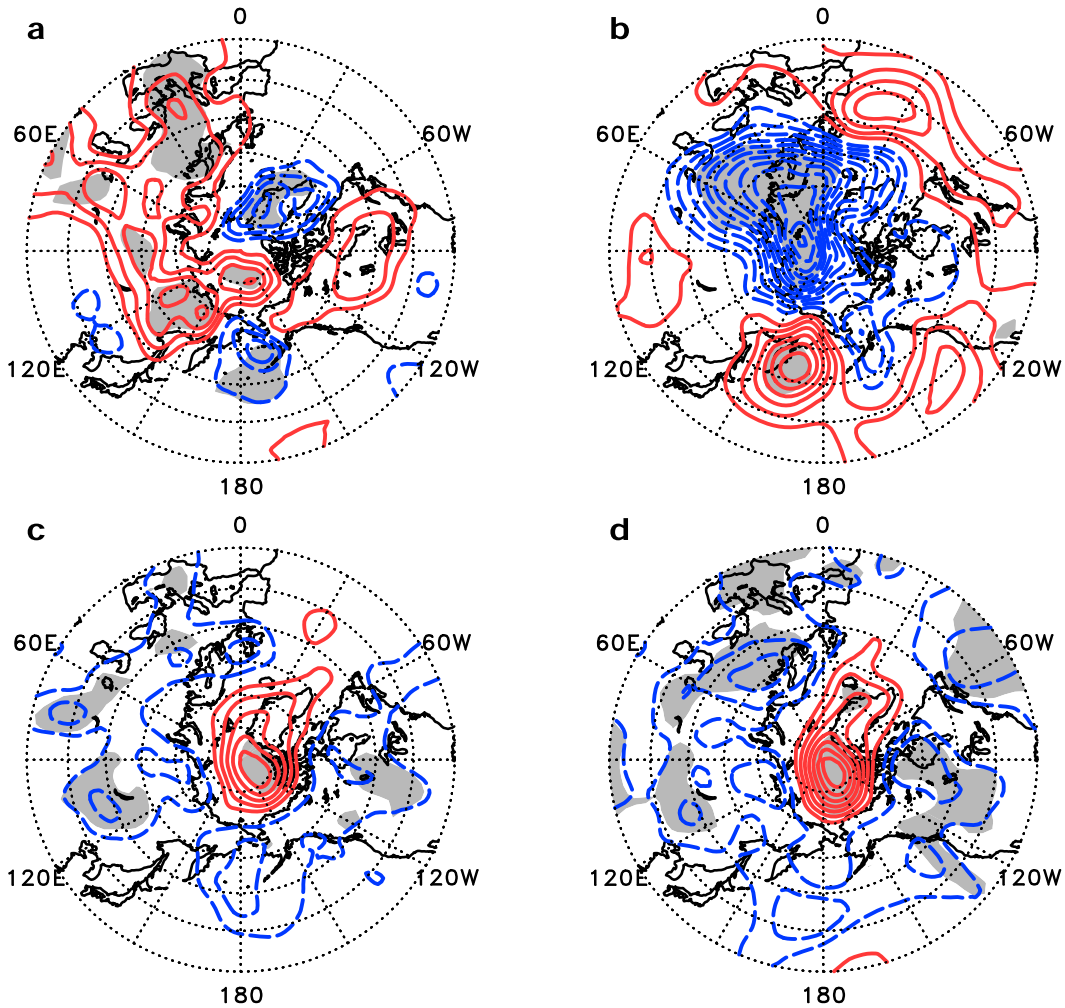

FIG. 1. (a) Spring (March–May) 1000-hPa air temperature (°C) regressed linearly on the standardized inverted June Eurasian SCE for the period 1988–2011. The contour interval is 0.2°C (positive value: solid red contours; negative values: dashed blue contours), with the zero contour omitted. (b) As in (a), but for early spring (March and April) 1000-hPa geopotential height (2-m contour interval). (c) As in (b), but for summer (June–August). (d) As in (c), but for regression on inverted September Arctic SIE. Shaded regions indicate statistical significance at the 95% level.

a phase change in the NAM pattern from positive to negative, when June Eurasian SCE decreases. To identify the linkage between summer sea ice and spring snow, we need to understand why the atmospheric circulation pattern changes phase when earlier spring snowmelt occurs. We examined the time evolution of the zonal-mean atmospheric circulation associated with June Eurasian SCE anomalies during the snowmelt and postsnowmelt seasons (Fig. 2).

Corresponding to earlier Eurasian snowmelt as indicated by June SCE, a positive NAM appears in April, causing lower-tropospheric and surface warming at about 50°–60°N (Figs. 2 and 1a), where downward motion appears. In May, however, the anomalous vertical meridional circulation is reversed. A rising motion occurs over the warmer land around 50°–55°N and subsidence occurs over the cold Arctic and/or subarctic, giving rise to Arctic lower- to midtropospheric warming as a result of adiabatic heating (Thompson and Wallace 2000). The change in vertical atmospheric circulation from April to May is, in fact, a manifestation of the phase transition in the NAM pattern from positive to negative.

After snowmelt in July, when the land–sea ice thermal contrast across the Arctic coastline is the strongest, the rising motion moves poleward to around 55°–65°N and the subsidence extends to the entire Arctic, forming cyclonic anomalies over northern landmasses and anticyclonic anomalies over the Arctic. This persistent, negative NAM contributes to strong Arctic warming in the lower-to-middle troposphere into August.

To further understand the dynamics of earlier spring snowmelt forcing and maintaining a negative NAM

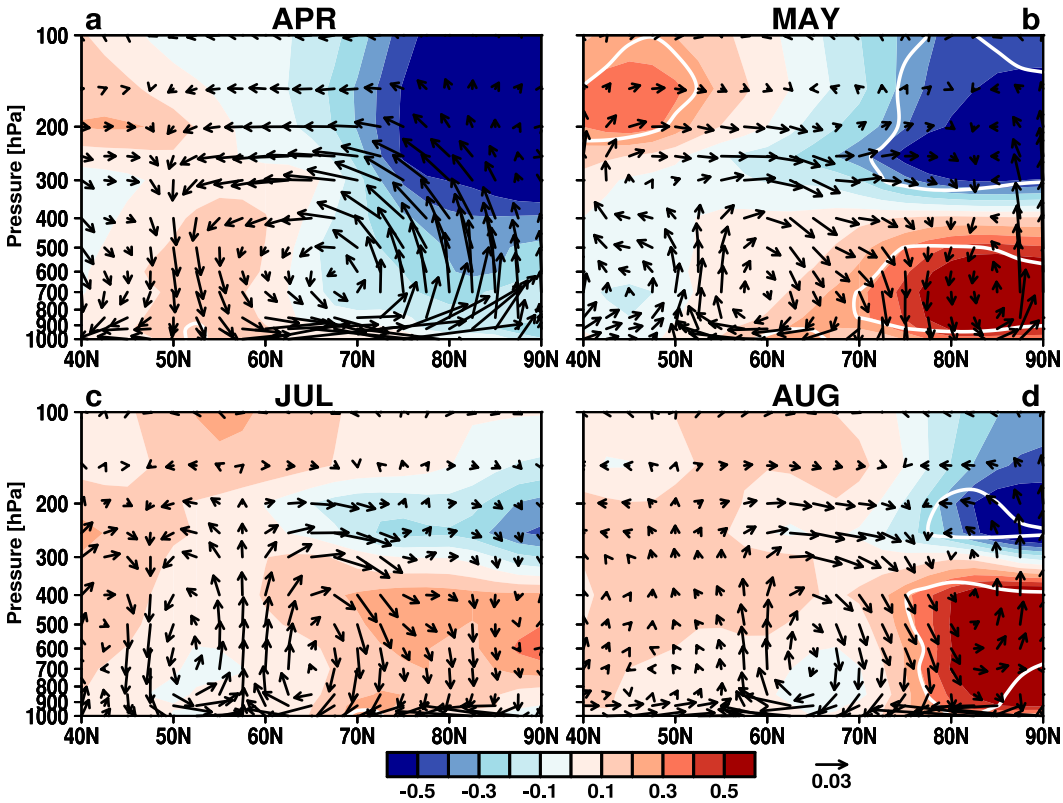

FIG. 2. Zonal-mean temperature (shaded; °C) and mean meridional circulation (vectors; m s^{-1}), regressed onto the standardized, inverted June Eurasian SCE for (a) April, (b) May, (c) July, and (d) August. White contours indicate statistical significance at the 95% level for zonal-mean temperature.

from late spring throughout summer, we examined the wave–mean flow interaction associated with June Eurasian SCE anomalies, using Eliassen–Palm (EP) flux (Andrews and McIntyre 1976) (Fig. 3). In April, when NAM stays in positive phase, waves are generated from the surface at high latitudes and first propagate upward and then turn equatorward in the upper troposphere. In May, however, waves are emanated from the anomalously warmed land surface because of earlier snowmelt over 40°–50°N; they propagate upward and then poleward in the upper troposphere where the EP flux converges, resulting in deceleration of the subpolar jet. Changes in stationary Rossby waves and resulting deceleration of the subpolar jet drive the NAM to change phase from positive to negative.

After the snowmelt season, in July, wave forcings move poleward along with increasing land–sea ice thermal contrast and the same wave generation and propagation pattern is retained. On the other hand, the largest thermal contrast strengthens subpolar jet, which may weaken spring SCE forced anomalous easterlies and the negative NAM-like circulation. In August, when the land–sea ice thermal contrast begins to weaken, upward waves disappear and only poleward waves propagate in the upper troposphere, continually contributing to EP flux convergence and deceleration of the subpolar jet. Consequently, negative NAM is maintained throughout the summer by wave forcings. The persistent and even larger deceleration of the subpolar jet in August could be a feedback consequence from decreased sea ice.

The previous statistical analysis has demonstrated changes in the atmospheric circulation from spring to summer because of anomalous snow cover forcing. To further isolate the snow impact and minimize potential impact from other factors involved in the data, we extended our previous atmospheric general circulation model (AGCM) experiments (Matsumura et al. 2010) to examine response of the hemispheric-scale circulation to spring snow forcing. Specifically, the AGCM experiments include 10 ensembles spanning from 21–30 April to the end of August and were initialized using light and heavy Eurasian SCE. Climatological sea surface temperature (SST) and sea ice cover were prescribed in all experiments, excluding impacts of SST and sea ice variability on the atmospheric circulation, which reduce the model freedom and constrains model simulations. A dominant number of the model simulations have sufficiently produced the nearly same results solely because

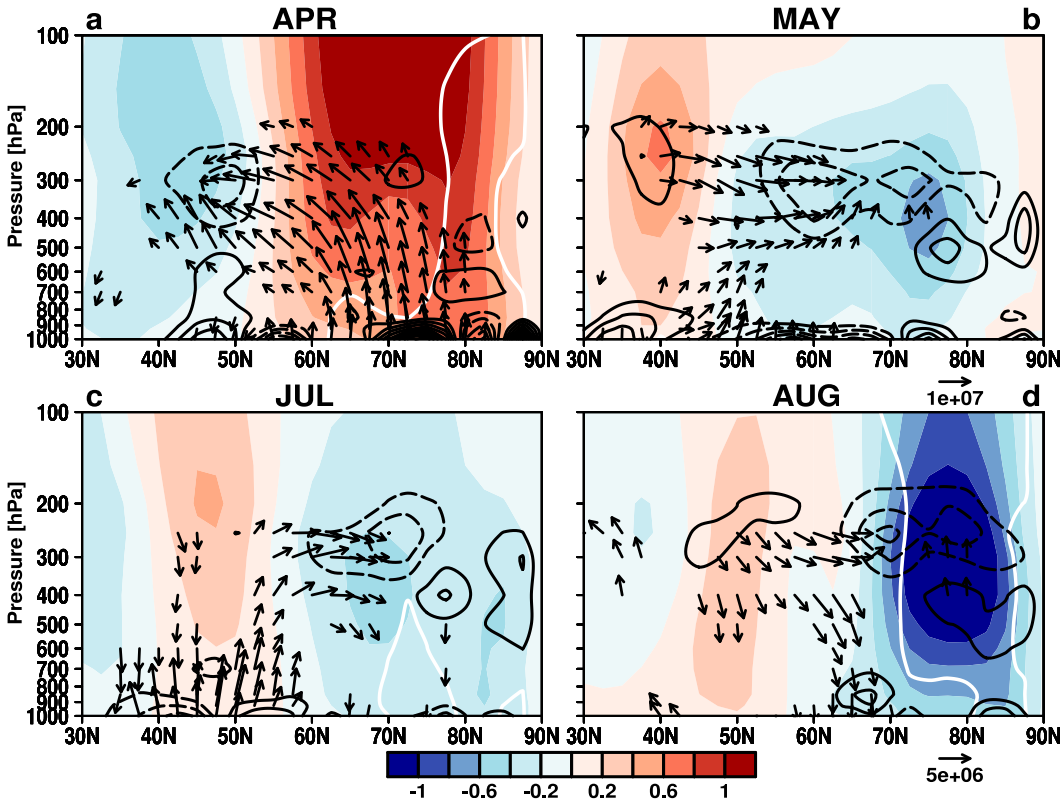

FIG. 3. Zonal-mean zonal wind (shaded; $m\,s^{-1}$), EP flux (vectors; $kg\,s^{-2}$), and the EP flux divergence (contour interval is $0.3\,m\,s^{-1}\,day^{-1}$ with the zero contour omitted) regressed onto standardized June Eurasian SCE for (a) April, (b) May, (c) July, and (d) August. Convergence (divergence) is indicated by dashed (solid) contours. Vertical length of the vector is 200 times larger than its horizontal length. White contours indicate statistical significance at the 95% level for zonal-mean zonal wind.

of Eurasian SCE forcing, demonstrating robustness of the model results.

Figure 4 shows the simulated sea level pressure (SLP) and zonal-mean vertical structure differences between light and heavy snow runs for early summer. The model simulated June SLP anomaly patterns well capture its strong projection on the negative NAM phase as identified in the observations, although the significance level of the statistical analysis is relatively smaller than that shown in the observational data because of the small number of model ensembles. The June SLP anomaly patterns are also similar to the results of Overland et al. (2012). At the same time, rising motion occurs over around 50°N, while subsidence occurs over subpolar latitudes contributing to subarctic lower- to midtropospheric warming. In July, the rising motion moves northward over around 60°–70°N, and subsidence extends to the entire Arctic, causing Arctic warming in the lower-to-middle troposphere. These results are consistent with and reinforce the observational and dynamic results analyzed above (Figs. 1c and 2): that is, earlier spring snowmelt leads to anomalously negative SLP over Eurasia and positive SLP over the Arctic, which has strong projection on the negative phase of NAM. In late summer, however, Eurasian snow cover is completely gone and feedback from decreased sea ice becomes more prominent, which may amplify the deceleration of the subpolar jet originally forced by earlier snowmelt (Fig. 3d), leading to a persistently and strongly negative NAM-like atmospheric circulation anomalies.

Summer zonal-mean wind anomalies and tropospheric warming over the Arctic associated with the June Eurasian SCE and September Arctic SIE are also remarkably similar (not shown). This negative NAM is marked by strong easterly anomalies (deceleration of the subpolar jet) over the subpolar region, forming surface cyclonic anomalies over northern landmasses and anticyclonic anomalies over the Arctic Ocean (Figs. 1c,d). The intensified surface anticyclonic circulation favors sea ice transport via transpolar drift and export out of the Arctic Ocean through Fram Strait (Ogi and Wallace 2007), which in turn contribute to Arctic sea ice loss (Fig. 5). It shows a pronounced reduction of sea ice occurring in all shelf seas where September sea ice exist

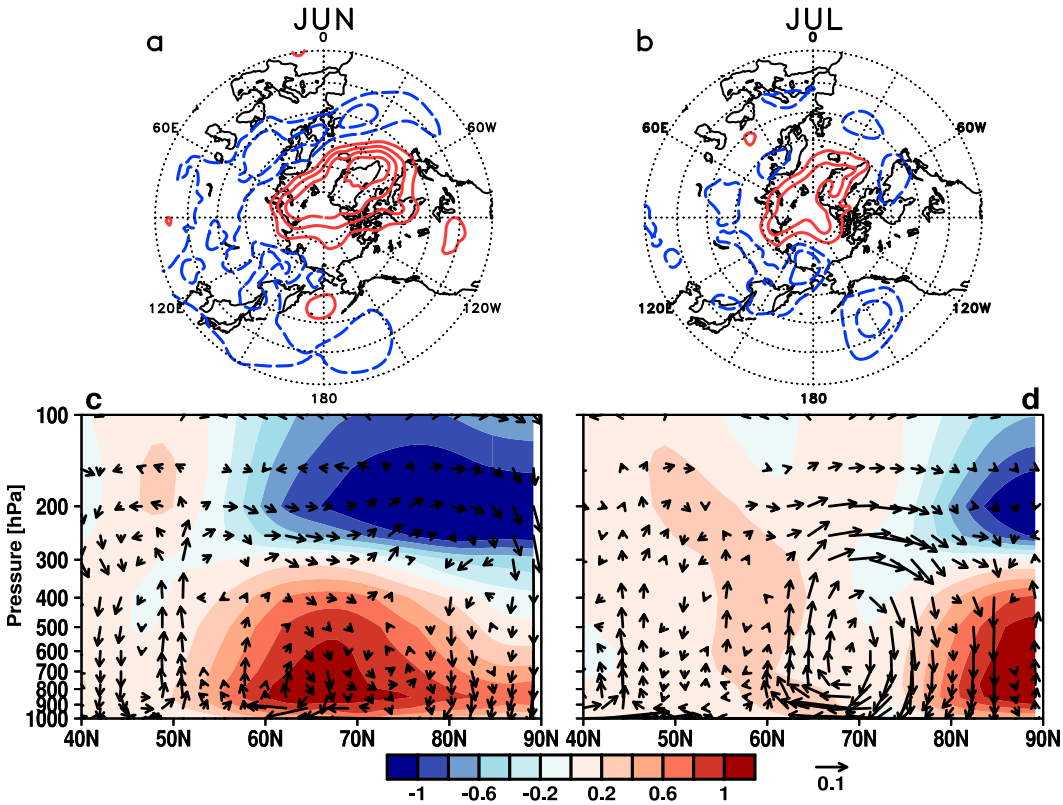

FIG. 4. Sea level pressure (hPa) differences between Eurasian light and heavy snow runs (light − heavy) in (a) June and (b) July, based on the modeling results (Matsumura et al. 2010). The contour interval is 1.0 hPa with the zero contour omitted. (c),(d) As in (a),(b), but for zonal-mean temperature (shaded; °C) and mean meridional circulation (vectors; m s^{-1}) differences.

and the reduction extends to the central Arctic, when June SCE is less than average (i.e., early snowmelt occurs). Indeed, correlations between June Eurasian SCE and late summer NH SIE remain statistically significant at the 99% confidence level and correlations associated with May Eurasian SCE also hold at the 95% confidence level (not shown). Further regression analysis on June SIE suggests that June sea ice anomaly cannot force circulation changes as that forced by spring SCE anomalies. The autocorrelation analysis also indicates that the persistence of SIE anomalies dramatically decreases from June to September. Therefore, the phase transition of NAM-like summer atmospheric circulation and its forcing role in the accelerated summer sea ice melt originate from anomalous spring SCE forcing. The predominant occurrence of negative summer NAM during the last two decades may have played an important role in rapid summer Arctic sea ice reduction.

4. Discussion and conclusions

We have examined the impact of spring Eurasian snow cover on summer Arctic atmospheric circulation during recent decades. Synthesis from comprehensive data analysis, dynamic diagnosis, and model experiments indicate that earlier Eurasian spring snowmelt and the resultant surface warming leads to anomalously negative SLP over Eurasia and positive SLP over the Arctic, which has strong projection on the negative phase of NAM in summer through the wave–mean flow interaction. The intensified anticyclonic circulation contributes to the rapid sea ice decline observed during the last two decades. Our results here identify interannual relationships between spring Eurasian snow cover and summer Arctic sea ice extent by using the detrended data. At the same, this finding may also suggest a potential mechanism to explain some parts of the recent September SIE trends, considering the observed long-term trends of the spring snow cover.

Various studies have investigated instant, across-season, and decadal-scale cumulative impacts of the atmospheric circulation on summer sea ice variability (e.g., Rigor et al. 2002; Zhang et al. 2003; Ogi and Wallace 2007; Deser and Teng 2008; Zhang et al. 2008; Overland and Wang 2010). However, the question of how changes in atmospheric circulation forced by spring

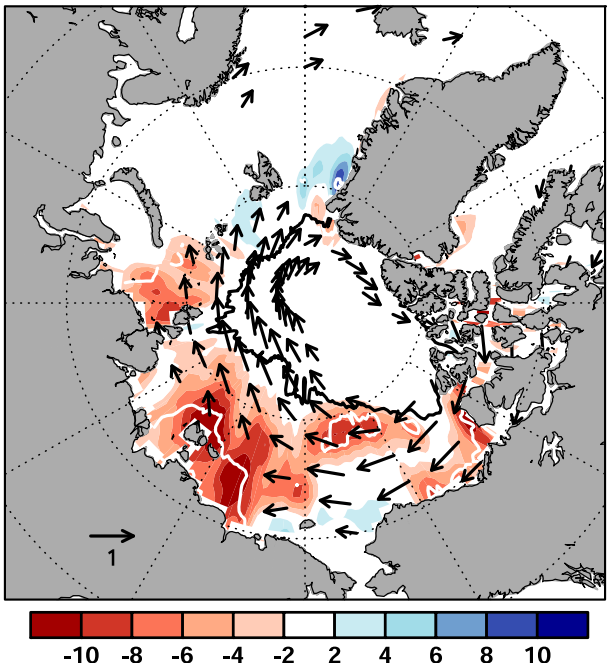

FIG. 5. Detrended September sea ice concentration (shaded; %) and summer (June–August) 925-hPa wind (vectors; m s^{-1}) regressed linearly on the standardized inverted June Eurasian SCE for the period 1988–2011, based on the Met Office Hadley Centre Sea Ice and Sea Surface Temperature dataset, version 1 (Rayner et al. 2003). White contours indicate statistical significance at the 95% level. Black contours indicate SIC of 90% averaged for the period 1988–2011.

snow anomalies affect seasonal sea ice evolution and shape summer sea ice state has not been examined before. In this study, we investigated an across-season relationship between spring snow and summer sea ice through changed atmospheric circulations. Our study focuses on the time period from 1988 to 2011, because the state and behaviors of both sea ice and/or snow and the atmospheric circulation are different during this period from earlier period. In particular, substantial Arctic multiyear ice has been lost since the late 1980s (Maslanik et al. 2007); in consequence, thinned and first-year ice has become more vulnerable to atmospheric circulation forcing during the transition season from spring to summer. Although observational data are short, synthesis from comprehensive data analysis, dynamic diagnosis, and model experiments enhances robustness of the statistical analysis results. Therefore, the finding here augments existing knowledge about the interplay between snow, atmospheric dynamics, and sea ice. It may also have significant implications for improving our capability to forecast seasonal sea ice.

Acknowledgments. This research was funded through grants to the University of Alaska Fairbanks International Arctic Research Center from the Japan Agency for Marine-Earth Science and Technology, the Green Network of Excellence Program (GRENE) Arctic Climate Change Research Project, and the U.S. National Science Foundation Grants ARC 1023592 and 1107509. S. Matsumura was supported by the Institutional Program for Young Researcher Overseas Visits in Japan Society for the Promotion of Science.

REFERENCES

Andrews, D. G., and M. E. McIntyre, 1976: Planetary waves in horizontal and vertical shear: The generalized Eliassen-Palm relation and the mean zonal acceleration. *J. Atmos. Sci.,* **33,** 2031–2048, doi:10.1175/1520-0469(1976)033<2031:PWIHAV>2.0.CO;2.

Bojariu, R., and L. Gimeno, 2003: The role of snow cover fluctuations in multiannual NAO persistence. *Geophys. Res. Lett.,* **30,** 1156, doi:10.1029/2002GL015651.

Brown, R., C. Derksen, and L. Wang, 2010: A multi-data set analysis of variability and change in Arctic spring snow cover extent, 1967–2008. *J. Geophys. Res.,* **115,** D16111, doi:10.1029/2010JD013975.

Comiso, J. C., C. L. Parkinson, R. Gersten, and L. Stock, 2008: Accelerated decline in the Arctic sea ice cover. *Geophys. Res. Lett.,* **35,** L01703, doi:10.1029/2007GL031972.

Derksen, C., and R. Brown, 2012: Spring snow cover extent reductions in the 2008–2012 period exceeding climate model projections. *Geophys. Res. Lett.,* **39,** L19504, doi:10.1029/2012GL053387.

Déry, S. J., and R. D. Brown, 2007: Recent Northern Hemisphere snow cover extent trends and implications for the snow-albedo feedback. *Geophys. Res. Lett.,* **34,** L22504, doi:10.1029/2007GL031474.

Deser, C., and H. Teng, 2008: Evolution of Arctic sea ice concentration trends and the role of atmospheric circulation forcing, 1979–2007. *Geophys. Res. Lett.,* **35,** L02504, doi:10.1029/2007GL032023.

Fetterer, F., K. Knowles, W. Meier, and M. Savoie, 2002: Sea ice index. National Snow and Ice Data Center, Boulder, CO, digital media. [Available online at http://nsidc.org/data/G02135.]

Graversen, R. G., T. Mauritsen, M. Tjernström, E. Källén, and G. Svensson, 2008: Vertical structure of recent Arctic warming. *Nature,* **451,** 53–56, doi:10.1038/nature06502.

Groisman, P. Ya., R. W. Knight, V. N. Razuvaev, O. N. Bulygina, and T. R. Karl, 2006: State of the ground: Climatology and changes during the past 69 years over northern Eurasia for a rarely used measure of snow cover and frozen land. *J. Climate,* **19,** 4933–4955, doi:10.1175/JCLI3925.1.

Kanamitsu, M., W. Ebisuzaki, J. Woollen, S.-K. Yang, J. J. Hnilo, M. Fiorino, and G. L. Potter, 2002: NCEP–DOE AMIP-II Reanalysis (R-2). *Bull. Amer. Meteor. Soc.,* **83,** 1631–1643, doi:10.1175/BAMS-83-11-1631.

Maslanik, J. A., C. Fowler, J. Stroeve, S. Drobot, J. Zwally, D. Yi, and W. Emery, 2007: A younger, thinner Arctic ice cover: Increased potential for rapid, extensive sea-ice loss. *Geophys. Res. Lett.,* **34,** L24501, doi:10.1029/2007GL032043.

Matsumura, S., and K. Yamazaki, 2012: Eurasian subarctic summer climate in response to anomalous snow cover. *J. Climate,* **25,** 1305–1317, doi:10.1175/2011JCLI4116.1.

——, ——, and T. Tokioka, 2010: Summertime land-atmosphere interactions in response to anomalous springtime snow cover in northern Eurasia. *J. Geophys. Res.,* **115,** D20107, doi:10.1029/2009JD012342.

Ogi, M., and J. M. Wallace, 2007: Summer minimum Arctic sea ice extent and the associated summer atmospheric circulation. *Geophys. Res. Lett.,* **34,** L12705, doi:10.1029/2007GL029897.

Overland, J. E., and M. Wang, 2010: Large-scale atmospheric circulation changes are associated with the recent loss of Arctic sea ice. *Tellus,* **62A,** 1–9, doi:10.1111/j.1600-0870.2009.00421.x.

——, J. A. Francis, E. Hanna, and M. Wang, 2012: The recent shift in early summer Arctic atmospheric circulation. *Geophys. Res. Lett.,* **39,** L19804, doi:10.1029/2012GL053268.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.,* **108,** 4407, doi:10.1029/2002JD002670.

Rigor, I. G., J. M. Wallace, and R. L. Colony, 2002: Response of sea ice to the Arctic Oscillation. *J. Climate,* **15,** 2648–2663, doi:10.1175/1520-0442(2002)015<2648:ROSITT>2.0.CO;2.

Robinson, D. A., K. F. Dewey, and R. R. Heim, 1993: Global snow cover monitoring: An update. *Bull. Amer. Meteor. Soc.,* **74,** 1689–1696, doi:10.1175/1520-0477(1993)074<1689:GSCMAU>2.0.CO;2.

Serreze, M. C., M. M. Holland, and J. Stroeve, 2007: Perspectives of the Arctic's shrinking ice cover. *Science,* **315,** 1533–1536, doi:10.1126/science.1139426.

Thompson, D. W. J., and J. M. Wallace, 2000: Annular modes in the extratropical circulation. Part I: Month-to-month variability. *J. Climate,* **13,** 1000–1016, doi:10.1175/1520-0442(2000)013<1000:AMITEC>2.0.CO;2.

Xie, S.-P., H. Noguchi, and S. Matsumura, 1999: A hemispheric-scale quasi-decadal oscillation and its signature in Northern Japan. *J. Meteor. Soc. Japan,* **77,** 573–582.

Zhang, X., M. Ikeda, and J. E. Walsh, 2003: Arctic sea-ice and freshwater changes driven by the atmospheric leading mode in a coupled sea ice–ocean model. *J. Climate,* **16,** 2159–2177, doi:10.1175/2758.1.

——, A. Sorteberg, J. Zhang, R. Gerdes, and J. C. Comiso, 2008: Recent radical shifts of atmospheric circulations and rapid changes in Arctic climate system. *Geophys. Res. Lett.,* **35,** L22701, doi:10.1029/2008GL035607.

——, J. He, J. Zhang, I. Polyakov, R. Gerdes, J. Inoue, and P. Wu, 2013: Enhanced poleward moisture transport and amplified northern high-latitude wetting trend. *Nat. Climate Change,* **3,** 47–51, doi:10.1038/nclimate1631.