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Influence of changes in sea ice concentration and cloud cover on recent Arctic surface temperature trends

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[1] The influence of trends in sea ice concentration (SIC) and cloud cover on trends in surface temperature over the Arctic Ocean from 1982 to 2004 is investigated analytically, and evaluated empirically with satellite products. The results demonstrate that changes in SIC and cloud cover played major roles in the magnitude of recent Arctic surface temperature trends. Significant surface warming associated with sea ice loss, over 0.9 K decade^{-1}, is found over the Chukchi and Beaufort Seas in autumn, accounting for most of the observed 1.1 K decade^{-1} warming trend. If the mean SIC over the Arctic Ocean in each season is reduced by half, our analysis shows that the surface temperature will increase by approximately 10 K in winter and 6 K in spring and autumn. In winter, surface temperature trends associated with changes in cloud cover are negative over most of the Arctic Ocean, and with cloud cover trends explaining −0.91 out of −1.2 K decade^{-1} of the surface temperature cooling. In spring, 0.55 K decade^{-1} of the total 1.0 K decade^{-1} warming can be attributed to the trend associated with cloud cover changes. After eliminating the effects of changes in SIC and cloud cover on surface temperature trends, the residual surface temperature trends can be used in a more robust diagnosis of surface warming or cooling in the Arctic. The same procedure can be applied to study the impact of changes in sea ice thickness, ocean inflow, and other parameters on the temperature trends, and to completely different sets of climate variables, whether they are measured or modeled.
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1. Introduction

[2] The Arctic has been experiencing dramatic changes in recent decades. Surface temperature, the most fundamental of all variables that can be used to assess climate change [*Chapman and Walsh*, 2007; *Chen et al.*, 2002], has changed significantly over the last 20 years [*Rigor et al.*, 2000; *Comiso*, 2003; *Wang and Key*, 2005b]. The albedo-temperature feedback has the potential to amplify greenhouse warming in the Arctic [*Serreze and Francis*, 2006]. Surface temperature responds to changes in large-scale atmospheric circulation [*Zhang et al.*, 2008], cloud amount [*Liu et al.*, 2008], sea ice cover, and other parameters. *Rigor et al.* [2002] argued that observed trends in sea ice concentration (SIC), extent, and thickness contributed to the surface temperature trends. Simulations with global coupled models show significant warming over regions of the Arctic Ocean with sea ice in the present climate but absent in the projections [*Chapman and Walsh*, 2007]. The impact of changes in cloud cover is unclear.

[3] It is not surprising that changes in surface temperature will result from changes in sea ice and cloud cover, as sea ice insulates the atmosphere from the ocean, and clouds have a strong radiative effect on the surface. The question is, how much? The objective of this study is to quantify the effect of SIC and cloud cover changes on recent surface temperature trends over the Arctic Ocean in each season. The results provide insights into the causes of recent surface temperature trends, and are important for projecting future changes in the Arctic climate.

2. Data and Method

[4] A linear model was previously developed by *Liu et al.* [2008] to study the influence of cloud cover changes on surface temperature trends. With the unprecedented loss of Arctic sea ice in recent decades and probable decrease through this century [*Maslanik et al.*, 2007; *Serreze et al.*, 2007], the influence of sea ice changes together with cloud cover changes on the Arctic surface temperature trends become extremely important. In this study, that formulation is extended here to study the effect of changes in SIC and cloud cover on surface temperature trends. The change in surface temperature, T, over time can be partitioned into three components (see Text S1 of the auxiliary material for derivation):[3]

$$\frac{dT}{dt} = Trend\_A + Trend\_B + Trend\_C \qquad (1)$$

The first component, Trend_A, is the observed surface temperature trend caused by cloud cover changes and the surface temperature difference under cloudy- and clear-sky conditions as expressed in equation (2), which is described by *Liu et al.* [2008]. The second component, Trend_B, represents the observed surface temperature trend caused by SIC changes with the surface temperature difference over ice and water under both cloudy- and clear-sky conditions as expressed in equation (3), which is the focus of this study. The third component, Trend_C, represents surface temperature trends associated with changes in other parameters and climate processes. Trend_C can be calculated as the residual

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trend by extracting Trend_A and Trend_B from the total trend.

$$Trend\_A = (T_{cld} - T_{clr}) \cdot \frac{dF_{cld}}{dt} \tag{2}$$

$$Trend\_B = F_{clr} \cdot (T_{clr\_ice} - T_{clr\_water}) \cdot \frac{dF_{ice}}{dt} + F_{cld} \cdot (T_{cld\_ice} - T_{cld\_water}) \cdot \frac{dF_{ice}}{dt} \tag{3}$$

In equations (2) and (3), T_{cld} and T_{clr} are surface temperatures under cloudy- and clear-sky conditions; F_{ice} is the ice fraction or ice concentration; F_{clr} and F_{cld} are clear- and cloudy-sky fraction; T_{clr_ice}, T_{cld_ice}, T_{clr_water}, and T_{cld_water} are surface temperatures over ice and water surface under clear- and cloudy-sky conditions, respectively. In deriving equation (1), changes in SIC and cloud cover are assumed to be independent. Areas of open water in the Arctic Basin might contribute to positive cloud fraction anomalies due to stronger vertical moisture fluxes over open water as in autumn 2007 [*Evan et al.*, 2008]. Further work is needed to confirm this relationship and its effect on equation (1).

[5] To calculate the values of the second component, Trend_B, seasonal means of clear- and cloudy-sky fraction, surface temperature over ice and water surface under clear- and cloudy-sky conditions, and SIC trends are needed. The seasons are defined as winter (December, January, and February), spring (March, April, and May), summer (June, July and August), and autumn (September, October, and November).

[6] Daily SIC on a 25 km × 25 km grid for the period January 1982–December 2004 were obtained from the National Snow and Ice Data Center (NSIDC) with the NASA Team algorithm [*Cavalieri et al.*, 1999]. Monthly and seasonal mean SIC are calculated from daily data. Seasonal SIC linear trends from 1982 to 2004 with statistical confidence levels are calculated based on SIC seasonal means.

[7] The Advanced Very High Resolution Radiometer (AVHRR) Polar Pathfinder (APP) products [*Fowler et al.*, 2000] have been extended to include cloud physical and optical properties, all-sky surface temperature and albedo, and other parameters (APP-x). The APP-x dataset includes daily composites at both 04:00 and 14:00 local solar time (LST) from January 1982 to December 2004 at a 25 km spatial resolution. In this paper, the results at 1400 LST are presented, but conclusions based on both times are similar. The APP-x product, algorithms used, validation outcome, and inter-satellite calibration are described elsewhere [*Wang and Key*, 2003, 2005a, 2005b; *Liu et al.*, 2008; *Key et al.*, 2001, 2002; *Key and Intrieri*, 2000].

[8] Annual seasonal means are derived from daily values of SIC and the daily 1400 LST values of cloud cover and surface temperature over ice and water under clear- and cloudy-sky conditions. The surface type is considered to be water when SIC is less than 15%. Water freezing temperature for an ice pixel is set to be 271.3 K by deriving from the simplified relationship T = 273.1−0.055 × S_w, where seawater salinity S_w is 32.0 ppt. To minimize the effect of temporal sampling in the derived seasonal means directly from daily means, a 10-day mean is derived first from the daily means, and then the annual seasonal mean is calculated as the mean of all 10-day means in that season to include evenly temporal sampling. Seasonal mean is calculated as the mean of all the seasonal means.

Table 1. Surface Temperature Trends Over Regions 1–8, 10, and P[a]

Region	Winter	Sumer	Spring	Autumn
All-sky Surface Temperature Trend (1982–2004) in Winter, Spring, Summer, and Autumn				
1	0.088	**1.1**	−0.19	**1.2**
2	**−1.14**	**1.6**	−0.095	**1.0**
3	−0.34	**1.3**	0.24	0.26
4	**−1.6**	**1.3**	0.11	0.29
5	**−2.0**	**0.85**	0.038	−0.25
6	**−1.9**	0.74	0.36	−0.41
7	**−2.2**	**1.0**	0.27	−0.45
8	**−1.6**	0.74	0.017	−0.54
10	1.0	**1.6**	0.19	0.62
P	**−1.2**	**1.0**	0.14	0.17
Surface Temperature Trend Caused by Cloud Cover Changes (Trend_A)				
1	**−0.63**	**0.52**	0.013	−0.070
2	**−0.80**	**0.65**	−0.00	−0.12
3	**−0.95**	**0.67**	0.087	**−0.36**
4	**−1.3**	**0.76**	0.036	**−0.37**
5	**−1.2**	**0.68**	−0.00	**−0.29**
6	**−1.4**	**0.40**	0.047	**−0.58**
7	**−1.5**	**0.64**	0.030	**−0.47**
8	**−0.70**	**0.52**	−0.011	**−0.25**
10	−0.23	**0.44**	−0.024	−0.00
P	**−0.91**	**0.55**	0.015	**−0.26**
Surface Temperature Trend Caused by Sea Ice Concentration Changes (Trend_B)				
1	−0.14	−0.089	0.13	**0.71**
2	−0.16	−0.029	0.12	**1.1**
3	**−0.39**	**−0.25**	0.024	−0.12
4	−0.12	−0.10	0.062	0.25
5	**−0.12**	−0.049	0.054	0.24
6	−0.00	**−0.12**	0.2	−0.017
7	−0.08	−0.15	0.032	0.089
8	0.21	0.10	0.047	0.19
10	**0.94**	**0.27**	0.11	**0.70**
P	−0.048	−0.056	0.055	**0.34**
Surface Temperature Residual Trend				
1	0.86	0.71	−0.33	0.55
2	−0.18	1.0	−0.21	0.047
3	1.0	0.85	0.13	0.73
4	−0.16	0.66	0.016	0.41
5	−0.72	0.22	−0.012	−0.20
6	−0.44	0.46	0.29	0.19
7	−0.68	0.55	0.21	−0.066
8	−1.15	0.12	−0.019	−0.49
10	0.31	0.85	0.11	−0.077
P	−0.19	0.53	0.069	0.086

[a]All-sky surface temperature trends, surface temperature trends caused by cloud cover changes (Trend_A), surface temperature trends caused by sea ice concentration changes (Trend_B), and surface temperature residual trends averaged over Region 1 (Beaufort Sea), 2 (Chukchi Sea), 3 (Canada Basin), 4 (Central Arctic), 5 (Laptev Sea), 6 (North Pole), 7 (Nansen Basin), 8 (Kara Sea), 10 (Baffin Bay), and P (ocean area poleward of 70°N latitude) with seasonal mean sea ice concentration larger than 15%. Unit: K decade^{-1}. Trends with confidence level higher than 95% are in bold.

3. Results

[9] All-sky surface temperature from 1982 to 2004 based on the APP-x product shows strong cooling trends in winter, but strong warming trends in spring over most of the Arctic Ocean (Figure 2a). Mean surface temperature trends averaged over the ocean area poleward of 70°N latitude are −1.2 and 1.0 K decade^{-1} in winter and spring, respectively. Table 1 gives values of trends averaged over selected regions

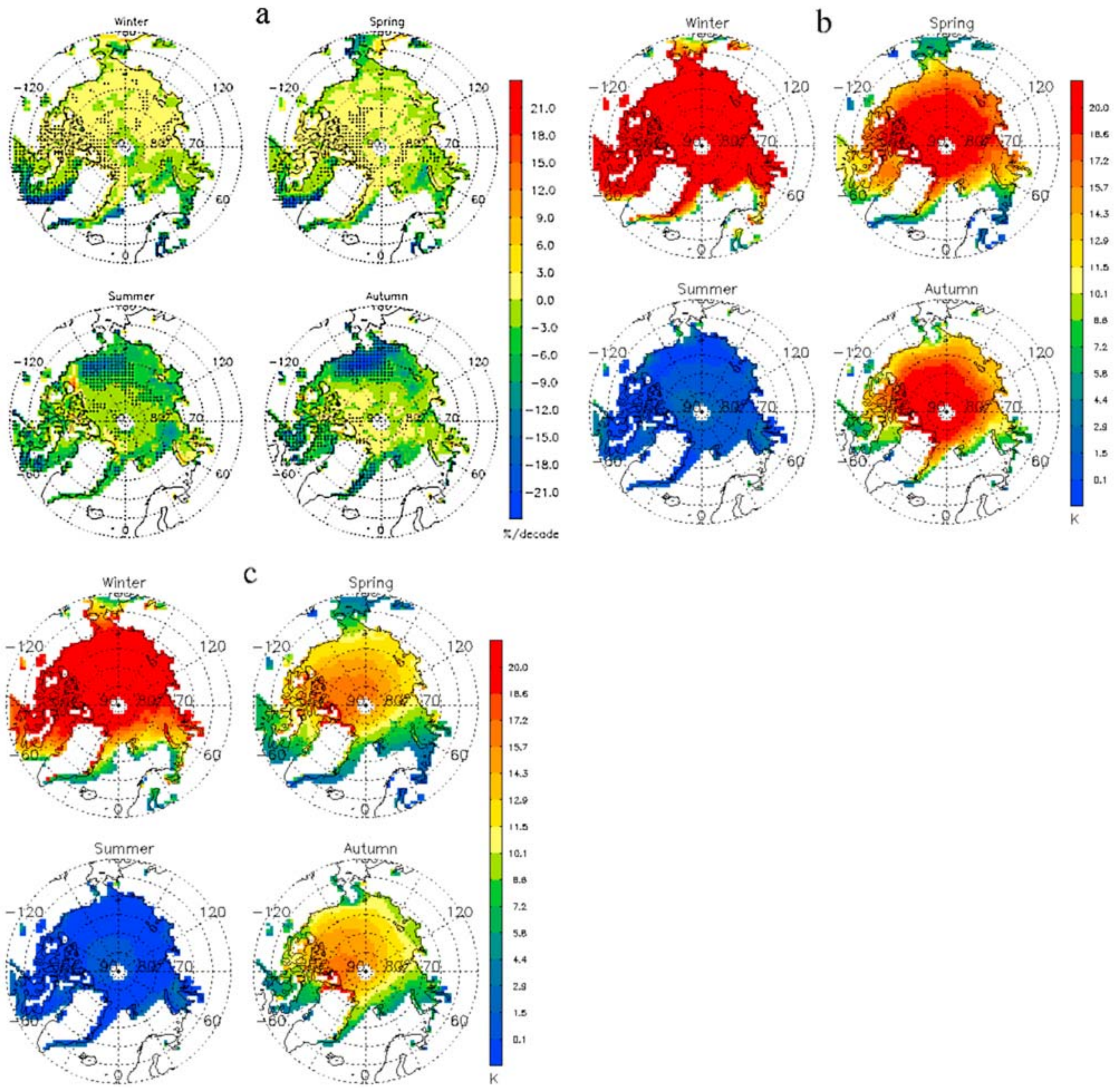

Figure 1. (a) Sea ice concentration trend from 1982 to 2004. A concentration trend with a confidence level larger than 95% is indicated with a small plus sign. (b) The surface temperature difference over water and ice surfaces under clear-sky conditions. (c) The surface temperature difference over water and ice surfaces under cloudy-sky (right) conditions.

(regions defined as by *Wang and Key* [2005a, Figure 1]). In summer, there are no substantial temperature changes over the Arctic Ocean during the study period. In autumn, surface temperature increased over the Chukchi and Beaufort Seas, with slight cooling over the Kara and Barents Seas. The all-sky surface temperature warming and cooling patterns in four seasons are similar to those in other studies [*Rigor et al.*, 2000; *Comiso*, 2003].

[10] Changes in SIC from 1982 to 2004 are different in sign, magnitude, and spatial distribution in the four seasons (Figure 1a). Winter and spring SIC trends exhibit slight positive values over the Canada Basin and most of the central Arctic Ocean. Negative trends are near the ice edges in the Nansen Basin and the Barents and Kara Seas, with an absolute magnitude less than 2.0% decade^{-1}. Strong negative trends in Baffin Bay are more than -7.0% decade^{-1}. In summer and autumn, SIC trends exhibit negative values over most of the Arctic Ocean. The largest SIC decrease exists over the Chukchi and Beaufort Seas, with an average trend of -6.1% decade^{-1} in summer, -9.8% decade^{-1} in autumn, and over -15% decade^{-1} over part of the Chukchi Sea in autumn. The sign, magnitude, spatial pattern of SIC trends shown here are consistent with those of SIC trends calculated using same dataset from 1979 to 2006 [*Deser and Teng*, 2008].

[11] The surface temperature difference between water and ice is, not surprisingly, positive under both cloudy- and clear-sky conditions in all seasons (Figures 1b and 1c). The winter surface temperature difference between water and ice is largest, at 30.1 K and 21.5 K averaged over the Arctic Ocean

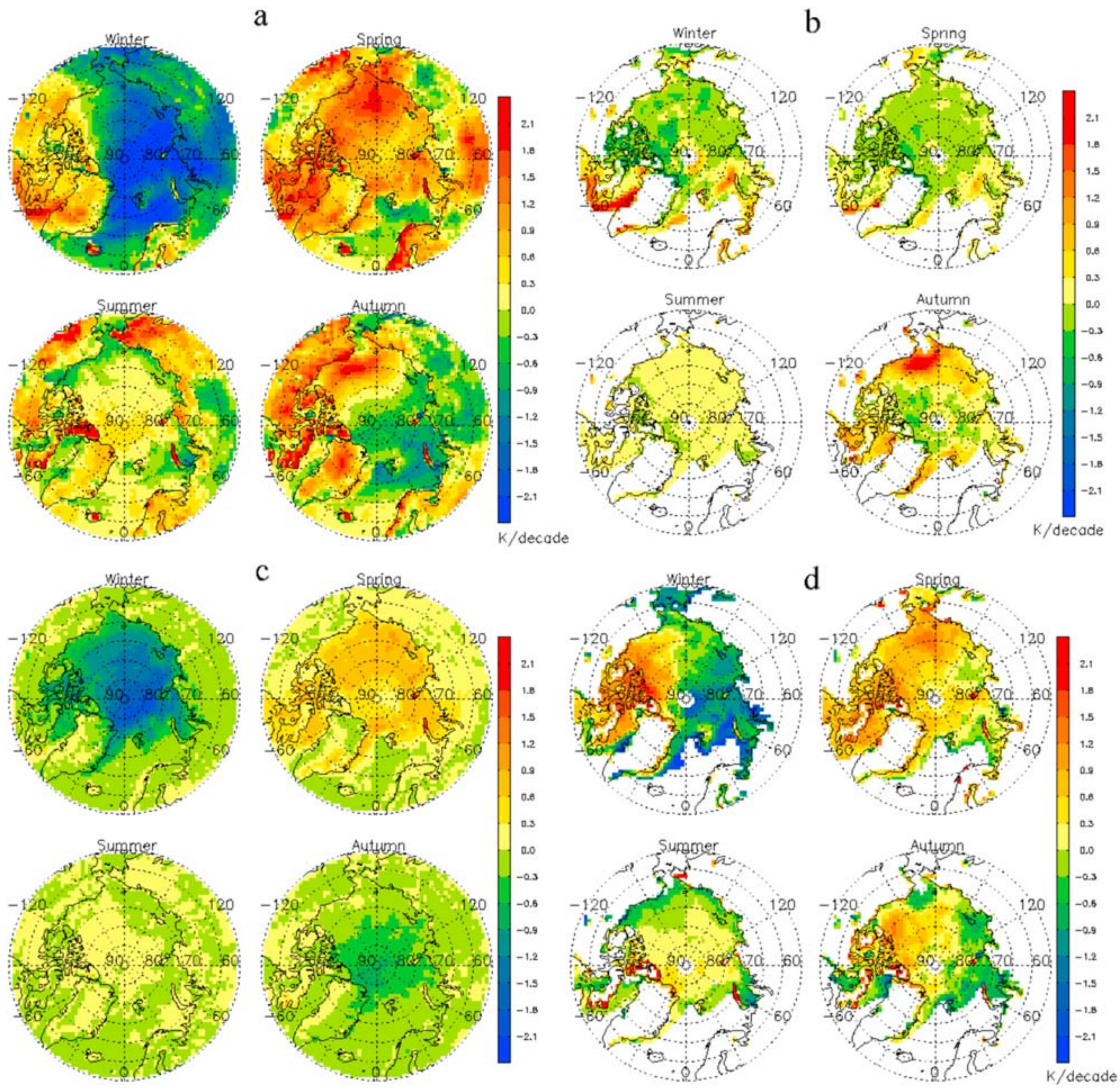

Figure 2. (a) The seasonal all-sky surface temperature trend, (b) Trend B, (c) Trend A, and (d) residual trends from 1982 to 2004. The residual trend is the difference between the all-sky surface temperature trend (1982–2004) and the sum of Trend_A and Trend_B.

under clear- and cloudy-sky conditions, respectively. The summer surface temperature difference is small, typically less than 2 K under both clear- and cloudy-sky conditions due to the fact that the melting sea ice surface has a temperature similar to that of the surrounding open water. Surface temperature differences in spring and autumn are similar in magnitude and spatial pattern, with the largest differences over the Canada Basin and the smallest difference around the ice edges. In spring (autumn), the mean differences averaged over the Arctic Ocean are 18.0 (16.2) K and 12.4 (11.7) K under clear- and cloudy-sky conditions respectively. Over the Arctic Ocean, clouds warm the surface at all times of the year except during a portion of the summer [*Intrieri et al.*, 2002]. The surface temperature difference between water and ice under cloudy-sky conditions is smaller than under clear-sky conditions in winter, spring, and autumn due to the cloud warming effect.

[12] Surface temperature trends from 1982 to 2004 caused by SIC changes due to temperature differences between water and ice are calculated as Trend_B in equation (3), using the data shown in Figure 1 and the seasonal mean cloud cover (Figure 2b). In winter, Trend_B exhibits large positive values over Baffin Bay, with a mean of 0.94 K decade^{-1} and positive values over the ice edges in the Nansen Basin and the Barents and Kara Seas. These positive trends arise from the significant SIC decreases and large surface temperature difference between water and ice surfaces. Trend_B is slightly negative over most of the Arctic Ocean due to small SIC increases. In spring, Trend_B has patterns similar to the winter trends, with relatively smaller magnitude due to the smaller surface

temperature difference between water and ice surfaces in spring. In summer, Trend_B is slightly positive over most of the Arctic Ocean due to the very small surface temperature difference between water and ice. In autumn, large positive values of Trend_B, with means of 0.71 and 1.1 K decade^{-1} respectively and 0.9 K decade^{-1} as mean, appear over the Chukchi Sea and the Beaufort Sea, which is attributable to the large negative SIC trends and accounts for most of the observed 1.1 K decade^{-1} warming trend as mean.

[13] Surface temperature trends caused by cloud cover changes as a result of the surface temperature difference under cloudy- and clear-sky conditions are shown in Figure 2c. These trends are calculated as Trend_A in equation (2) [see *Liu et al.*, 2008]. Trend_A is negative over the Arctic Ocean in winter due to decreasing cloud cover, and positive over the Arctic Ocean in spring due to increasing cloud cover. The mean trends are -0.91 and 0.55 K decade^{-1} in winter and spring averaged over the Arctic Ocean poleward of 70°N. In summer and autumn, Trend_A is small over the Arctic Ocean, with slightly positive trends in summer and negative trends in autumn. The mean trends are 0.015 and -0.26 K decade^{-1}.

[14] The surface temperature residual trends, calculated as the difference between the total all-sky surface temperature trend and the sum of Trend_B and Trend_A, are shown in Figure 2d. These residual trends illustrate to what extent the changes in SIC and cloud cover do not explain the total all-sky surface temperature trend. In winter, residual trends are positive over the western Arctic Ocean and negative over the eastern Arctic Ocean. Though the mean residual trend averaged over the Arctic Ocean is -0.19 K decade^{-1}, the positive trend over the Canada Basin is as high as 1.0 K decade^{-1}, and the negative trend over the Laptev Sea is as low as -0.72 K decade^{-1}. In spring, residual trends have large positive values over most of the Arctic Ocean, with a mean of 0.53 K decade^{-1}. In summer, the residual trends are not significant over most of the Arctic Ocean. In autumn, the residual trends show a pattern similar to that in winter, but with a smaller magnitude.

4. Discussion and Conclusions

[15] Surface temperature trends caused by changes in SIC (Trend_B) and cloud cover (Trend_A) are two components of the observed surface temperature trends. The overall trend would not be the same if there were no changes in SIC or cloud cover. For example, the total surface temperature trend and Trend_A are -1.2 and -0.91 K decade^{-1}, respectively, in winter averaged over the Arctic Ocean poleward of 70°N from 1982 to 2004. If there were no changes in cloud cover, the total surface temperature trend would be much smaller, -0.29 K decade^{-1}.

[16] Trend_A tend to have the same sign as the total surface temperature trend. In winter, Trend_A is negative over most of the Arctic Ocean, with the same sign as the total trend. More than 70% of the surface temperature cooling trends over the Arctic Ocean come from Trend_A (-0.91 out of -1.2 K decade^{-1}). In spring, a positive Trend_A is found over most of the Arctic Ocean. Trend_A contributes half of the surface temperature warming trend during that season (0.55 out of 1.0 K decade^{-1}). Trend_B exhibit more regional differences. Trend_B exhibits higher positive values over regions with larger SIC changes, mainly over the sea ice edge, and relatively smaller values over the central Arctic Ocean in spring, autumn, and winter. Trend_B has positive values over Baffin Bay, the ice edge in the Nansen Basin, the Barents and Kara Seas in winter, spring and autumn, where dramatic sea ice loss occurred over the past two decades. In autumn, positive Trend_B over the Chukchi Sea (0.71 K decade^{-1}) and Beaufort Sea (1.1 K decade^{-1}) explains most of the positive trends in the overall surface temperature trends. Over the eastern Arctic Ocean in winter, the residual trends are more negative due to a negative total surface temperature trend and positive Trend_B over the same region. In winter, Trend_B does not explain the cooling surface temperature pattern; on the contrary, it makes the trend pattern with warming over the western Arctic Ocean and cooling over the eastern Arctic Ocean even stronger. Changes in cloud cover and ice concentration can have opposite effects on the total surface temperature trend. For example, in autumn, positive values of Trend_B (0.34 K decade^{-1}) and negative values of Trend_A (-0.26 K decade^{-1}) appear over the ocean area poleward of 70°N latitude. Table 1 has a complete list of the trend relationships for all seasons and regions. Trend_B is determined to be significant when the ice and water surface temperatures are significantly different, and SIC trends are significant. Trend_A is determined to be significant when the surface temperatures under cloudy- and clear-sky conditions are significantly different, and cloud amount trends are significant.

[17] The residual trends shown in Figure 2d may allow for a more robust diagnosis of causes for surface warming or cooling in the Arctic by eliminating the effects of SIC and cloud amount changes. Considering the complexity of the Arctic climate system, changes in parameters other than cloud amount and SIC are very likely to contribute to the residual trends. Potentially significant processes not considered in the formulation presented here include changes in the heat convergence due to shifting atmospheric circulation patterns, changes in Atlantic and Pacific Ocean inflow, and changes in atmospheric composition other than cloud fraction. For example, poleward sensible heat flux convergence derived from TIROS-N Operational Vertical Sounder (TOVS) Polar Pathfinder data set exhibit negative trends over the Arctic Ocean in winter except over the Laptev Sea, and negative trends over the eastern Arctic Ocean in autumn except over the Laptev Sea. The negative trends are consistent with the cooling trends shown in the residual trends over the Arctic Ocean.

[18] The equations to calculate Trend_A and Trend_B can be applied to project potential future climate change over the Arctic Ocean due to SIC changes, albeit in a rather simplistic way. If the SIC over the Arctic Ocean is reduced by half, equation (3) shows that the surface temperature will increase by approximately 10 K in winter and 6 K in spring and autumn. These numbers, without taking into account the complex feedbacks, provide a theoretical range of the temperature changes due to sea ice changes.

[19] This study applies a linear model to estimate the influence of changes in SIC and cloud cover on recent Arctic surface temperature trends based on multiple satellite products. Though this estimation does not indicate the cause and effect of these trends, it gives the quantitative estimation of influences of different physical parameters, SIC and cloud

cover, on the overall surface temperature trend. In doing so, it helps identify the potential causes of surface warming and cooling. Results show that changes in SIC and cloud cover played crucial roles in the recent surface temperature trends, and will likely contribute to future changes. This model can be extended to study the influences of changes of other parameters, including sea ice thickness, ocean inflow, etc., on the Arctic surface temperature trends. The same procedure can also be applied to completely different sets of climate variables, whether they are measured or modeled.

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