



## Possible causes of decreasing cloud cover in the Arctic winter, 1982–2000

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[1] Satellite and reanalysis datasets show a decrease in wintertime (Dec., Jan., Feb.) cloud cover over most of the Arctic Ocean from 1982 to 2000. Concurrently, wintertime moisture convergence has decreased significantly over the Nansen Basin and parts of the Barents and Kara Seas (NBK; 75–90°N, 45–90°E). Over this region, correlation coefficients between monthly anomalies in the satellite-derived cloud cover and moisture convergence in the cold season are large and statistically significant. This reduction in moisture convergence results in a decrease in cloud formation due to weakening cyclone activity over the NBK region. Reduced cloud amount over this area leads to decreased cloud cover over the entire central Arctic because less cloud is advected to other regions. The same mechanism has been observed over northeastern Russia and the Bering Strait area (RBS; 65–75°N, 150–200°E) and is therefore an additional, and perhaps more important, control over cloud cover in the Chukchi/Beaufort Seas and the Laptev Sea region. **Citation:** Liu, Y., J. R. Key, J. A. Francis, and X. Wang (2007), Possible causes of decreasing cloud cover in the Arctic winter, 1982–2000, *Geophys. Res. Lett.*, *34*, L14705, doi:10.1029/2007GL030042.

### 1. Introduction

[2] Wang and Key [2003, 2005b] presented cloud fraction trends from 1982 to 1999 over the area north of 60°N. They found increasing cloud fraction during spring and summer (3%/decade in spring and 1.5%/decade in summer), and associated these trends with increasing cyclonic activity. They also found a statistically significant decrease in cloud fraction over the central Arctic in autumn, and over most of the Arctic in winter (–5 %/decade in winter), while cyclone frequency and intensity in winter increased over the Arctic as a whole [Serreze *et al.*, 1997; Key and Chan, 1999; Zhang *et al.*, 2004].

[3] Cloud formation mechanisms in the Arctic are not well understood. Curry *et al.* [1996] stated that clouds in the marginal ice zone are frequently associated with frontal systems; the formation of mid- and upper-level clouds over the Arctic Ocean is closely associated with frontal systems and cyclone activities; and low-level clouds form when relatively warm, moist air is advected into the polar basin and cools radiatively. Beesley and Moritz [1999] examined

three factors that control low cloud amount over the Arctic Ocean, including moisture flux convergence, surface evaporation, and microphysical processes related to atmospheric ice. They further suggested that temperature-dependent ice-phase processes are essential in low cloud formation based on model simulations.

[4] In this study the decreasing winter cloud cover trend over the Arctic Ocean from 1982 to 2000 is examined, and causes for this trend are proposed. Possible cloud formation mechanisms over the Arctic Ocean in winter are also investigated.

### 2. Data and Method

[5] The extended AVHRR Polar Pathfinder (APP-x) product includes cloud parameters: fractional cover, optical depth, particle phase and size, and other parameters. This information is derived with the Cloud and Surface Parameter Retrieval system [Key, 2002]. Clouds are detected with a variety of spectral and temporal tests optimized for high-latitude conditions [Key and Barry, 1989]. Detection of winter cloud in Arctic is more difficult than in other seasons [Liu *et al.*, 2004b], but the APP-x dataset performs well [Wang and Key, 2005a]. Products have been successfully validated with data collected during the Surface Heat Balance of the Arctic field experiment [Wang and Key, 2003, and references therein]. The recently updated APP-x includes daily composites at both 04:00 and 14:00 local solar time (LST) from January 1982 to December 2000 at a 25 km spatial resolution, which is then sub-sampled to 100 km to match other products. Only the results at 14:00 LST are presented, but conclusions based on both times are similar.

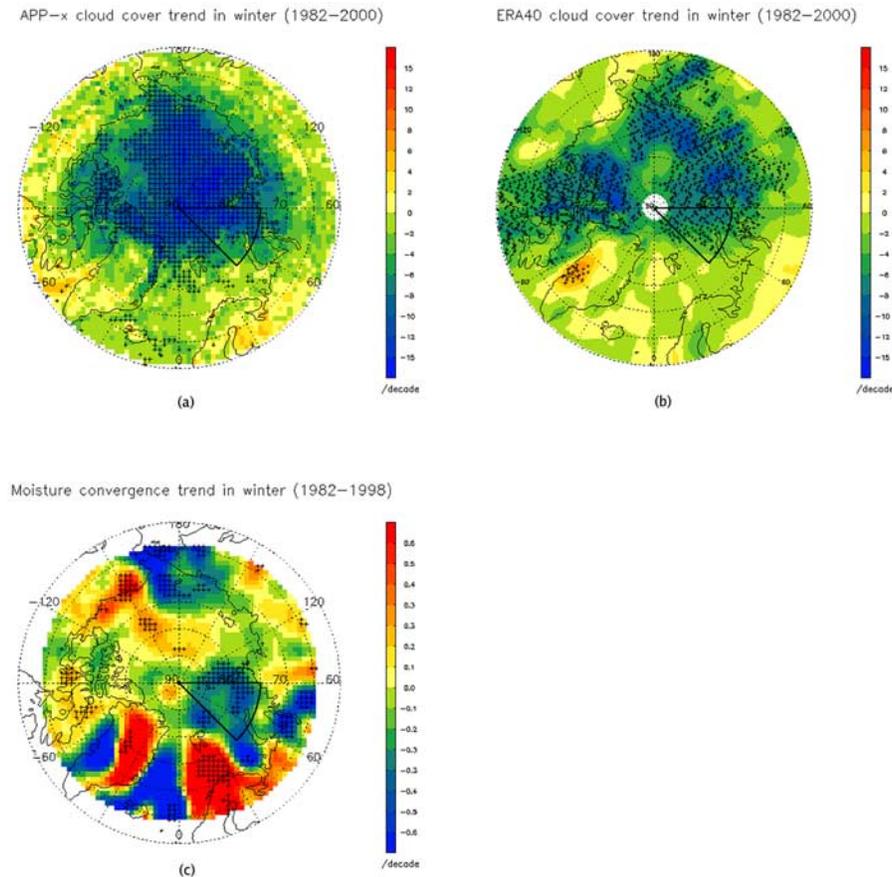
[6] By combining precipitable water retrievals from the TIROS Operational Vertical Sounder (TOVS) Polar Pathfinder (Path-P) dataset with wind and surface pressure fields from the NCEP-NCAR reanalysis, Groves and Francis [2002a] created a dataset of the Arctic atmospheric moisture budget at a horizontal resolution of 100 km from 1979 to 1998. This dataset provides 19 years of daily, vertically integrated precipitable water flux convergence (hereinafter TOVS Path-P moisture convergence).

[7] This study also incorporates monthly means of total cloud cover and surface evaporation, four-times daily cloud cover, and relative vorticity at 850 hPa from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-40) from January 1982 to August 2002. Some TOVS radiances were assimilated in the ERA-40, but AVHRR data were not. A simple algorithm is developed to define cyclonic and anticyclonic conditions based on the 850 hPa relative vorticity. For this study, a model grid point is identified as cyclonic (anticyclonic) if the relative vorticity

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**Figure 1.** Decadal trends in Arctic winter (a) cloud cover from APP-x (%/decade), (b) cloud cover from ERA-40, (c) moisture convergence (cm/month/decade) from TOVS Path-P. Trends with a confidence level higher than 95% based on the F-test are indicated with a plus. The NBK region is identified with a solid black outline.

is larger (smaller) than  $2.0 \times 10^{-5} \text{ s}^{-1}$  ( $-2.0 \times 10^{-5} \text{ s}^{-1}$ ). Monthly cyclone (anticyclone) frequencies are calculated as the percentage of cyclonic (anticyclonic) conditions occurring relative to all records per month (e.g. 30 day  $\times$  4 time/day). Monthly mean cyclonic (anticyclonic) cloudiness is calculated as the mean cloud amount under cyclonic (anticyclonic) conditions during each month.

[8] Monthly means of each parameter are calculated from daily values. Seasonal means of each parameter in winter (defined as December, January, and February) are calculated from monthly means, and seasonal trends from 1982 to 2000 are derived from seasonal means using least-squares-fit linear regression.

### 3. Results

#### 3.1. Trends in Cloud Cover and Moisture Convergence in Winter

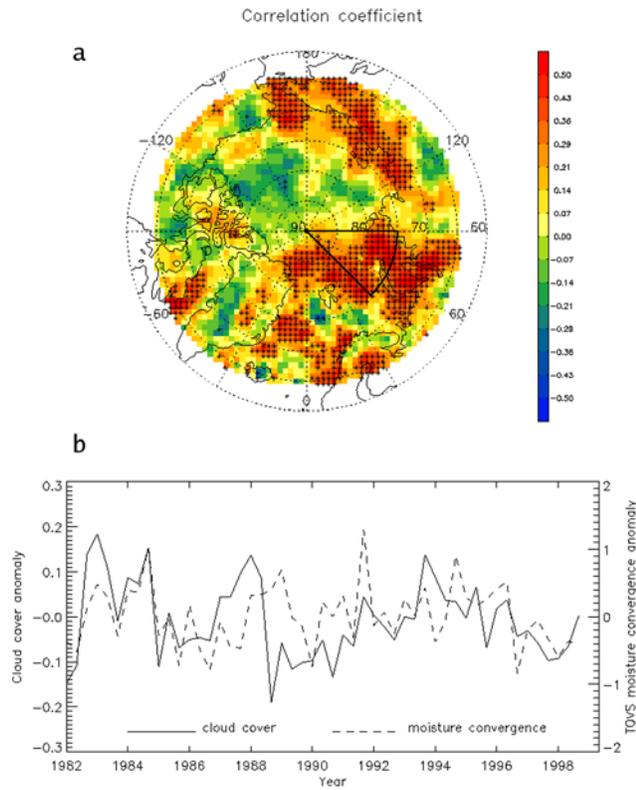
[9] Significant decreasing cloud cover in APP-x from 1982 to 2000 (Figure 1a) is apparent over most of the Arctic Ocean, with a maximum decadal trend of approximately  $-12\%$  over most of the eastern portion. Schweiger [2004] also reported significant decreasing cloud cover from TOVS Path-P over the winter Arctic Ocean from 1982 to 2001, as did Comiso [2003] over sea-ice-covered areas based on AVHRR data using a different retrieval algorithm. Winter cloud cover trend from 1982 to 2000 in ERA-40 (Figure 1b) is also generally negative over the Arctic Ocean. Negative

trends in surface skin temperature over the Arctic Ocean in winter [Wang and Key, 2005b; Comiso, 2003] and in ERA-40 2-meter air temperature are also evident (not shown). Differences in outgoing longwave radiation [Liebmann and Smith, 1996] for January–March 2000–2005 minus January–March 1980–1985 also correspond reasonably well to the trends in the winter cloud cover (not shown). This corroboration among trends in cloud cover from different satellite sensors, retrieval algorithms, and the ERA-40 reanalysis provides further confidence in the decreasing winter cloud cover over the Arctic Ocean.

[10] Positive seasonal trends of moisture convergence in the Arctic winter from 1982 to 1998 (Figure 1c) are apparent over the Beaufort Sea, eastern Greenland-Iceland-Norwegian Seas, and the western Barents Sea. Negative trends are observed over the Bering Strait as well as a region including the Nansen Basin and part of the Barents and Kara Seas bounded by  $75\text{--}90^\circ\text{N}$  and  $45\text{--}90^\circ\text{E}$  (hereinafter “NBK”). The pattern of moisture convergence trends is consistent with the decadal difference (1989 to 1998 minus 1980 to 1988) changes in cold-season net precipitation [Groves and Francis, 2002b, Figure 14].

#### 3.2. Possible Causes of Decreasing Cloud Cover Over the Arctic Ocean

[11] Winds transport moisture from low to high latitudes on average, where some of the moisture condenses to form



**Figure 2.** (a) Correlation between monthly anomalies in APP-x cloud cover and TOVS moisture convergence during the cold season from 1982 to 1998. Confidence level higher than 95% based on student-t test, with adjustments for temporal autocorrelations, are indicated with a plus. The NBK region is identified with a solid black outline. (b) Time series of anomalies in APP-x cloud fraction and TOVS Path-P moisture convergence (cm/month) during the cold season from 1982 to 1998 averaged over the NBK region (75–90°N; 45–90°E).

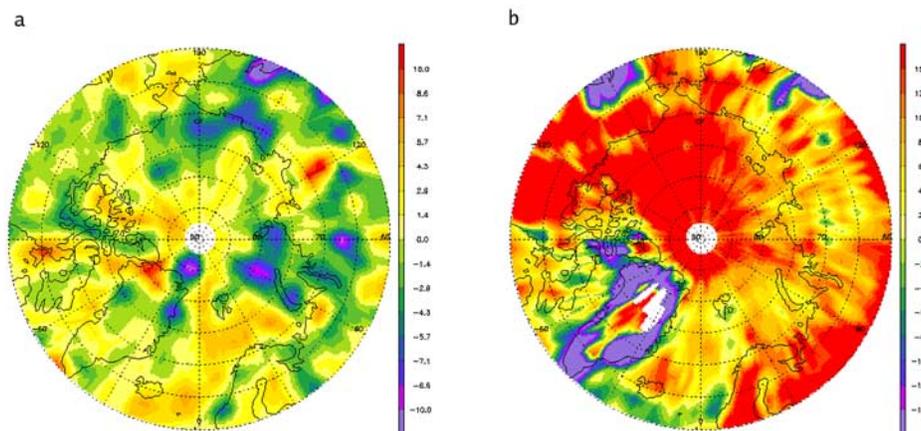
clouds. Decreasing Arctic cloud cover in winter, consequently, may be associated with changes in moisture convergence. This possibility is investigated with winter anomalies in

APP-x cloud cover and TOVS moisture convergence that are calculated by subtracting individual monthly means from the long-term monthly means and detrending. Correlation coefficients (CCs) between these two monthly anomalies (Figure 2a) show that significant positive correlations occur over northeastern Russia/Bering Strait and over NBK, where negative trends in both moisture convergence and cloud cover occur. Time series of these two monthly anomalies averaged over NBK in winter (Figure 2b) are generally in phase, with a correlation coefficient of 0.55. This suggests a correspondence between changes in cloud cover and moisture convergence over this region.

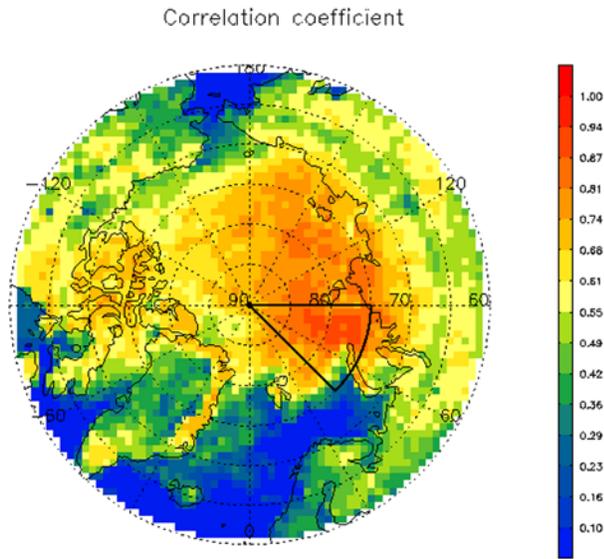
[12] Negative trends in moisture convergence and cloud cover over NBK may result from weaker cyclonic activity in the area, as cyclonic disturbances provide lift that cools and condenses atmospheric water vapor into clouds. Cyclone frequency and intensity in the Arctic overall increased from 1982 to 2000, but changes may vary over different regions and seasons. *Serreze et al.* [1997] found opposite tendencies in cyclone activity over the Barents and Kara Seas during the positive mode of the North Atlantic Oscillation (NAO) from 1966 to 1993. The NAO index during winter has been in a predominantly positive mode since the mid-1970s, suggesting a decrease in cyclonic activity over NBK during 1982 to 2000. *Zhang et al.* [2004] showed that Arctic-mean cyclone activity increased during the second half of the 20th century, along with fewer closed lows over NBK [*Zhang et al.*, 2004, Figure 13c].

[13] Differences in the ERA-40 winter cyclone frequency (1990 to 2000 minus 1982 to 1989, Figure 3a) show decreases over most of NBK, with a mean difference around -3.0%, where the mean cyclone frequency is approximately 29%. Meanwhile, difference in winter cloud amount from ERA-40 under cyclonic versus anticyclonic conditions is positive over most of the Arctic (Figure 3b), suggesting that less frequent cyclones are associated with reduced cloud cover. Difference in winter cloud amount from APP-x shows a very similar pattern but with a smaller magnitude. The relationship between cloud amount and cyclone frequency is insensitive to the threshold selected to identify cyclones and anticyclones.

[14] The correspondence between moisture convergence, cyclone frequency and cloud amount is similar in the Pacific



**Figure 3.** (a) Winter (Dec., Jan., Feb.) ERA-40 cyclone frequency difference (1990 to 2000 minus 1982 to 1989) in %. (b) ERA-40 cloud amount (%) difference under cyclonic and anticyclonic conditions in winter.



**Figure 4.** Correlation between APP-x cloud cover monthly anomalies in each grid cell and those averaged over (75–90°N; 45–90°E) in the cold season from 1982 to 2000.

side of the Arctic, northeastern Russia, and the Bering Strait bounded by 65–75°N, 150–200°E (hereinafter “RBS”). Reduced moisture convergence and cyclone frequency from 1982 to 2000 over RBS is associated with decreased cloudiness. CCs between monthly anomalies in cloud cover and moisture convergence are approximately 0.40 over RBS, slightly lower than those observed over NBK (Figure 2a).

[15] Figure 1a shows significant decreasing trends in cloud over not only in NBK and RBS, but over most of the Arctic Ocean. Though the negative cloud cover trends in NBK and RBS appear to be associated with decreased moisture convergence and weaker cyclone activity, the reduced cloud cover over other regions is still unexplained.

[16] *Serreze and Barry* [1988] found that cyclones from the North Atlantic and the Barents Sea coastline merge near 75–90°N, 30–90°E, then track eastward to northeastward. This raises the possibility that reduced cloud cover over NBK may be a source of decreased cloud cover over regions “downstream”. To investigate this possibility, an index is created as averaged monthly anomalies in cloud cover over NBK. Monthly anomalies of cloud cover at each grid point in the Arctic are then spatially correlated with that

index in winter from 1982 to 2000 (Figure 4). High positive correlations are found over most of the Arctic Ocean, with larger values in the eastern portion. This pattern suggests that cloud cover anomalies over most of the Arctic Ocean are in phase.

[17] Cloud cover anomalies over other regions in the Arctic Ocean might be affected by, or originate from, cloud cover anomalies over NBK. To examine this possibility, the Arctic Ocean is divided into five areas, each 45 degrees of longitude (from 45°E to 270°E), sequentially eastward around the Arctic, as regions 1 to 5 (1: NBK, 2: Laptev Sea, 3: East Siberian Sea, 4: Chukchi/Beaufort Seas, and 5: Canada Basin). All five areas exhibit decreasing cloud cover trends in winter. From December to the following February, daily APP-x cloud cover over each of these five regions is averaged, and daily anomalies are calculated by subtracting 30-day means. CCs between the daily anomalies over NBK and over the other four regions are then calculated, with NBK leading other regions by 0 to 7 days. An example of the resulting CCs and their significance for 1995 winter is presented in Table 1. CCs within NBK itself decrease with time; the correlation between NBK (1) and the Laptev Sea (2) is highest within 2 days, after which it decreases. Values between NBK, the East Siberian Sea (3), and the Chukchi/Beaufort Seas (4) are small within a 2-day lag but become larger later, with maxima at 3- and 4-day lags. Correlations between NBK and the Canada Basin (5) are largest at 5- and 6-day lags. The cloud-cover anomalies over NBK appear to be advected successively to the Laptev Sea, the East Siberian Sea, the Chukchi/Beaufort Seas, and the Canada Basin. CCs between the Canada Basin and the Chukchi/Beaufort Seas and then for NBK, however, do not exhibit this pattern.

[18] Cloud cover anomalies over RBS affect cloud cover over other regions in a similar manner. CCs between cloud-cover anomalies over RBS are higher over Chukchi/Beaufort Seas and the Laptev Sea. *Serreze and Barry* [1988] found that cyclones from the North Atlantic and the Barents Sea rarely penetrate into the western Arctic. Cyclones entering from the Bering Strait region usually take a northerly track. Consequently, reduced cloud cover over RBS might have a stronger influence on the Chukchi/Beaufort Seas and the Laptev Sea.

#### 4. Discussion

[19] *Beesley and Moritz* [1999] suggest temperature dependence of ice-phase microphysical processes is an

**Table 1.** Correlation Coefficients (CCs) of Cloud Cover Anomalies Between Five Regions Over Arctic Ocean in Winter in 1995<sup>a</sup>

	Region 1 NBK (75°–90°N)(45°–90°E)	Region 2 Laptev (75°–90°N)(90°–135°E)	Region 3 E. Siberian (75°–90°N)(135°–180°E)	Region 4 Chukchi/Beaufort (75°–90°N)(180°–225°E)	Region 5 Canada Basin (75°–90°N)(225°–270°E)
0_day lag	1.00	0.48 <sup>a</sup>	0.15	0.17	0.23
1_day lag	0.68 <sup>a</sup>	0.45 <sup>a</sup>	0.15	0.25	0.25
2_day lag	0.45 <sup>a</sup>	0.39 <sup>a</sup>	0.25 <sup>a</sup>	0.29 <sup>a</sup>	0.14
3_day lag	0.28 <sup>a</sup>	0.28 <sup>a</sup>	0.31 <sup>a</sup>	0.34 <sup>a</sup>	0.14
4_day lag	0.17	0.16	0.29 <sup>a</sup>	0.36 <sup>a</sup>	0.22
5_day lag	0.07	–0.08	0.19	0.32 <sup>a</sup>	0.36 <sup>a</sup>
6_day lag	0.04	–0.13	0.16	0.27	0.30 <sup>a</sup>
7_day lag	0.06	–0.19	0.03	0.16	0.19

<sup>a</sup>CCs with confidence levels, based on student-t test with adjustments for temporal autocorrelation, higher than 95%.

essential factor in explaining the annual cycle of low cloud amount in the Arctic. A cloud containing ice particles would dissipate more quickly than one with liquid droplets owing to faster fall rates, so cloud fraction would be lower for ice clouds [Vavrus, 2004]. Trends in cloud phase from the APP-x, which corresponds mainly to cloud-top particles, suggest the percentage of ice cloud has indeed increased over most of the central Arctic Ocean. While these trends are statistically significant only over the Nansen Basin, they are consistent with the mechanism of decreased cloud cover suggested by Beesley and Moritz [1999] and may augment the reduction of cloud cover in the central Arctic Ocean.

[20] Changes in surface evaporation could also influence cloud amount. Latent heat flux over leads, with values larger than  $100 \text{ W m}^{-2}$ , is much greater than that over the ice pack in the Arctic winter [Andreas and Cash, 1999]. Sea-ice concentration has decreased over most of the Arctic Ocean [Liu et al., 2004a], which might lead to increasing surface evaporation. If cloud-cover trends were dominated by the surface moisture source, however, the cloud cover would increase rather than decrease. Furthermore, ERA-40 shows no significant trend in winter evaporation over the Arctic Ocean from 1982 to 2000, and thus appears to be an unlikely explanation for observed cloud change in this region.

## 5. Summary

[21] Decreased winter cloud cover over the Arctic Ocean from 1982 to 2000 is apparent in the APP-x, TOVS Path-P, and ERA-40. Cloud cover anomalies over NBK are significantly correlated with moisture convergence anomalies. Over NBK, cyclone frequencies decreased during the same period, which may account for the decreasing cloud cover and moisture convergence over this region. Cloud cover anomalies over NBK are strongly correlated with anomalies over the central Arctic Ocean, with NBK anomalies apparently preceding those over regions to the east (regions numbers 2, 3, 4, 5 in Table 1). Decreased cloud over NBK appears to result in less cloud advected into the central Arctic Ocean, contributing to lower cloud amounts basin-wide. The same mechanism is observed over RBS; reduced cloud cover over RBS appears to have a stronger influence on cloud cover in the Chukchi/Beaufort Seas and the Laptev Sea than does cloud change in NBK.

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