The Correlation and Regression Analysis on Aerosol Optical Depth, Ice Cover and Cloud Cover in Greenland Sea

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***Abstract*—Researches on Arctic aerosol, ice cover and cloud cover have received great attention and it related to the regional even global climate changing. We here study the distributions and the coupling relationships of AOD, cloud cover (CLD) and ice cover (ICE) in the Greenland Sea (20°W-10°E, 70°N-80°N) during 2003-2012. Enhanced statistics methods, such as lag regression method and co-integration analysis method are used for correlation and regression analysis. According to the 10 years satellite data, AOD was high in spring, and low in summer. Generally, AOD was higher down south and lower up north. CLD and AOD mainly had negative correlations and ICE and AOD had positive correlations. According to the lag regression analysis by statistical software EViews, both the peaks of CLD and peaks of ICE were all 1 month earlier than the peak of AOD. The co-integration test suggested that both ICE(-1) and CLD(-1) and AOD were all zero-order integration, and there was no unit root in the residual, so there all had long-run equilibrium relationships. ICE and AOD were stationary series, and the residual had no unit root, they were good coupling. The melting of sea ice and decreasing of cloud cover would all result in the increasing of the AOD content. However, the relationship between AOD and CLD was weaker than the relationship between AOD and ICE, indicating that the aerosol in Arctic mostly came from the sea rather than from the air.**

Keywords—correlation; Aerosol Optical Depth; ice cover; cloud cover; Arctic

I. INTRODUCTION

An aerosol is a suspension of solid or liquid particles in the air. Sulfate, nitrate, organics, soil-dust, sea-salt, ammonia, black carbon and trace metals are all aerosols. Those include natural gases and anthropogenic gases. Nearly 50% of fine aerosols are from anthropogenic sources. There are about more than 50% off the fine aerosols is sulfate (Ramanathan et al., 2007).

Aerosols are important to climate. They scatter and absorb radiation in the atmosphere, hence they change the microphysical structure and cloud lifetimes as well. The scattering of solar radiation acts to cool the earth, while absorption of solar radiation acts to warm the air directly. Clouds act both scattering solar radiation and absorbing thermal radiation. Aerosol optical depth is a measure of the strength of interaction of clouds with radiation. Hence, changes in aerosol concentrations would greatly influence the radiation balance and the climate. Climate sensitivity is related to the changes in clouds, water vapor, sea-ice cover and snow.

Sea-ice is a source of sea salt aerosols and the rapid decrease of sea-ice extend in Arctic Ocean could result on the sea salt aerosol emission increasing, in turn could lead to increase the natural AOD about 23% (Struthers et al., 2011). The physical drivers of sea salt aerosol are the sea-ice cover, surface wind speed and sea surface temperature (Nilsson et al., 2007). The ice cover plays a significant role among the three drivers.

Winter cloud amount changes would alter AOD signal. The increase of winter time cloud fraction would likely decrease the natural AOD in Arctic (Struthers et al. , 2011). It is suggested that the cloudiness and cloud radiative forcing are strongly coupled to Arctic sea-ice cover (Struthers et al., 2011). How the AOD correlated with sea-ice cover and cloud cover in Arctic Ocean? Within ice cover and cloud cover, which one has more effect on AOD? We will use statistical methods to find out the answers in Greenland Sea of west part of Arctic Ocean.

II. THE DATA AND METHOD

Our study region is in Greenland Sea 20°W-10°E, 70-80°N (Figure 1), for the 10 years' time period: 2003-2012. The satellite data is only valid from March to September. We choose MODIS satellite afternoon (Aqua), 8-day, 4-km, level 3, mapped data for retrieving global aerosol optical depth (AOD) data. MODIS web site is located in http://modis.gsfc.nasa.gov/. The image analysis package SeaWiFS Data Analysis System (SeaDAS 6.4) (http://seadas.gsfc.nasa.gov/) was then used to get subset data for our focused study region.

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Global Sea-ice weekly data was obtained from NOAA (ftp://sidads.colorado.edu/pub/DATASETS). Ice cover is from following locations http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP/.EMC /.CMB/.GLOBAL /.Reyn_SmithOIv2/. Cloud Cover (CLD) is from http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=MODISMONTHLY _L3.

EViews statistical software is used for correlation and regression analysis. Enhanced statistics methods, such as lag regression method and co-integration analysis method are used for correlation analysis and long term equilibrium relationship between two variables.

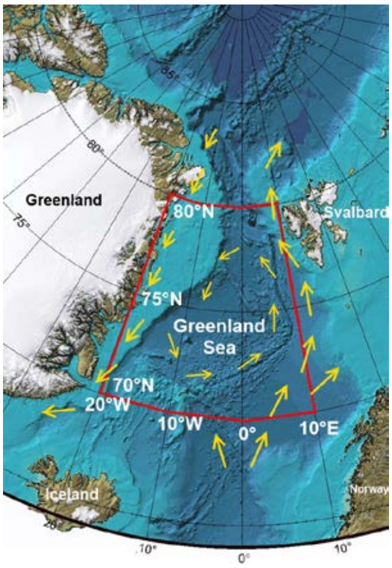

Fig. 1. The study region in Greenland Sea *(Yellow Arrows indicate the current direction around and within the study region).*

III. RESULTS

A. The Distributions

Mean AOD in the study region (70°N -80°N, 20°W-10°E) is shown in Figure 2. Generally, AOD was higher in spring and lower in summer and further increased in autumn. Vertical bars are the standard deviations.

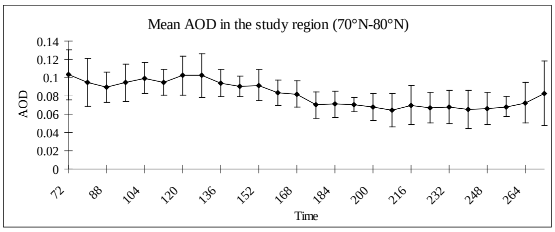

Fig. 2.Mean 8-day AOD in the study region averaged for 2003-2012.

Mean AOD along latitude in the study region is shown in Figure 3. Generally AOD were higher up south and lower down north. Year 2009 had higher AOD within 73°N -80°N. Year 2003 had higher AOD down the south. The higher 2003 AOD was most likely influenced by the 2003 Russian fire. Year 2010 had relative lower AOD throughout the year.

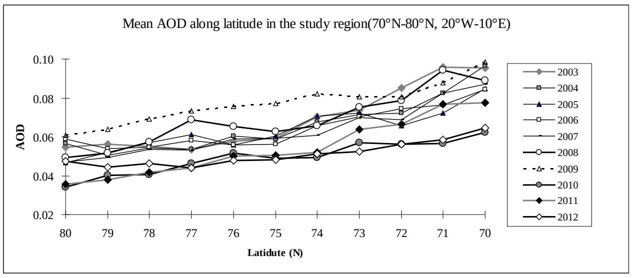

Fig. 3. Mean AOD along latitude in the study region.

The mean ice cover in the 10 years in the study region was generally higher in March and decreased through summer and reached to the valley in August. We divided the study region into two sub-regions: 70°N-75°N and 75°N-80°N (Figure 4). In 70°N-75°N, more ice cover happened in spring and summer of 2012. Higher ICE occurred in spring and early summer in 2010. More ice cover happened in 75°N-80°N. There was a dip in year 2009 in spring. Less ice cover occurred in 2004 and 2003 in late summer and early autumn.

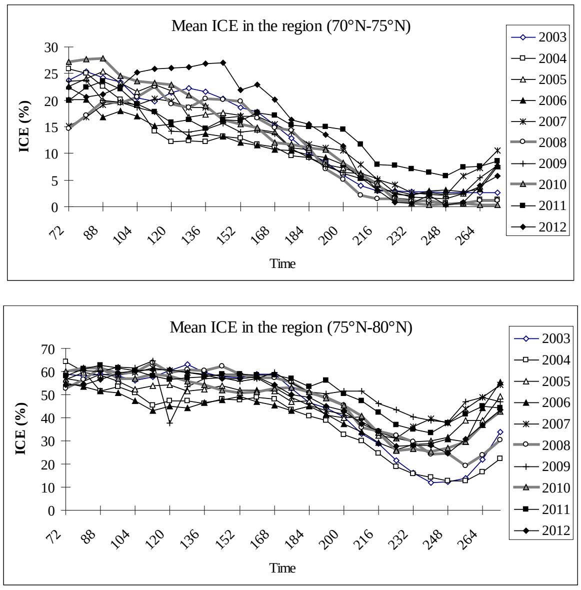

Fig. 4. Weekly mean ice cover time series in year 2003-2012 for 70°N-75°N and 75N°-80°N *(20°W-10°E).*

Figure 5 is the mean cloud cover in the study region for each year. Generally, the cloud cover is around 0.8. Year 2009 had the least cloud cover in April. Least summer cloud cover happened in year 2008 and 2011. April is the month with the most fluctuations. August and September had the least fluctuations.

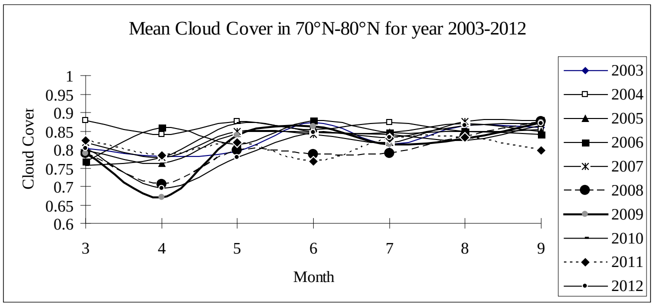

Fig. 5. Weekly mean ICE time series in year 2003-2012

B. *The Correlation Analysis for AOD, ICE and CLD*

Figure 6 is monthly mean AOD and ice cover in both 70°N -75°N and 75°N -80°N regions. The peaks of ice cover were generally 1 month ahead of AOD. The ice cover up north was much higher than down south. In 70°N -75°N, Year 2004, 2010 and 2012 had higher ice cover. AOD was lower in year 2010 and 2012, but much higher in year 2009. In 75°N -80°N, Ice cover had no much decrease in the recent years. Year 2006 had lower ice cover. AOD had decreased trend in late 3 years (2010-2012). AOD had two peaks in 2009 and the highest peak happened in 2008.

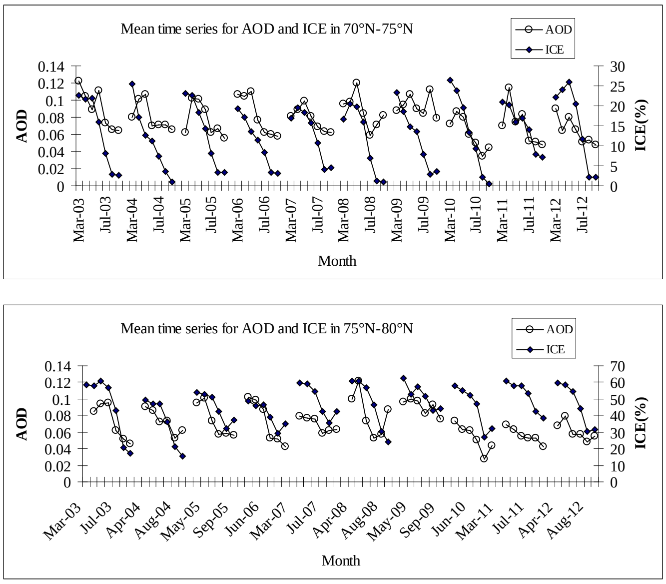

Fig. 6. Monthly mean AOD and ice cover time series in 70°N -75°N and 75°N -80°N * *(data is only available from March-September).*

The correlation coefficients between AOD and ice cover ranged from 0.58 to 0.88 apart from year 2009 where negative correlation occurred (-0.43). Year 2003 and 2007, 2012 had higher correlation coefficient values (0.76-0.88). The peak time of ice cover usually was 1 month ahead of AOD.

Melting ice is calculated by subtract the ice cover data from previous week to this week, AOD and melting ice had negative relationship during early spring and summer (Figure 7). This again confirmed the 2010 year low AOD is caused partly by more melting ice in the year.

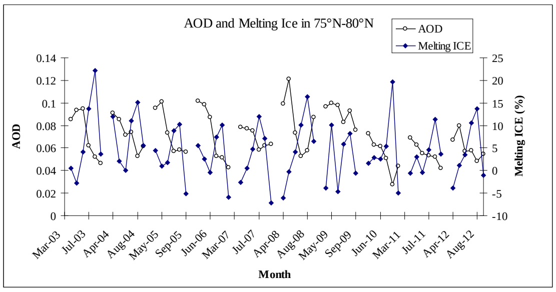

Fig. 7. Monthly mean Melting Ice and AOD time series in 75°N -80°N.

C. *The regression and lag analysis for AOD and ICE*

We are more interested in the 75°N -80°N region where more ice cover and more ice melting happened. Time lag regression analysis is done by using EViews statistical software (Pang, 2007) to find out the exactly lag time between AOD and ice cover (ICE).

TABLE I. LAG ANALYSIS BETWEEN ICE AND AOD IN 75°N-80°N (DEPENDENT VARIABLE IS AOD)

Variable	Coefficient	Std. error	*t*-Statistic	*P*-value
C	0.0298	0.0209	1.4226	0.1599
ICE(-1)	0.0010	0.0003	3.4654	0.0010
ICE(-2)	0.0005	0.0003	1.5552	0.1251
ICE(-3)	-0.0005	0.0003	-1.4081	0.1642
ICE(-4)	-0.0004	0.0003	-1.4244	0.1594
R^2= 0.4517	*F*-statistic: 12.5638		Prob (*F*-statistic): 0.0000	

Different from all other lag, the P-value of ICE(-1) is 0.001 which is significant smaller than 0.05 (Table I). Hence, if ice cover lagged 1 month behind, ice cover and AOD would have more significant relationship. This is coincident with the previous result.

TABLE II. THE LINEAR REGRESSION ANALYSIS BETWEEN ICE(-1) AND AOD IN 75°N -80°N (DEPENDENT VARIABLE: AOD)

Variable	Coefficient	Std. error	*t*-Statistic	*P*-value
Constant (C)	-0.0115	0.01143	-1.0084	0.3169
ICE(-1)	0.0015	0.00023	6.5617	0.0000
R^2= 0.3912	*F*-statistic: 43.056		Prob (*F*-statistic): 0.0000	

Table II shows that P-value of ICE(-1) is 0.0000 which is significant smaller than 0.05，hence, there was a significant correlation between AOD and ICE(-1). The regression equation is

$$AOD=-0.011532+0.001530ICE \tag{1}$$

Next, we do the unit root check to see if they are stationary sequence. As the unit root of critical value of AOD for level 1%, 5% and 10% are -3.540 、-2.909 、-2.592 respectively, they are all less than the t-test value (-1.828), hence, AOD is non-stationary sequence.

Now, we need to do first difference unit root checking for AOD. As the unit root of critical value for first difference unit root of AOD are -3.540198, -2.909206, -2.592215 for level 1%, 5% and 10% respectively, they are all greater than the t-test value (-4.268274), hence, first difference unit root for AOD was stationary sequence.

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The same rule can apply to the ice cover. As the unit root of critical value of ice cover for level 1%, 5% and 10% were all less than the t-test value. Hence, ice cover was non-stationary sequence. As the unit root of critical values for first difference unit root of ice cover are -3.540, -2.909, -2.592 for level 1%, 5% and 10% respectively, they were all greater than the t-test value (-3.998), hence, first difference unit root for ice cover was stationary sequence.

We then need to see if AOD and ICE had co-integration relationship. Regression analysis for the both parameters is for checking out whether their regression residuals were stationary. The least squares regression models is used to do the regression for ICE(-1) respect to AOD. Then do the residual unit root-test. We found that the t-test value (-8.135) was smaller than all critical values (-2.599, -1.946, -1.614) for level 1%, 5% and 10% respectively. The residual sequence had no unit root, it was stationary sequence. Hence, AOD and ice cover had co-integration relationship and they had long term equilibrium relationship.

D. The Correlation and Regression Analysis for AOD and CLD

Figure 8 is the AOD and Cloud Cover (CLD) time series for the 10 years (from March to September). It shows the negative relationship between them. The overall correlation coefficient was -0.233. AOD was 1 month lagged behind CLD.

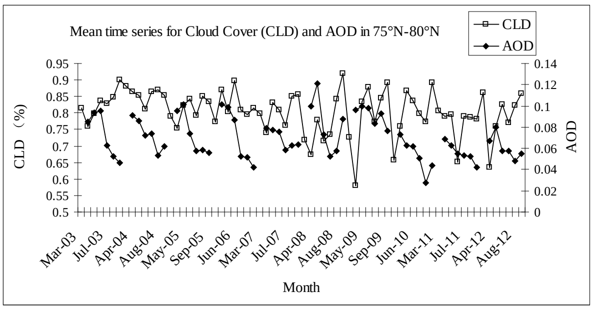

Fig. 8. AOD and CLD time series for year 2003-2012 in 70°N -80°N.

After shifting CLD 1 month behind, the correlation coefficient between CLD and AOD would change from 0.078 to -0.39. AOD and CLD was less well correlated comparing to AOD and ICE in general. For precisely calculating the correlation coefficient between AOD and CLD, EViews is again used to do regression analysis. Cloud cover was shifted 1, 2, 3 and 4 months behind (Table III).

TABLE III. THE LAG REGRESSION FOR CLD AND AOD IN 75°N -80°N (DEPENDENT VARIABLE: AOD)

Variable	Coefficient	Std. error	*t*-Statistic	*P*-value
C	0.1579	0.07978	1.9799	0.0522
CLD(-1)	-0.1797	0.05567	-3.2270	0.0020
CLD(-2)	-0.02198	0.05520	-0.3982	0.6919
CLD(-3)	0.02225	0.05514	0.4035	0.6880
CLD(-4)	0.05741	0.05572	1.0304	0.3069
R^2= 0.1790	*F*-statistic: 3.3254		Prob (*F*-statistic): 0.0158	

Table III shows that CLD (-1) had the best results. The P-value was the smallest （0.002<0.05）. This result is coincident with the previous observations that cloud cover was 1 month ahead of AOD.

TABLE IV. LINEAR REGRESSION ANALYSIS RESULTS FOR CLD(-1) AND AOD IN 75°N -80°N (DEPENDENT VARIABLE: AOD)

Variable	Coefficient	Std. error	*t*-Statistic	*P*-value
Constant (C)	0.2057	0.04152	4.9535	0.0000
CLD(-1)	-0.1798	0.05148	-3.4918	0.0009
R^2= 0.1540	*F*-statistic: 12.193		Prob (*F*-statistic): 0.00085	

Table IV shows CLD(-1) had influence on AOD, as the P-value of CLD(-1) was 0.0009 (< 0.05)， the correlation between AOD and CLD(-1) was significant. We do the unit root checking for CLD with the null hypothesis: cloud cover has a unit root.

TABLE V. UNIT ROOT CHECKING FOR CLD

		t-Statistic	Prob.
Augmented Dicky-Full test statistic		-6.5872	0.0000
Test critical values	1% level	-3.5300	
	5% level	-2.9048	
	10% level	-2.5899	

As t-test statistical value was -6.587, it was less than the 3 critical values of 3 levels in the table. Hence, cloud cover sequence did not have unit root. That means it was the stable sequence. Now we test to see if AOD and CLD had co-integration relationship. We do regression analysis again and followed by checking the smoothness of the regression residuals.

TABLE VI. UNIT ROOT CHECKING FOR RESIDUALS BETWEEN AOD AND CLD

		t-Statistic	Prob.
Augmented Dicky-Full test statistic		-3.5585	0.0095
Test critical values	1% level	-3.5402	
	5% level	-2.9092	
	10% level	-2.5922	

Table VI shows the residual sequence had no unit root, it was the stationary sequence (-3.558511 is less than the three critical values). Hence, the first-order difference of AOD and CLD had co-integration and they have a long term equilibrium relationship.

We have found AOD lagged CLD 1 month behind. There were certain negative correlations between CLD and AOD. That means the increasing of CLD would reduce the AOD content in some degree. On the other hand, reducing CLD would increase AOD relatively. That explained there were less CLD and more AOD in April.

The correlation coefficients between AOD and CLD after shifting were -0.935, -0.548, -0.548 respectively for year 2003, 2009 and 2012. Year 2003 had very high negative correlations between CLD and AOD.

Generally, AOD and CLD had less degree of correlation comparing the correlation between AOD and ICE. That means the Arctic aerosols were mainly from sea water rather than from the high cloud.

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E. The Relationship among AOD, ICE and CLD

To find the relationships among AOD, ICE and CLD, a linear model needs to be set up. We still focus on the region 75°N -80°N.

TABLE VII. REGRESSION ANALYSIS AMONG AOD, ICE AND CLD (DEPENDENT VARIABLE: AOD)

Variable	Coefficient	Std. error	*t*-Statistic	*P*-value
Constant (C)	-0.0614	0.0347	-1.7681	0.0824
CLD	0.0978	0.0363	2.6909	0.0093
ICE	0.0012	0.0002	6.1173	0.0000
R^2= 0.3987	*F*-statistic: 18.899		Prob (F-statistic): 0.00001	

The relationship equation is as follows:

$$AOD=-0.061414+0.097762CLD+0.001158ICE \quad (75°N\ -80°N) \quad (2)$$

In Table VII, Goodness of fit R^2 =0.3987. The t-test and F-test values were all refusing the original hypothesis. P value of ICE and CLD were all less than 0.05. That means equation (2) is significant. Both ICE and CLD all had influence on AOD.

IV. CONCLUSIONS AND DISCUSSIONS

The distributions and correlation analysis between AOD and ICE, AOD and melting ice (MI), AOD and CLD (cloud cover) are all studied. We focus the region in 75°N -80°N for correlation analysis where ice melted more. We found out that NAO and MI had significant influence on CHL.

Different from CHL with peak in June in generally, AOD was higher in spring and lower in summer. Year 2009 had higher AOD and year 2010 had lower AOD. CLD was generally overcastted and with April less overcastted and more fluctuations.

ICE was generally 1 month ahead of AOD and there were good correlation between ICE(-1) and AOD. AOD and MI would have negative relationship during early spring and summer. AOD and CLD also had negative relationship, with AOD 1 month lagged behind CLD. Both ICE and CLD all had influence on AOD. However, ICE had more impact on AOD than CLD. The correlation was higher for ICE comparing to AOD. That means, AOD had less effect coming from cloud cover and more effect from sea-ice aerosols. Besides, AOD and ICE, AOD and CLD all have long term equilibrium relationship.

There was a positive relationship between AOD and ICE, less significant correlations between CLD and AOD. However, there were other factors could be the external driving forces to AOD, hence to the radiative balances. The Arctic anthropogenic aerosol concentration and composition, the commercial shipping through Arctic when sea-ice is reduced, the black carbon aerosol on the snow and ice albedo are the other three driving forcings for AOD. Other reasons could due to the response of DMS cycle to changes in sea-ice cover and furthermore, to the arctic marine biology and the large scale ocean circulation's changes.

As we mentioned in the first section that sea salt aerosol mainly caused by ice cover, non-sea salt aerosol includes sulphate, particulate organic matter, mineral dust and black carbon. Gabric et al. (2005) suggested that the gaseous dimethylsulfide (DMS) cycle in Arctic Ocean is depended on the sea-ice extent. Here DMS is the main sulfate aerosol released from ocean in Arctic. The melting of ice caused ice algae contributed significant rate of phytoplankton biomass in Arctic, hence promoted the growth of DMS.

The sulfate aerosols mainly off set the climate warming by cooling down the temperature. The most effect area of sulfate aerosol is in northern hemisphere Arctic Ocean. If the greenhouse-gas emissions remains constant, with the increase of sulfate aerosol in Arctic Ocean, the greenhouse-gas impacts would decrease in the future and climate would cooling down. If the short life time sulfate aerosol did keep pace with the long life greenhouse-gases, the global warming would still accelerate. However, with control of greenhouse-gases emission, the cooling effect from sulfate aerosol cannot be ignored (Gabric et al., 2013).

Our research on the correlation analysis among AOD, ice cover and cloud cover is just on its primary stage. More and comprehensive statistical methods are expected to carry out in the future, to show a better picture of the relationships.

ACKNOWLEDGMENT

Thanks the NASA's Ocean Biology Processing Group for providing MODIS aqua, Level 3 (4-km equi-rectangular projection) 8-day mapped data for aerosol optical depth (AOD). Thanks to NOAA NCEP EMC CMB GLOBAL Reyn-SmithOIv2 for providing weekly and monthly sea-ice concentration. Thanks to NASA http://gdata1.sci. gsfc.nasa.gov for providing cloud cover data. Finally, big thanks should go to the Chinese National Natural Science Funding (Funding No. 41276097) for providing funding for this project.

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