Statistical Analysis of Satellite Data to investigate Asian Dust Transport to North America

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Abstract of the Thesis

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This research studies the features of long-distance dust transport from Asia to the US over the Pacific Ocean statistically in order to reveal the climatological characteristics of dust transport, such as its inter-annual variability and intra-seasonal variability. The aerosol index (AI) of the Total Ozone Mapping Spectrometer (TOMS) satellite data(1979-2007) is used in this research as observation. The Gobi desert is a very important source region. The daily AI values averaged over the Gobi region in April are the highest with the highest variability compared to the other spring months, March and May. It is found that there is a very high correlation of AI between Gobi and the west coast of the United States region. Also from the TOMS satellite image, we can see very strong plumes going from Asia to the American western coast in about 5 days during the strong dust storm period.

This analysis suggests that there is a source-receptor relationship between the Gobi source region and the west coast of the United Stares receptor region. In order to derive the transport time between Gobi and West coast, lag cross-correlations of the time series is calculated between Gobi and US west coast by using satellite data. Then a lag time of 5 to 6 days is found from Gobi to the US west coast. The result is statistically significant at the 5% level, which suggests that the average transport time for Asian dust from the Gobi desert to the west US off-shore receptor region is about 5 to 6 days. Based on this source-receptor relationship, a statistical method is developed to capture the dust signals by using this lagged cross correlation function. This is an objective method of how to determine the trajectory of dust transport and the transport time at different locations along the trajectory across the Pacific.

Table of contents

List of Figures

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1. Introduction

Asian Dust is known as a seasonal meteorological phenomenon which affects much of East Asia sporadically during the springtime months. The formation of dust storms is based on two basic circumstances: dust sources, such as deserts, Gobi, bare earth surface, etc; and climatic and synoptic conditions, such as cyclone systems, strong winds. An increase in strong winds effectively increases dust outbreaks in the regions with frequent dust storms; the stronger the surface wind, the higher possibility for the dust storm to break out. (Kurosaki and Mikami, 2003). At present, there are three main regions where dust commonly is emitted from North Africa, Central Asia, which includes northwest of China, and Middle East Asia.

The dust from Taklamakan and Gobi deserts is believed as primary source of mineral dust storm in East Asia region. The occurrence of dust storms which originate from this region does not only impact the climate within the local region greatly, but it furthermore transported across the Pacific Ocean to North America, especially the west coastal regions especially after the dust is elevated to the higher level of the free atmosphere by the storm. The dust does not impacts climate solely but also affects biologic systems throughout the Pacific basin (Wilkening et al., 2000), and eventually influences air quality in the US (Van Curen and Cabill, 2002). In addition, VanCuren and Cahill (2002) and Cameron-Smith et al. (2005) discover in their analysis of IMPROVE data that Asian dust is a regular component of the troposphere over western North America and even across the US. Quantifying this contribution is an essential issue in order to establish meaningful background values and standards for particulate matter.

There was a major Asian dust storm during April 1998 crossed the Pacific Ocean in 5 days and caused significant influence over North America (Husar et al., 2001). The dust subsided to the surface along the mountain ranges between British Columbia and California, and impacted severely the optical properties of the atmosphere and the concentration of particulate matter in the region. In eastern Asia the dust clouds increased the albedo over the cloudless ocean and land by up to 10-20%. Since it reduced the near-UV cloud reflectance, as a result, a yellow coloration was formed on all surfaces. Over the west coast of the US, the dust layer has increased the spectrally uniform optical depth to about 0.4, reduced the direct solar radiation by 30-40%, and doubled the diffuse radiation. This event raised the surface-level dust aerosol concentration over the valleys of the West Coast to about 20-50 ug m^{-3} with local peaks larger than 100 ug per cubic meter. The April 1998 dust event has impacted the surface aerosol concentration 2-4 times more than any other dust event since 1988. The dust events were observed and interpreted by an ad hoc international web-based virtual community (Husar et al., 2001).

The prevailing mid-latitude westerlies provide an effective mechanism for the transport from Asia to North America (Schwarzhoff 2003). As for the seasonal variation, trans-

Pacific dust transport occurs primarily from April to May. According to the Nimbus 7 (TOMS) observations, dust aerosol originating from the arid deserts of Mongolia and China can be observed frequently during this period throughout East Asia. Most frequent occurrence of Asian desert aerosol over Korea is observed in April (Lim et al., 2002). By the study of regional scale dust-transport models, the long-term trend of dust days in the Gobi desert region showed a remarkable declining trend from the early 1980s-1997. Analysis of time variation of meteorological parameter in the Gobi region showed that the decreasing trend of dust days in this region is explained by the decreased frequency of strong winds and also indicated that invasion of polar cold air played an important role in increasing dust phenomena (Hara et al., 2006).

Zhao et al. (2004) suggested that the main climatic factors controlling dust storm frequency in Inner Mongolia of China are the number of days with gale, the intensity index of Asian polar vortex, and area index of the northern hemispheric polar vortex which are good representatives for large-scale cold air activities. The polar vortex is the major circulation system over the Arctic. It determines most of the synoptic systems of the middle and high latitude of the whole Northern Hemisphere. The expansion and shrinking of polar vortex reflect activities of the polar cold air, which not only affect the change of the Northern Hemisphere climatic zone but also affect the air circulation and climate change. Middle latitude gale of the Northern Hemisphere usually occurs when a middle latitude cyclone (such as Mongolia cyclones) develops. Thus strengthening and weakening of large synoptic or planetary factors such as polar vortex is a good indicator of the number of days with gale. With the analysis of these factors related to dust storms, they detected a declining trend of dust storm frequency. But Chung et al. showed that there was a slight increase in the occurrence in recent years (1979-1994) according to dust days (Chung et al., 1995).

The cross-Pacific transport of dust and, by extension, of accompanying anthropogenic pollutants is well documented by studies using satellite data, in-situ measurements and models (Duce et al., 1980; Shaw, 1980; Merrill et al., 1989; Husar et al., 1997; Jaffe et al., 1999; Zhao et al., 2006; Gong et al., 2006). A number of studies focus on cases of intense dust events such as the April 1998 dust storm (Husar et al., 2001; Tratt et al., 2001) and the April 2001 dust storm (Szykman et al., 2003) with clear signatures in the atmosphere in the western US. For these cases the dust plume could be visually tracked in satellite data, and a transport time of approximately 6 days has been derived for both cases. The transport time is an important quantity because aerosols chemical properties continue to change in the atmosphere due to condensation of gases and/or coagulation with other aerosol particles. This applies to mineral dust as shown in e.g. Sun et al. (2005) and Hwang and Ro (2006). The impact of the aged aerosol particles on radiation, human health, cloud condensation activity and ocean chemistry after deposition is modified accordingly.

As can be seen from the literature review above, the research on dust storms has a very long history. Some studies revealed the climatological characteristics of dust in a certain region (e.g. Zhou, 2001), but little process was made to detect the climatological characteristics of long-distance dust transport features. Therefore, developing a statistical method to detect the source-receptor relationship is considerably meaningful goal for our study.

After this introduction, the data and the method of analysis are described in the section 2, and the results are shown in the section 3. The conclusion and discussion part are contained in section 4.

2. Data and Method

Total Ozone Mapping Spectrometer (TOMS) satellites data

Several previous studies have shown that TOMS satellite data is suitable for detecting the occurrence of dust events over the continents and the subsequent transport over the ocean (Herman et al.,1997; Chiapello and Moulin, 2002; Chiapello et al., 2005; Riemer et al., 2006). TOMS provides the Aerosol Index (AI) as a semi-quantitative measure for the atmospheric aerosol loading (Herman et al., 1997; Torres et al., 1998).

The distinction between different types of UV absorbing aerosol (dust or smoke) requires additional assumptions, such as the choice of geographic domain or a certain season where only one type dominates. Another known shortcoming of the TOMS aerosol index is its dependence on the height of the aerosol layer (Torres et al., 2002; Hsu et al., 1996). For a certain total column aerosol concentration, the AI will be larger if the aerosols are located higher in the atmosphere compared to the same amount of aerosol at a lower altitude.

The record of UV radiances started in October 1978 with measurements by the TOMS sensor on board the Nimbus-7 satellite and extended continuously until April 1993. After a 18-month data gap, the TOMS data record restarted from August 1996 from the Earth Probe (EP) satellite (Torres et al., 2001). Recently a new instrument (OMI) is providing the service from August 2004. The TOMS AI (Herman et al., 1997) is a very efficient method of space-based aerosol detection. It can detect aerosols over all land and ocean surfaces, even those places covered by ice/snow and over cloud, which is one of the unique advantages (Torres et al., 2001). Here we apply the absorbing aerosol index for our analysis.

A new version of TOMS AI is available (Version 8) after recent algorithms updated (see http:/toms.gsfc.nasa.gov/news/news.html). We first calculate the spatial average of AI of the source regions: Gobi desert（40°N-50°N, 100°E-110°E）, and the west coast of US region: north California (40°N-55°N, 140°W-120°W) for the period 1979-1993 (TOMS/Nimbus-7), 1997-2001 (TOMS/Earth Probe) and 2005-2007 (OMI). Data after 2001 is excluded for that a certain error has existed in the TOMS data since 2002, so data since that time should not be used for trend analysis (Kiss et al., 2007). Using TOMS data can clearly show that big dust events transporting over Pacific Ocean towards the west coast of the US (Husar et al., 2001).

With the version 8, the AI is defined as:

$$AI = -100\log_{10}[(I_{331}/I_{360})_{meas} - (I_{331}/I_{360})_{calc}] \qquad (1)$$

Where I_{mean} is the measured backscattered radiance at a given wavelength and I_{calc} is the radiance calculated at the wavelength assuming a purely gaseous atmosphere (Torres et al., 2001).

For the earlier version 7, AI is positive for absorbing aerosols, i.e. dust, smoke, etc, close to zero with the existing of clouds or large size (0.2 um or larger) non-absorbing aerosols and negative for small size nonabsorbing particles (pure scattering) (Riemer et al., 2006, Torres et al., 2001). In version 8, only positive values for absorbing aerosol index are available (Riemer et al., 2006).

The lagged cross correlation function:

To derive the transport time and the transport path we evaluate the lagged cross-correlation function $r(k)$ of the time series at the source region and at the receptors for year l:

$$r(k,l)=\frac{\sum_{i=1}^{n-k}[(x_i-\overline{x}_-)(y_{i+k}-\overline{y}_+)]}{\sqrt{\sum_{i=1}^{n-k}(x_i-\overline{x}_-)^2\sum_{i=1}^{n-k}(y_i-\overline{y}_+)^2}}$$

Where n is the number of data points, in our case the number of daily AI values from March 1 to May 31 in year *l*, and *k* is the number of lag days. The daily AI values for the source region are denoted with x_i, their average is $\overline{x}_-$. The corresponding AI values at the receptor region are y_i and $\overline{y}_+$, respectively. The subscripts “-“ and “+” indicate sample means over the first and last n-k data values, respectively. After computing $r(k,l)$ for each year *l*, we average over all 19 years.

3. Results

a. Relationship between the Gobi desert and the west coast region of the USA

Figure 1 shows the satellite images on the April 20th, 1998 and April 22nd, 1998, respectively, the second day and the fourth day after the intense Asian dust break out on the April 19th in the Gobi desert. On the April 20th, there was an apparent dust plume leaving off-shore from the Asian continent; and two days later, it can be seen clearly that the dust plume was transported across the Pacific Ocean moving towards the west coast of the US. It reached the American western coast in 6 days. This evolution is well captured by the satellite data, and coincided with previous study (Plate 2, Husar et al., 2001).

The monthly area-averaged AI temporal variation in the Gobi region is clearly shown in the Figure 2(a). As it can be seen, the AI of April and May is a somewhat higher than that of March and June before 1993. From 1997, an obvious increasing trend occurs to every month from March to June, especially for April.

Figure 2(b) illustrates the monthly area-averaged variation of dust in the west coast region of the USA. Compared to the source region, the value of AI is apparently smaller. The same increasing trend is also happened to the AI detected in the receptor region, which is consistent with the variation trend of the source region.

Since there is an apparent relationship between dust levels of the Gobi desert and the west coast region of the US are pretty similar, we firstly calculate the correlation of time series of the area average AI defined above between the Gobi desert and the west coast of US region in order to find the relationship between these two regions. The time series are monthly mean AI values of every year and they are from 1979 to 2001 (19 years altogether) for each spring month (March, April, May) with the last version (version 8) of the TOMS AI data. Very high correlation coefficients of AI between Gobi and west coast region of USA are found during the analysis, and they are even much higher than the 1% statistic significant level (Table 1).

In addition, it has been noticed that there are some small deserts located south of the defined U.S. west coast region. The correlation coefficients also have been calculated in order to find whether there is a certain influence coming locally. But the results show that those coefficients could not be higher than the 5% statistic significant level, therefore, we conclude that the local influence from the U.S. deserts is secondary (Table 1).

The Gobi desert is a consistent source of the dust for the atmosphere, and the daily AI in the source region varies year by year. Figure 3 shows the daily AI values over the Gobi region, averaged over 19 years and the standard deviation, including 1979 to 1993 from NIMBUS and 1997 to 2001 from Earth Probe. As mentioned in the previous studies (Duce et al., 1980; Sun et al., 2001; Zhao et al., 2006), the highest average values are found in April, which is confirmed by the TOMS data record. This figure also reveals that the highest variability is in the April.

Figure 4 illustrates the relationship between the Gobi region and the west coast region of the US in two years, 1998 and 1985 respectively. In 1998, there occurred serious dust storms, whereas in the 1985, such an event did not occur. From the figure, the largest dust storm on April 19th can be easily identified in the Gobi time series with the highest AI value about 3. It shows a maximum peak west off the American coast after 5 to 6 days and reaches a value over 1.2. This is consistent with the previous findings documented by Husar et al. (2001) where the transport time has been determined by the lab work. However for most of the remaining seasons and for other years like 1985, this kind of source-receptor relationship is not directly visible, but still could be identified by using the lagged cross correlation function:

As mentioned above, there are very high correlation coefficients found between the Gobi desert and the west coast region of the USA on a monthly basis. In order to confirm this relationship, backward seasonal correlations are calculated with 14 years NIMBUS data because it is the most reliable data among the three kinds of satellite data (NIMBUS, Earth probe and OMI) we use. For the so-called backward seasonal correlation, the spring season mean AI value for each grid point from 0 to 70°N and from 80°E to 100°W of each year is calculated; this results in a time series with 14 data points (one for each year).

Next the correlation coefficients between the west coast region of the USA and every grid point in this domain (from 0 to 70°N and from 80°E to 100°W) is calculated. From the Figure 5, it can be seen that apparently, most dust detected in the west coast region of the USA is from the Gobi desert based on the high correlation, and the transport path mainly concentrates between the 40°N and 60°N from Gobi to the west coast. The dust transport can certainly have an influence beyond this belt region, but this belt region is the main path that the dust is transported. Also it can be noticed that with the high standard, the correlation coefficients in the Taklamakan desert (30°N to 40°N, 80°E to 90°E) does not show up in the figure, which means that there is not a tight source-receptor relationship between the dust from the Taklamakan desert and the west coast region of the US. This is reasonable, because many high mountain ranges surround the Taklamakan desert, and it becomes incredibly hard for the dust to be elevated over the mountains at the very beginning, not to mention to be transported across the Pacific Ocean. Nevertheless, if the dust from that desert has a chance to be elevated over the mountains, there are still possibilities for it to be transported across the ocean.

Since there is the very strong relationship between the Gobi desert and the west coast region of the US, an investigation of the possible path of dust transport in more detail it is worthwhile. Figure 6 shows the result for the lagged cross correlation averaged over all 19 years including both NIMBUS and Earth Probe for two different receptor regions. The solid line shows the cross correlation for the Gobi region and the US west coast region where we find a lag time of 5 and 6 days that is statistically significant at the 5% level, indicated by the straight solid line. This suggests that the average transport time for Asian dust from the Gobi desert is about 5 to 6 days, which is consistent with the finding from the 1998 and 2001 case studies.

To corroborate this result further an investigation is conducted if it is possible to detect receptor boxes along the transport path over the Pacific with lag times smaller than 5 days, with the time lag increasing from west to east. This will give us insight into the transport path. The broken line is Figure 6 shows the result for the lagged correlation between the Gobi desert and a region over Korea (40-50°N, 120-130°E). Evidently the dust signal from the Gobi desert arrives at this region with a lag of one to two days. And 5 days later, this signal reaches the west coast region of the USA and remains there statistically significantly for about 2 days.

b. Tracking the dust plume over the Pacific:

Based on the source-receptor relationship between the Gobi desert and the west coast region of the USA, two different methods are used to capture the dust signal transport signal on its way over the Pacific. Those two methods have been investigated with NIMBUS alone, NIMBUS and Earth Probe together, and OMI data, but the results with NIMBUS alone and those with both NIMBUS and Earth Probe are similar, therefore, only the results with NIMBUS data are presented here.

1) Receptor boxes calculation

This calculation is to divide the whole region from 0 to 60°N and from 100°E to 80°W between the Gobi desert and the US west coast region into 10°by 10°receptor boxes first. Next we calculate the area average AI for each box on each day in the spring months (March, April and May) with NIMBUS data. By calculating the lagged cross correlation function, it is possible to reconstruct the transport paths that the dust takes during spring. Figure 7 indicates the locations of the receptor areas where we detect statistically significant signals for lags of 0, 1, 2, 3, 4, and 5 days, respectively. In order to get rid of the statistical noise as much as possible, correlation values of less than 0.3 are not displayed.

From Figure 7, following emission out of the Gobi source region, the dust signal reaches over the Korea region (40-50°N, 120-130°E) one day later (figure 7b), which is also mentioned above. The main signal generally is transported straight along the latitude confined between the 40°N and 50°N and reaches the US west coast (40°N-50°N, 130°W-120°W) on the fifth day (figure 7f). The plume can expand beyond the “belt region” between the 40°N and 50°N and even goes to the lower latitude, which may be because of the impact of the synoptic systems and the semi-permanent or permanent pressure systems.

The same method is also applied but only with OMI data. The results are similar, but it is noticed that OMI data shows that from 2005, the dust from Gobi desert extends further south over the Pacific Ocean. It goes straight first after leaving off-shore with extended influence to the lower latitude spreaded by the synoptic systems (Figure8 a, b, c, d). But 3 days later (Figure8 e, f, g, h), the main signal goes southward, reaching the west coast of the US at 30°N to 40°N which is south of the results of the NIMBUS (40°N-50°N). The signal from the OMI data transports over the Pacific Ocean and reaches the west coast of the U.S. in 7 days, longer than the 5 days found with the NIMBUS data.

From Figure 7, some boxes in the lower latitude which have nothing to do with the source region and the dust transport path also show the statistically significant, or some boxes show this kind of significance before the main dust signal comes, which are difficult to explain. But based on Fig.8, this is not a problem with OMI and it will be discussed in more details in the section 4.

2) Grid points signal tracking method:

In the receptor boxes method, the area average AI for each box is calculated on every date in spring months (March, April and May) with NIMBUS data, but using the area average can be problematic since that the dust signal is averaged over the whole box area, where in reality not the whole area may be influenced by the dust plume. In order to get rid of this kind of problem, the dust signal tracking method is developed by using the lagged cross correlation function grid point by grid point.

The method applied to the NIMBUS data are shown by Figure 9, and the color lines mark the places where the coefficients are statistically significant at 1% level. The dust source region over the Gobi desert is indicated in the Figure 9(a). One day after the dust goes into the free atmosphere, the dust plume reaches the place beyond 120°E over the Korea Peninsula, and even has an influence on the south of Japan (Figure 9b). One the next day, the dust plume transports off-shore toward the eastside of the Pacific Ocean (Figure 9c). On the fifth day, it reaches the west coast region of the US (Figure 9f).

But similar to the receptor box method, some locations have the significant coefficients that we can not explain now (Figure 9d and Figure 9e). It even seems that there is another source from the lower latitude to transport a certain absorbing aerosol eastward. This will be discussed later.

The same method is applied again with the OMI data and results are shown with the same standard (Figure 10). Compared to the results with the NIMBUS data, these figures do not have much statistical noise. Basically no significant coefficients come up beyond the possible transport path, which is generally straight from West to East here, but the main dust signal reaches further south than that with the NIMBUS data, and it takes 7 days, which is longer than that with NIMBUS data, to reach the west coast region of the US. Therefore, there is no significant difference of the results between the receptor box method and the grid point signal tracking method, but the latter is more precise and reasonable.

Conclusion and Discussion

In this thesis the climatological characteristics of long-distance dust transport from Asia to the US over the Pacific Ocean have been reported. The satellite data shows that the averaged daily AI values over the Gobi region in April are the highest with the highest variability among the whole dust active seasons: March, April and May, which is consistent with the previous studies. With statistical data analysis methods the fact has been proven that the dust from the Gobi could be transported cross the Pacific Ocean to reach the west coast region of the U.S., with a very high correlation of AI existing between the Gobi desert and the west coast region of the US. The annual variations of AI of both regions shows an increasing trend after 1997.

A lagged cross correlation for the Gobi source region and the west coast of the United States receptor region is detected with a lag time of 5 to 6 days. This suggests that the climatology averaged transport time for Asian dust from the Gobi desert to the west US off-shore receptor region is about a week. Based on the strong source-receptor relationship, two kinds of statistical dust transport methods are used; one is the receptor boxes method, the other is the grid point signal tracking method. Those methods have been applied to NIMBUS data and also to OMI data. Both methods with NIMBUS data indicate that after the dust breaks out in the Gobi source region, the dust signal reaches over the Korea region (40-50°N, 120-130°E) one day later. The main plume signal generally goes straight along the latitude confined between the 40°N and 50°N and reaches the US west coast (40°N-50°N, 130°W-120°W) on the fifth day. Furthermore, the plume signal can expand beyond the belt region between the 40°N and 50°N and even have an influence on the lower latitude, which may be because of the impact of the synoptic systems and the semi-permanent or permanent pressure systems. The OMI data reveals the similar characteristics with that from the NIMBUS but with some difference. According to the OMI data, the dust from Gobi desert can go further south, and the plume from the OMI data crosses the Pacific Ocean and arrives in the west coast of the US in 7 days, longer than the 5 days found with the NIMBUS data.

As has been mentioned before, it is unexplained in both methods that some places, that have nothing to do with the dust transport, are shown to be statistically significant, or some places show this kind of significance before the main dust signal arrives. In addition, from the figures of the grid points dust signal tracking model, it seems that there is another source from the lower latitude to transport a certain absorbing aerosol eastward. But as far as we know, in the lower latitude, the easterly dominates, therefore, some questions appear: 1) what is that absorbing aerosol, 2) how can they be transported eastward, 3) how can it influence dust transport?

In order to explain this, some seasonal mean Figure (Figure 11a) of 14 years from NIMBUS is made, which show that there is a very strong plume located in the lower latitude from 10°N to over 30°N and the highest value of this plume is about 10. It extends from the India to the east side of the Pacific Ocean across the international date line. This plume is very strong and stable. It is not for sure whether this plume could influence the statistical analysis of transport from Gobi or not, but it might be a possibility.

The studies also show that this kind of problem does not appear in the model results with the OMI data (figure 11b). According to the seasonal mean figure of OMI, this kind of plume is still located there, but the seasonal AI mean value is smaller than that of the NIMBUS. It might be because of this, the weak plume cannot affect the dust transport too much, and the OMI results are much cleaner.

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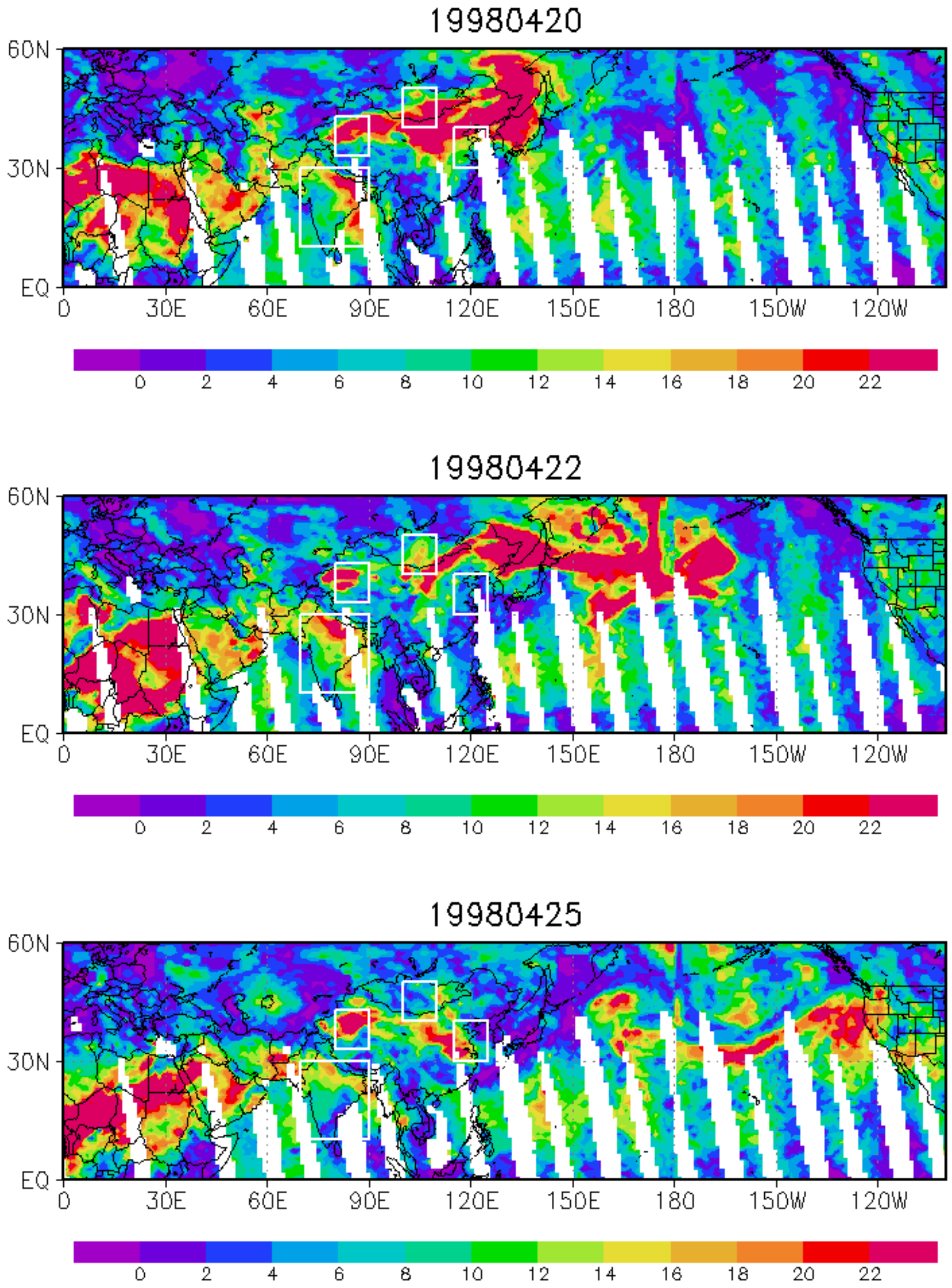
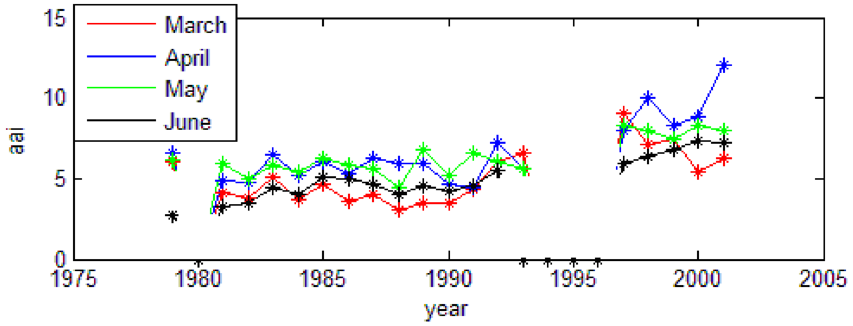
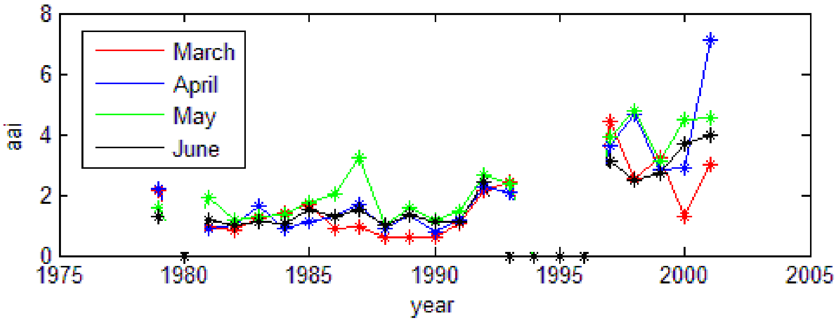


Fig.1. Top: Satellite image during the 1998 Asian dust event on the April 20th.
Middle: same as top but on the April 22nd.
Bottom: same as top but on the April 25th.



(a)



(b)

Fig.2. The yearly area-averaged AAI in (a) Gobi region and (b) the west coast region of the USA during the spring (including the March, the April and the May) from 1979 to 2001.

Gobi-WUS	March	April	May
Coefficients	0.83	0.62	0.54
Gobi-US desert	0.42	0.05	0.14

Table.1. Correlation coefficients between the Gobi desert and the west coast region of the US for each spring month, and between the Gobi desert and the U.S. desert for each spring month.

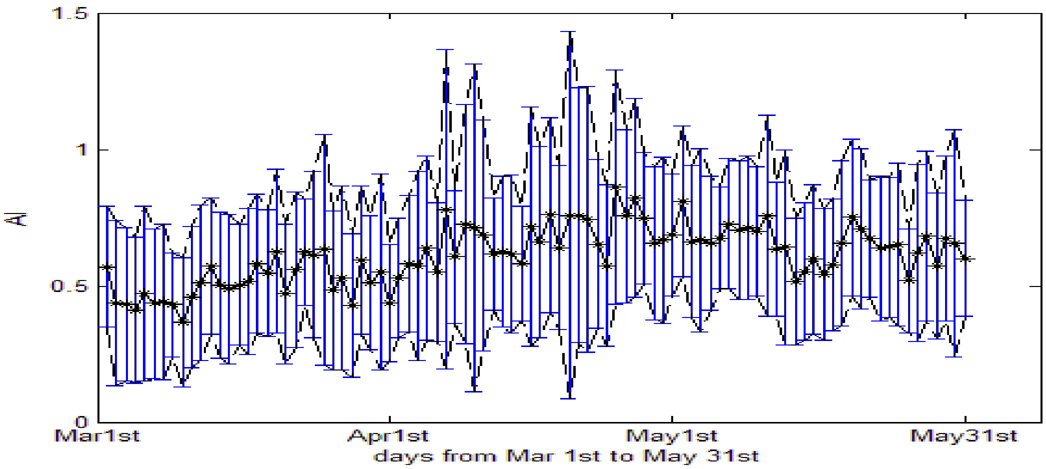
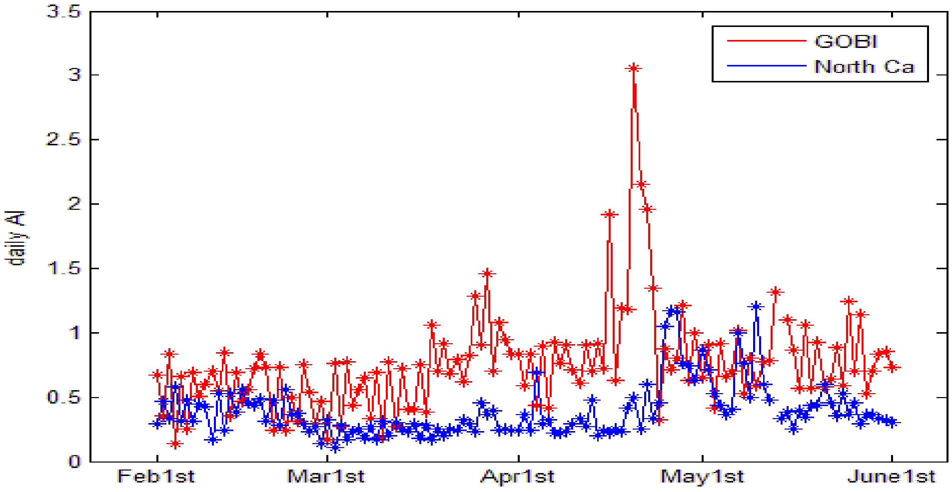
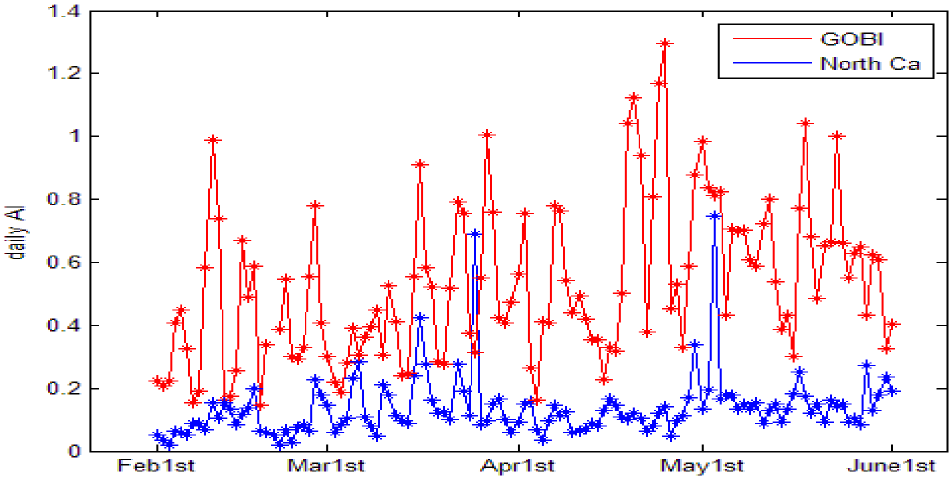


Fig.3. Solid line: 19-year average for the daily TOMS AI values, March 1st to May 31st. The time series is spatially averaged for the GOBI source area (40-50° N,100-110° E). Broken lines: standard deviation for the 19-year average.



(a)



(b)

Fig.4. (a) Daily TOMS AI values for Gobi source region (red line), and for the north California receptor region(blue line, 40-50°N, 120-130°W) in 1998, (b) same as (a) but in 1985.

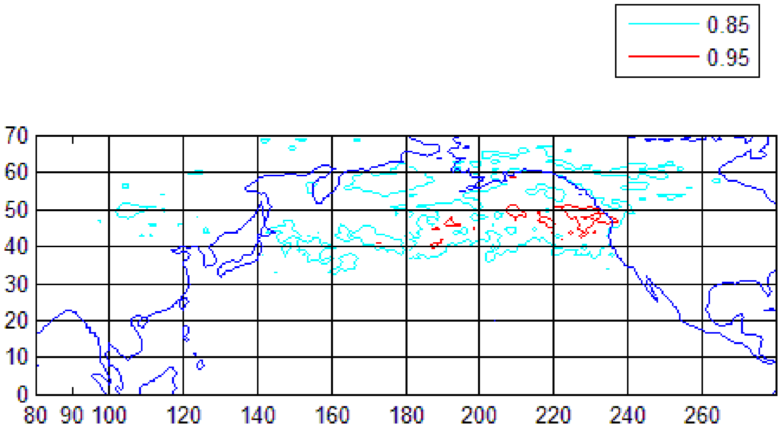


Fig.5. Backward annually averaged seasonal correlation with NIMBUS data. Red lines are showing the correlation coefficients as high as 0.95, and blue lines are for those as high as 0.85.

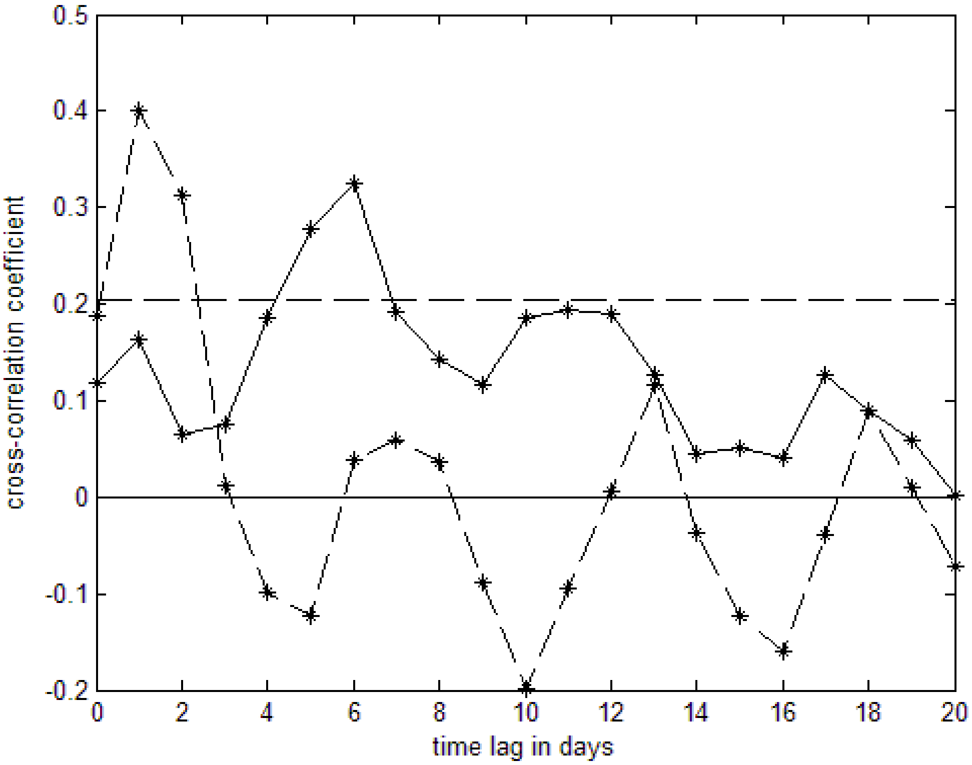
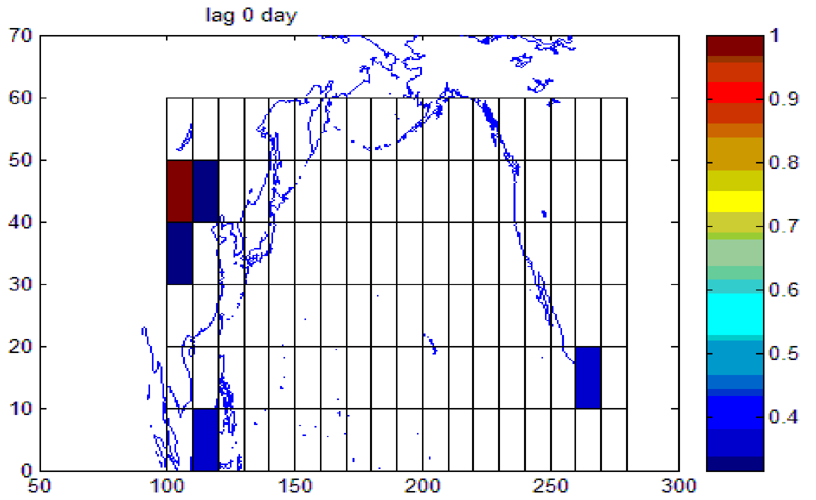


Fig.6. Lagged correlations for Gobi-Pacific North-west (solid line) and for Gobi-Korea (40-50°N, 120-130°E, broken line).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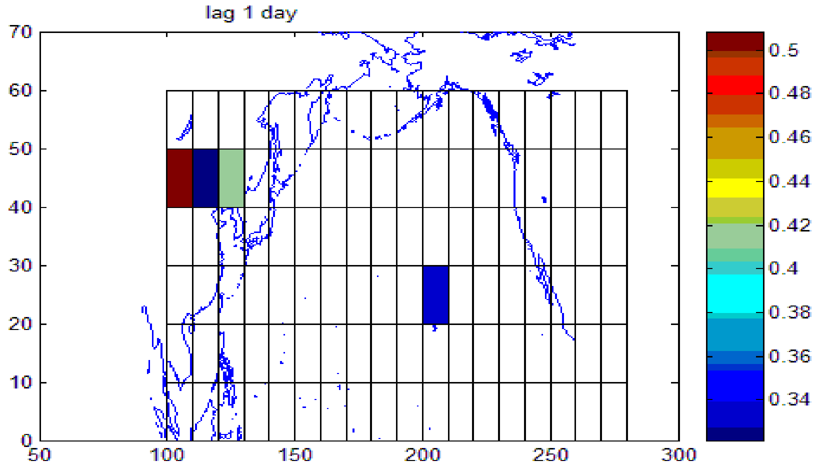
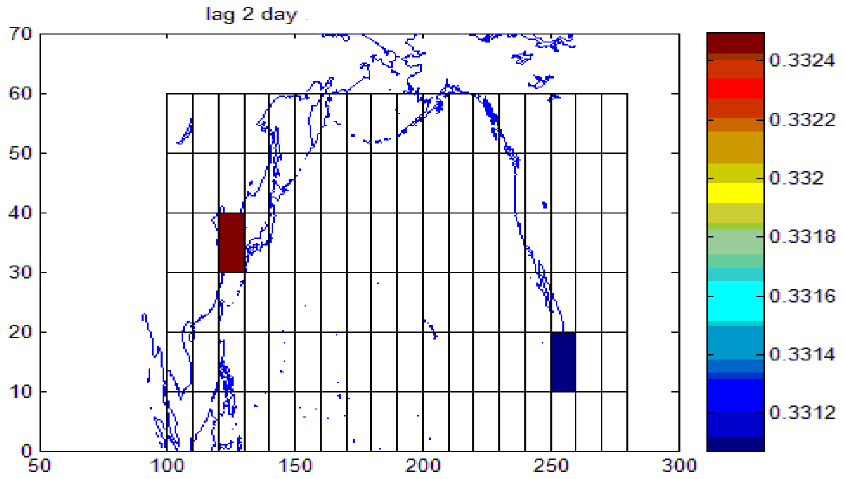
70
60
50
40
30
20
10
0
50
100
150
200
250
300
1
0.9
0.8
0.7
0.6
0.5
0.4

(a)


lag 1 day
70
60
50
40
30
20
10
0
50
100
150
200
250
300
0.5
0.48
0.46
0.44
0.42
0.4
0.38
0.36
0.34

(b)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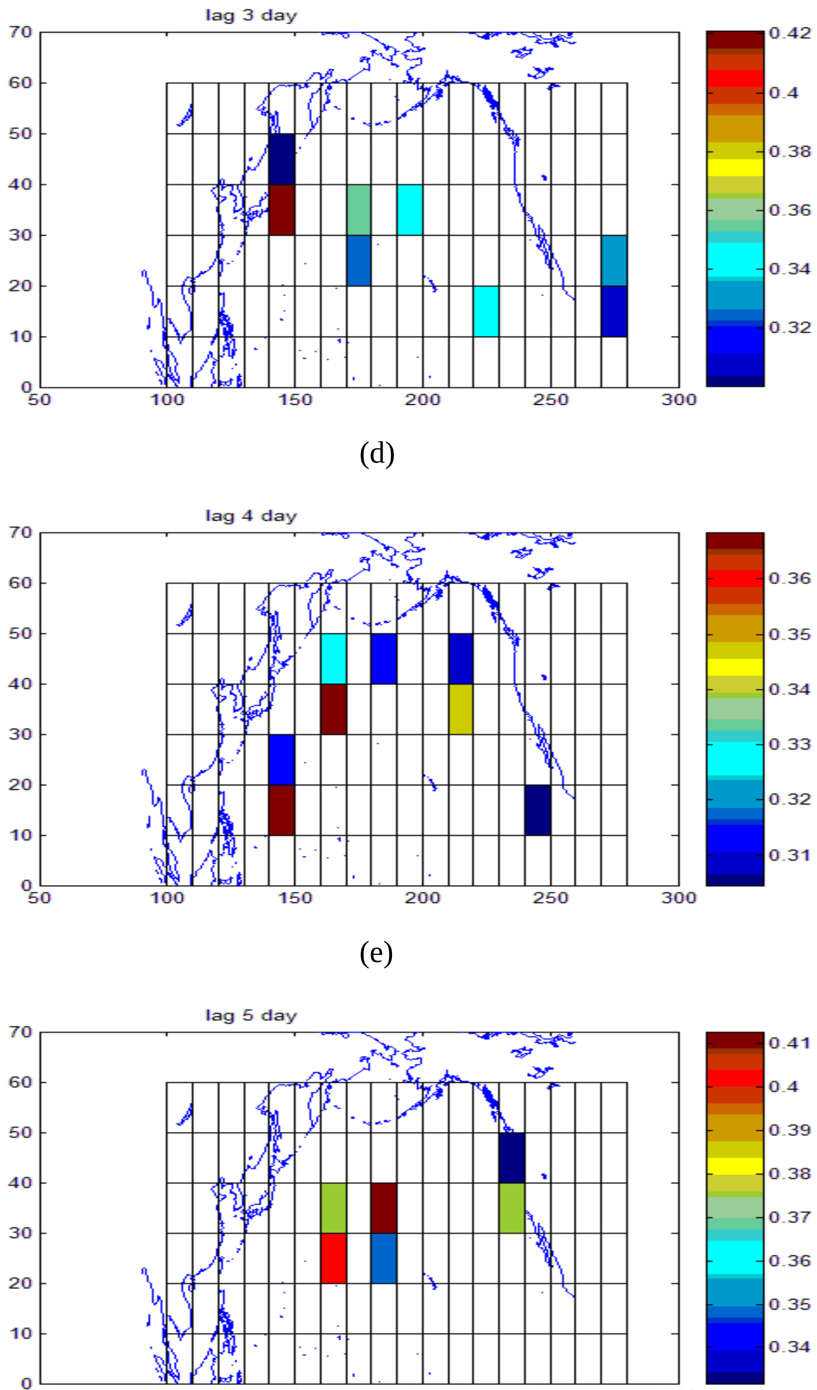
60
50
40
30
20
10
0
50
100
150
200
250
300
0.3324
0.3322
0.332
0.3318
0.3316
0.3314
0.3312

(c)

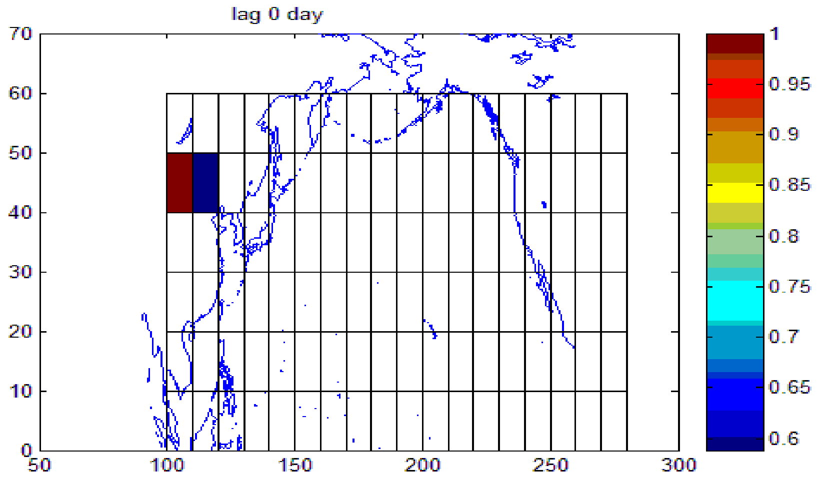


(d)

(e)

(f)

Fig.7. Areas where statistically significant lagged correlations between Gobi and the respective receptor area are found with NIMBUS data. The figures indicate the number of lag days: (a) lag 0 day, (b) lag 1 day, (c) lag 2 day, (d) lag 3 day, (e) lag 4 day, (f) lag 5 day. The figures mark the influence region of dust transport from Gobi to the US coast.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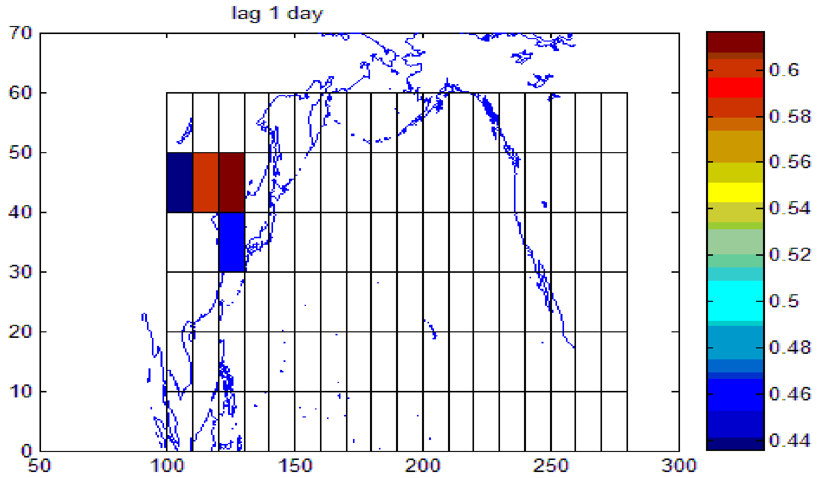
60
50
40
30
20
10
0
50
100
150
200
250
300
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6

(a)


lag 1 day
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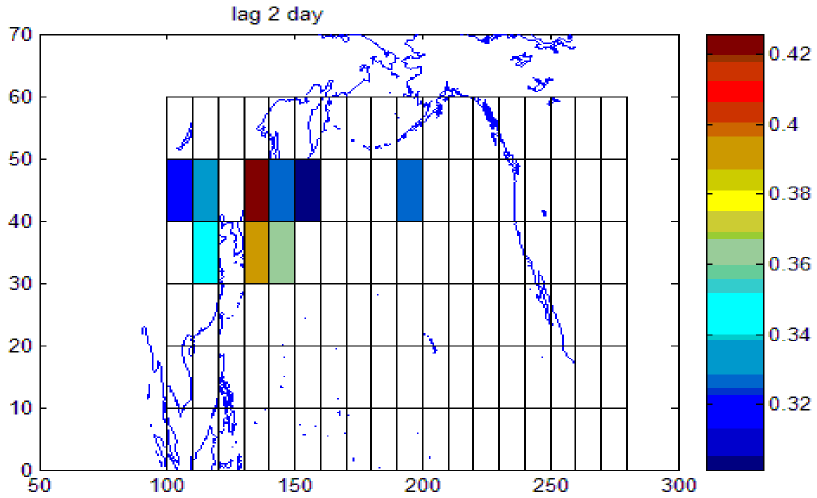
60
50
40
30
20
10
0
50
100
150
200
250
300
0.6
0.58
0.56
0.54
0.52
0.5
0.48
0.46
0.44

(b)


lag 2 day
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60
50
40
30
20
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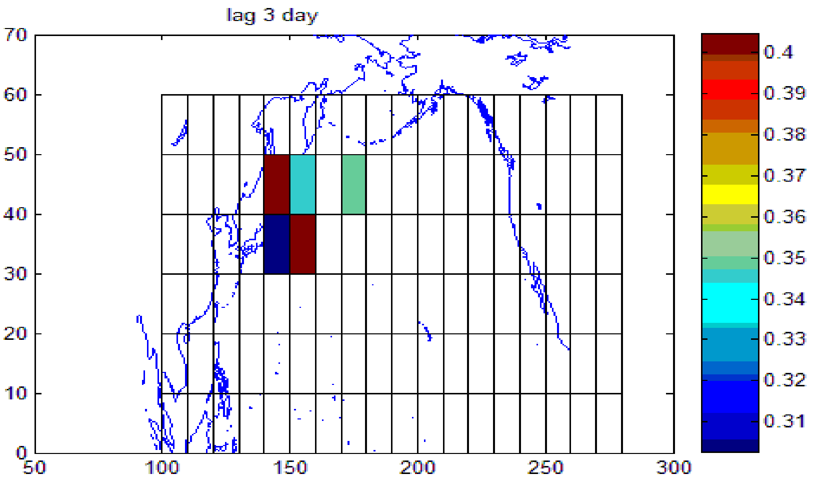
100
150
200
250
300
0.42
0.4
0.38
0.36
0.34
0.32

(c)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60
50
40
30
20
10
0
50
100
150
200
250
300
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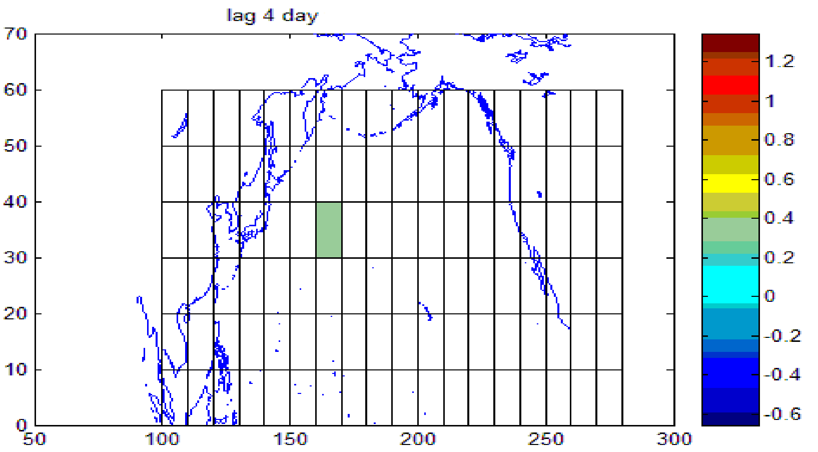
0.39
0.38
0.37
0.36
0.35
0.34
0.33
0.32
0.31

(d)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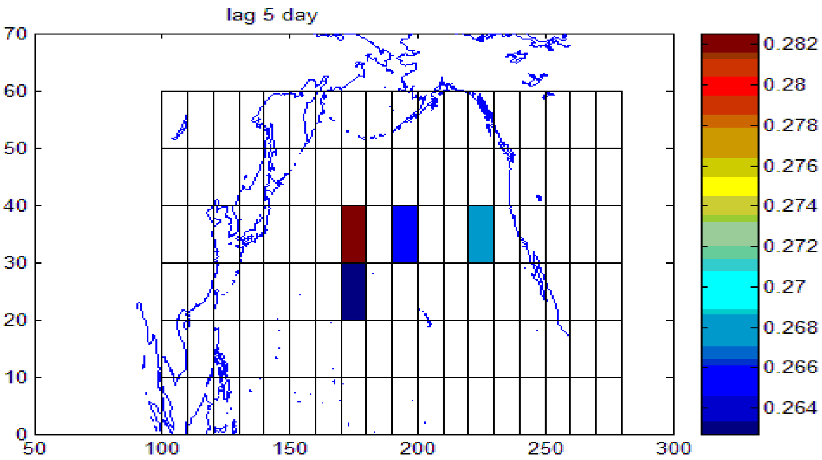
60
50
40
30
20
10
0
50
100
150
200
250
300
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6

(e)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50
40
30
20
10
0
50
100
150
200
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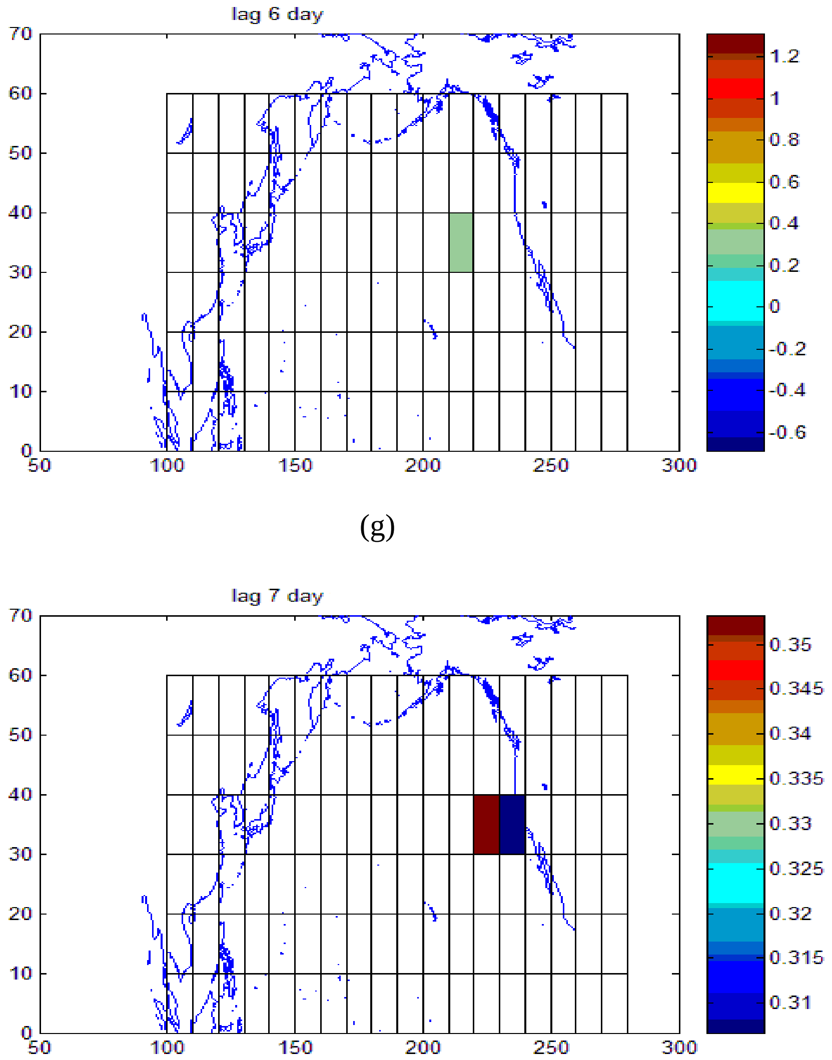
0.278
0.276
0.274
0.272
0.27
0.268
0.266
0.264

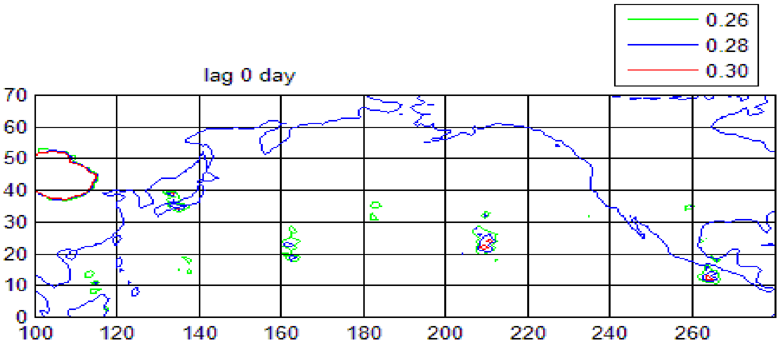
(f)



(g)

(h)

Fig.8. Areas where statistically significant lagged correlations between Gobi and the respective receptor area are found with OMI data. The figures indicate the number of lag days: (a) lag 0 day, (b) lag 1 day, (c) lag 2 day, (d) lag 3 day, (e) lag 4 day, (f) lag 5 day, (g) lag 6 day, (h) lag 7 day. The figures mark the influence region of dust transport from Gobi to the US coast.


0.26
0.28
0.30
lag 0 day
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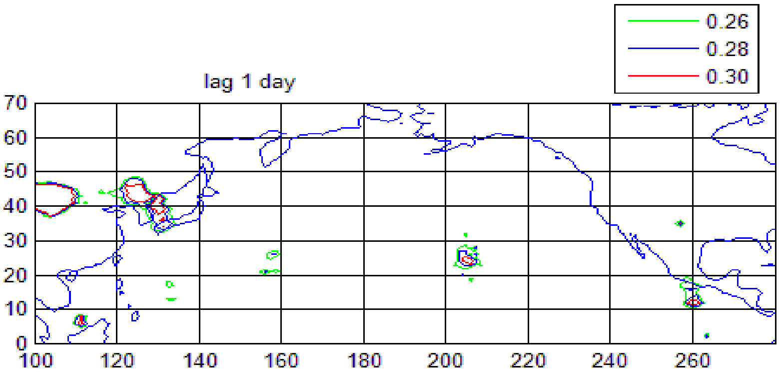
60
50
40
30
20
10
0
100
120
140
160
180
200
220
240
260

(a)


0.26
0.28
0.30
lag 1 day
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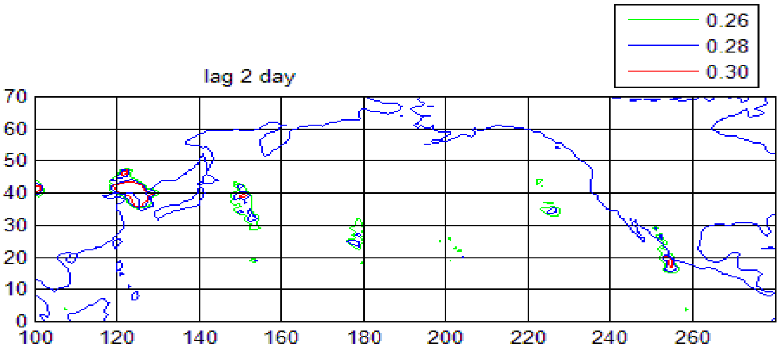
60
50
40
30
20
10
0
100
120
140
160
180
200
220
240
260

(b)


0.26
0.28
0.30
lag 2 day
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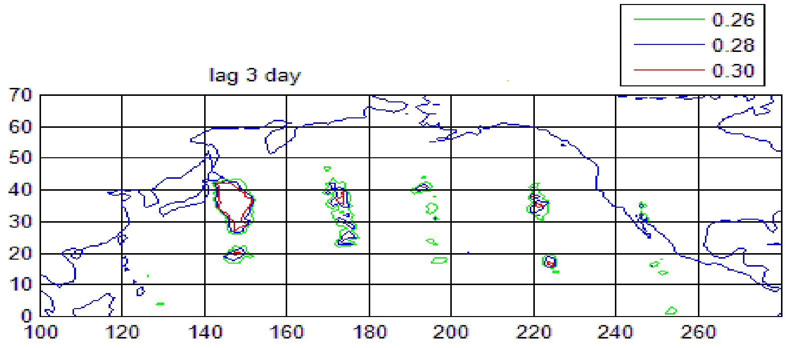
60
50
40
30
20
10
0
100
120
140
160
180
200
220
240
260

(c)


0.26
0.28
0.30
lag 3 day
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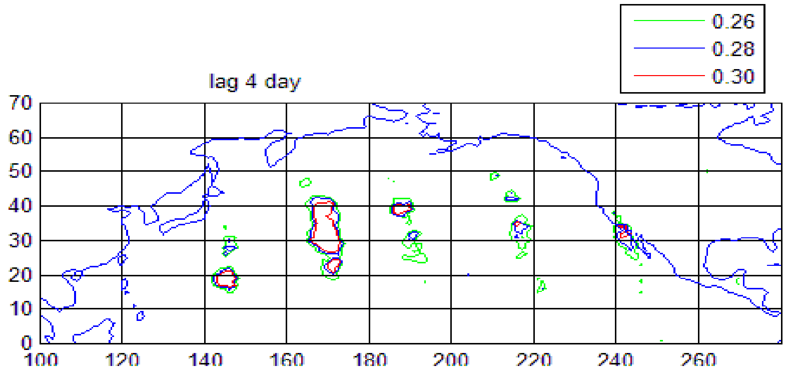
60
50
40
30
20
10
0
100
120
140
160
180
200
220
240
260

(d)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0.28
0.30
lag 4 day
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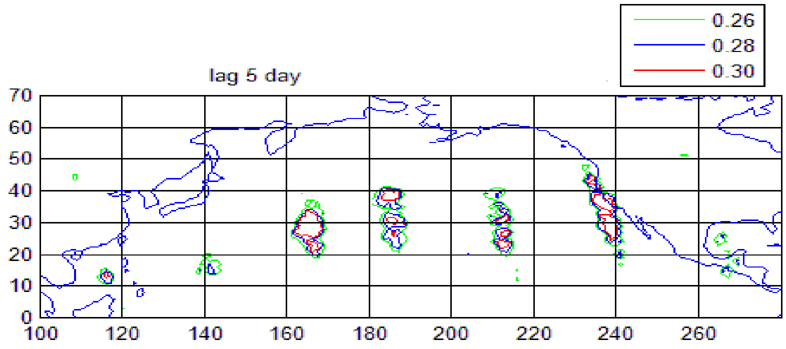
60
50
40
30
20
10
0
100
120
140
160
180
200
220
240
260

(e)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0.28
0.30
lag 5 day
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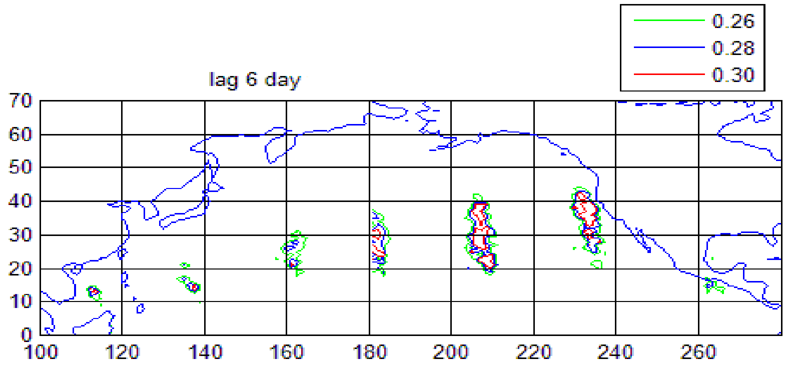
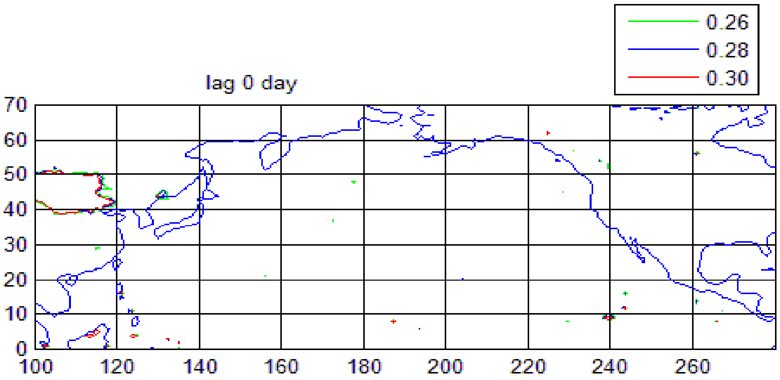
50
40
30
20
10
0
100
120
140
160
180
200
220
240
260

(f)

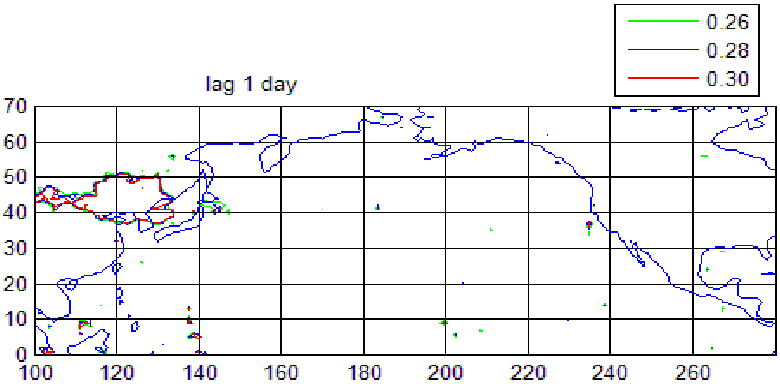


(g)

Fig.9. Areas where statistically significant lagged correlations between Gobi and every gird point in this domain are found with NIMBUS data. The figures indicate the number of lag days: (a) lag 0 day, (b) lag 1 day, (c) lag 2 day, (d) lag 3 day, (e) lag 4 day, (f) lag 5 day, (g) lag 6 day. The contours mark the influence region of dust transport from Gobi to the US coast.


0.26
0.28
0.30
lag 0 day
70
60
50
40
30
20
10
0
100
120
140
160
180
200
220
240
260

(a)


0.26
0.28
0.30
lag 1 day
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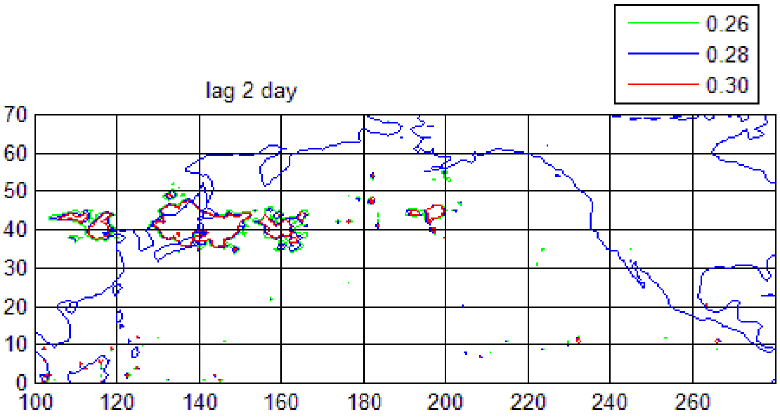
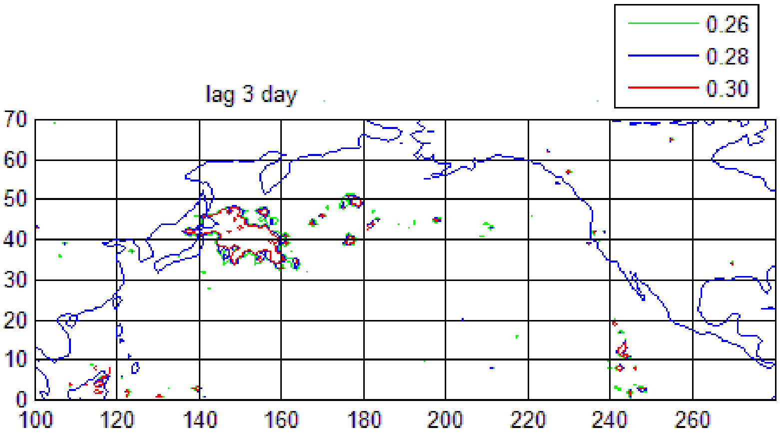
60
50
40
30
20
10
0
100
120
140
160
180
200
220
240
260

(b)


0.26
0.28
0.30
lag 2 day
70
60
50
40
30
20
10
0
100
120
140
160
180
200
220
240
260

(c)


lag 3 day
0.26
0.28
0.30
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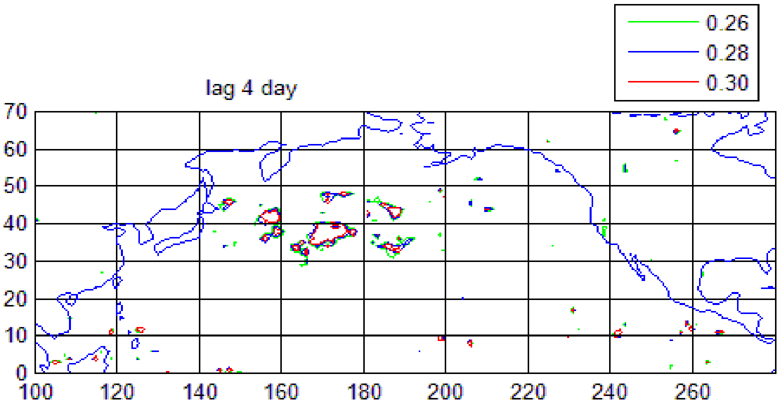
50
40
30
20
10
0
100
120
140
160
180
200
220
240
260

(d)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0.28
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50
40
30
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10
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140
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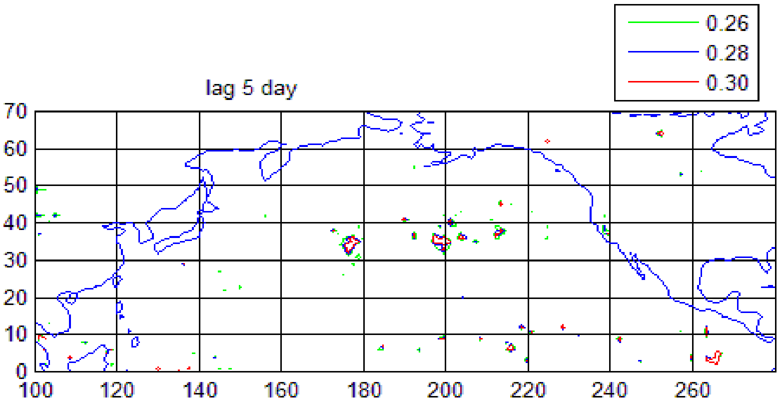
200
220
240
260

(e)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0.28
0.30
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50
40
30
20
10
0
100
120
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160
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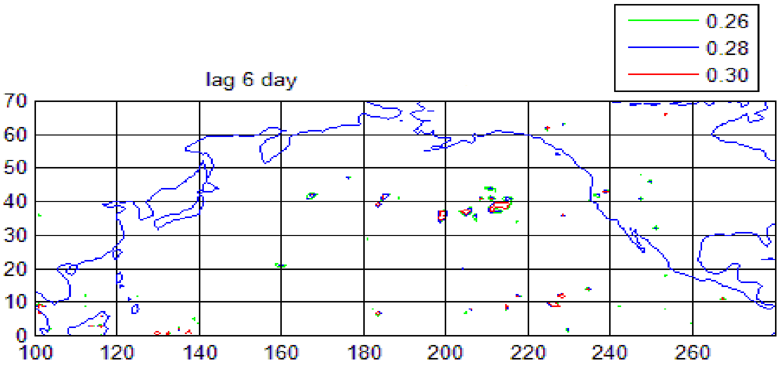
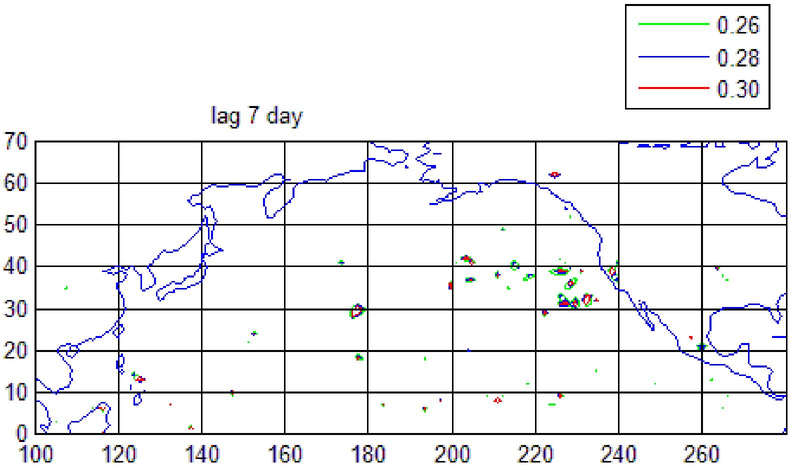
200
220
240
260

(f)

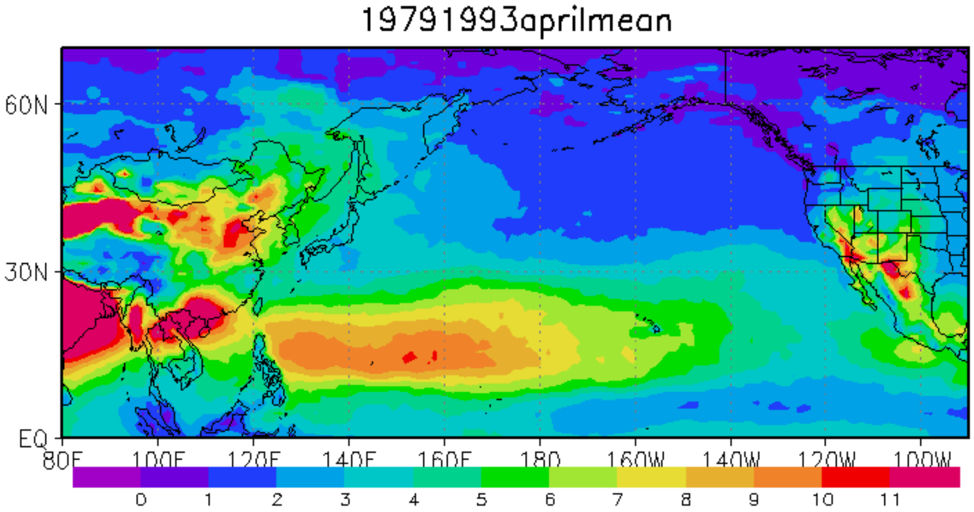


(g)

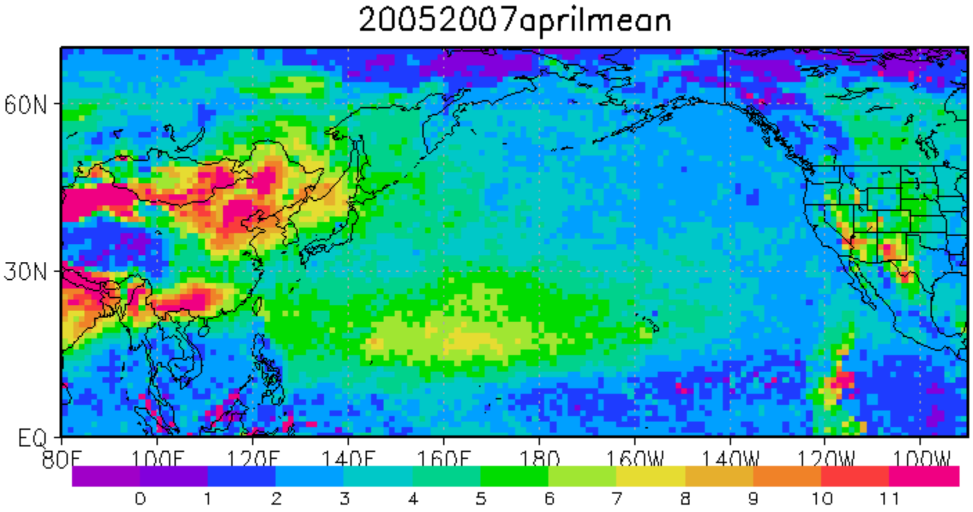


(h)

Fig.10. Areas where statistically significant lagged correlations between Gobi and every gird point in this domain are found with OMI data. The figures indicate the number of lag days: (a) lag 0 day, (b) lag 1 day, (c) lag 2 day, (d) lag 3 day, (e) lag 4 day, (f) lag 5 day, (g) lag 6 day, (h) lag 7 day. The contours mark the influence region of dust transport from Gobi to the US coast.



(a)



(b)

Fig.11. (a) Seasonal mean AI distribution image averaged in 14 years with NIMBUS data for the April from 0-70°N, 80°E-100°W. (b) is same with the (a) but averaged in 3 years with OMI data.