Atmos. Chem. Phys. Discuss., 9, C6397–C6410, 2009
www.atmos-chem-phys-discuss.net/9/C6397/2009/

Atmospheric Chemistry and Physics Discussions

Interactive comment on "Cluster analysis of an impact of air back-trajectories on aerosol optical properties at Hornsund, Spitsbergen" *by* A. Rozwadowska et al.

A. Rozwadowska et al.

ania@iopan.gda.pl

Received and published: 30 October 2009

The authors thank the Anonymous Reviewer #2 for the very helpful comments and remarks.

A detailed response to each question and comment is attached below.

1_1) "My first major concern is most evident in Fig. 5a. For most of the 8 clusters that contain

more than one case, the standard deviations of the mean AOD and alfa^2 are larger

than the separations between clusters. Thus one wonders whether the 10 clusters

are really statistically significant (or distinct). If not, how would the results have been

affected by using a smaller number of clusters that are more distinct from each other?"

We agree that not all clusters are statistically different in terms of AOT and Angstroem coefficient. Different trajectory directions and air mass sources can be characterized by similar AOT values and the opposite, clusters with similar trajectories do not have to have very similar optical properties. The aim of this paper was to determine the aerosol optical properties for different advection directions. Since the cases are grouped according to trajectory character and not optical properties, then the wider the clusters (and smaller their number) the greater the chance that a given cluster includes cases of different features influencing AOT even if the trajectories are similar. For example the clustering algorithm does not include the type of the surface and thus the same cluster includes trajectories from over the land and sea if their coordinates are similar. The surface factor is important both in summer (advection path) and in spring (source). Decreasing the number of clusters the probability of connecting clusters with different surface features increases.

Taking in consideration possible combinations of trajectory shapes and directions at 3 levels then 10 clusters are not many.

One of the criteria for the selection of the number of clusters involves the points of a strong increase of the minimized factor (equation 2) with a decrease in a number of clusters. One of the "breaks" in the function plot usually occurred in the range 7 to 11 clusters.

Decreasing the number of clusters does not influence shapes of curves given in Figs. 2 and 3 (relative variance of AOT versus a trajectory length) but results in increase in relative variance of AOT and diminishes amplitudes of the variance changes.

.

1_2) "This concern propagates into Figs. 2-4, which show how relative variance depends on

back-trajectory length and arrival height. One wonders how significant are the changes in relative variance shown compared to uncertainty in relative variance. These changes do not appear to be very systematic. For example, in Fig. 3a, for back-trajectory length 5 days, the relative variance is clearly less for arrival height 5 km than for 1 and 2.5 km, but this advantage disappears

completely for back trajectory length 8 days. In spite of this, the authors claim "cluster analysis of advection in free troposphere (trajectories at 5 km a.s.l.) decreases AOT variance twice as much as the clustering of boundary layer trajectories (advection at 1 km and a combination of altitudes of 1 and 2.5 km), which suggests a dominating role of advection in free troposphere in the AOT variability.[p15432, ll11-14]". No mention is made of (1) what trajectory length supports their claim, or, (2) more importantly, the fact that the difference in relative variance disappears at 8 days.

One is left with a general concern as to the significance of all the changes in relative variance shown in Figs. 2-4. This might be addressed by adding vertical bars showing the uncertainty in relative variance, or giving results of some other test of statistical significance."

The statistical importance of the results has been investigated and according to the authors the results are statistically significant. However, in order to clarify this issue the following information will be included in the final version of the paper.

In order to evaluate the statistical significance of the results the impact of different seed files on the relative variance has been investigated. The data clustering method

is not fully objective and its results depend, to some extent, on the seed file applied. In this paper three types of seed files were applied (2 in the first version). The first seed file included all trajectories from a given season. The second included a selection of trajectories from a given season with a range of different shapes of trajectories. The third seed file consisted of "artificial" trajectories, which originated in Hornsund and which after 8 days reached 45 or 65 deg N. Four (2 short and 2 long) of these "radii" were directed towards Asia, 2 to Europe, 2 to the Atlantic Ocean and 4 to North America, while last 2 towards the Bering Strait. With trajectory clustering at several levels simultaneously combination of these "radii" at has been used as a seed file. Depending on a seed file applied clusters may differ with respect to a "content", even though they described similar advection directions. The values presented in figures 2 and 3 are average values from the results obtained for 3 seed files. In figure 2 ranges of AOT relative variance values are presented (minimum and maximum from 3 cases). Usually the differences resulting from different seed files are significantly lower than the variability of an average relative variance related to trajectory length. The relative variance depending on air mass trajectory in cases of 5 km a.s.l. clustering is the exception loaded with a relatively high level of uncertainty. The observed minimum in the relative variance plot versus the air mass trajectory length in 5 km cases is not statistically significant.

Additionally, the conclusions drawn from the cluster analysis found their confirmation in the results of more direct approach to the trajectory classification. The following groups have been distinguished among the seasonal cases:

- none of the trajectories (3 levels) had contact with land, except for Greenland,
- at least one crossed over North America
- at least one crossed over Eurasia.

In each of these groups 2 subgroups have been distinguished: advection over the

Spitsbergen to the station and marine advection over the station.

In order to verify the impact of the "source area" on AOT, average AOT values for these 3 groups have been compared. The following mean values were obtained for summer: 0.043+/-0.004 (+/-standard error) (trajectories from over North America), 0.041+/-0.002 (Europe and Asia) and 0.039 +/-0.008 (sea). The differences among the averages are not statistically significant at a level of confidence of 0.1 (The null-hypothesis that the means are equal failed to be rejected at significance level of 0.1; two-sample unpooled t-test for means). Much higher differences were observed for AOT values for the same source but for trajectories, which crossed over Spitsbergen and for those which reached Spitsbergen from over the sea. The average summer AOT values for cases of advection from over Europe and Asia were 0.049 +/-0.005, while for advections from over the Spitsbergen equaled to 0.072 +/-0.017. The null-hypothesis that the means are equal was rejected at significance level of 0.11. In cases of advection from over the North America the average values of AOT for marine advections and the ones from over the Spitsbergen were as follows: 0.038 +/-0.002 and 0.060 +/-0.013, respectively. The difference is statistically significant at a level of confidence of 0.1. For trajectories without contact with the continents the difference between the direct advection to the station from the sea and from the island direction the null-hypothesis that the means are equal failed to be rejected at significance level of 0.1 (the respective means: 0.037 +/-0.002, 0.043 +/-0.005).

In spring the situation was different. The average AOT values for trajectories without contact with the continents and for the cases when at least one trajectory "touched" North America and cases with trajectories from Eurasia) equaled to 0.088 +/-0.009, 0.085 +/-0.008 and 0.1131 +/-0.006. The average AOT values for the marine and North America cases are identical, while the differences between the mean

AOT values for these groups and those for advections from over the Eurasia are statistically significant at a confidence level of 0.1. The impact of a direct advection over the station (marine or from over the island) is noticeable but the difference is not statisti-

cally significant at a level of confidence of 0.1. The average AOT values for air masses from over the Eurasia via the Spitsbergen or the sea are as follows: 0.104 +/-0.007 and 0.123 +/-0.010, respectively.

Statistical significance of the results is not high, but in order to obtain higher significance greater number of data is necessary. However, due to a specific features of the applied method (unobscured sun), the Arctic conditions as well as fast changes of climate the collection of a large data set may be impossible. Therefore, the authors think that despite the relatively small number of data their thorough analyses are worthwhile.

"My second major concern relates to the vertical coordinate of the trajectories. This concern has several sub-components.

2_1. Statements like "trajectories advected at an altitude of 5 km [p15432, l27 to p15433,

l1]", "trajectories were calculated for three atmospheric heights: 1 km, 2.5 km, and 5 km a.s.l [p15428, l24]", and "5 days for advection at 5km [p15432, l17]" at the very least give the impression that the authors envision that each trajectory described in the paper is at a constant altitude. In fact, as shown in Figs. R1-R3 of this review, NOAA HYSPLIT trajectories in general change altitude as a function of transit time (or horizontal location), and these altitude changes can be as large as several km. The terminology should be clarified as in the following examples: Change "trajectories advected at an altitude" to "trajectories arriving at an altitude" Change "trajectories were calculated for three atmospheric heights" to "trajectories were calculated for three arrival heights" Change: "5 days for advection at 5km" to "5 days for trajectory arrival at 5km" Change: "altitude of advection" to "arrival altitude of advection" or "altitude of arrival" Change: "clustering trajectories at a single altitude" to "clustering trajectories arriving at a single altitude" Change: "trajectory level" to "trajectory arrival level""

It will be corrected in the revised manuscript

2_2. "The statement "One-kilometer trajectory typically represents airflow in the boundary layer (BL), 5-km in free troposphere (FT), while 2.5-km in FT near the border between BL and FT (Engvall et al., 2008) [p15428, ll24-26]" needs to be buttressed by some data on actual boundary layer heights at Hornsund during the times and seasons of the AOD measurements. Since Hornsund is WMO station No. 01003, such data should be available.

Also mentioned should be the fact that air arriving over Hornsund within the boundary layer may have previously been above the boundary layer, and vice versa (see Figs. R1-R3 of this review)."

The information below will be included in the final version of the paper.

The trajectories were calculated for three arrival heights: 1 km, 2.5km and 5 km a.s.l.. These heights are comparable to those used by Engvall et al. (2008) for Ny Alesund. It must be noted that that trajectories in general change altitude as a function of transit time and these heights are only ones at which the air arrives at the station. The selection of 1 km as the lowest level resulted from the orography around the station. The fiord is surrounded by hills of 500 to 1000 m a.s.l. heights (highest peak 1431 m a.s.l.) and thus lower trajectories, even if they are calculated properly will be significantly influenced by the orography.

The is a lack of data regarding the boundary layer thickness over the Hornsund, however, it is not a typical Arctic BL over the ice-covered sea. The station is surrounded by

a spatially variable terrain: fiord and ocean, glaciers and tundra and rocks. The station is located at the mouth of the fiord to the warm ocean. From 1 to 2 km north of the station there is a peak of c. 500 m elevation. Most likely the boundary layer elevation often exceeds 1000 m a.s.l.. Spring occurrence of Cumulonimbus clouds confirm the presence of a relatively thick boundary layer, which is likely similar to that in Kongsfjorden (Spitsbergen). Engvall et al. (2008) assumed the thickness of the boundary layer in Ny Alesund (Kongsfjorden) at c. 2 km for April-June. They defined the boundary layer limits using the height of cloud tops.

2_3). "Eq. (1), which defines the Euclidian distance between a trajectory and its cluster mean trajectory, omits the vertical dimension. Thus, two trajectories having very different variations in the vertical but similar horizontal tracks would yield little difference via Eq. (1), when in fact the vertical difference could be very significant to the aerosols on the trajectory arriving over Hornsund."

The authors agree that the vertical difference could be significant to the aerosols on the trajectory arriving over Hornsund, but we do not have enough data in order to introduce another parameter (variable) to clustering. Similar influence would have other factors such as precipitation and clouds on the trajectory path. This paper is a first approach to the problem for the Hornsund station.

3)

Other recommendations:

Abstract: "The wording "in spring changes in AOT values over the Hornsund station were influenced by the at least 8-day trajectories of air, which was advected both in free troposphere and in the boundary layer" could be more clearly stated as "in spring changes in AOT values over the Hornsund station were most strongly influenced by air trajectories of duration 8 days or longer, arriving both in the free troposphere and in the boundary layer."

The Abstract has been rewritten according to the suggestions of the reviewers:

In this paper spectra of aerosol optical thickness from AERONET (AErosol Robotic NETwork) station at Hornsund in the southern part of Spitsbergen were employed to study the impact of air mass history on aerosol optical thickness for a wavelength lambda=500 nm (AOT(500)) and Angstroem coefficient. Backward trajectories computed by means of NOAA HYSPLIT model were used to trace air history. It was found that in spring changes in AOT values over the Hornsund station were strongly influenced by air mass trajectories of duration 8 days or longer, arriving both in the free troposphere and at 1 km a.s.l.. However, the free tropospheric advection was dominating. In summer the AOT variability was best explained by local direction and speed of advection (1-day trajectories) and was dominated by the effectiveness of cleaning processes. During the ASTAR 2007 campaign aerosols near Hornsund showed low AOT values ranging from 0.06 to 0.09, which is lower than the mean AOT(500) for spring seasons from 2005 to 2007 (0.110+/-0.007; mean+/-standard deviation of mean). The 9 April 2007 with AOT(500)=0.147 was an exception. Back-trajectories belonged to the clusters of low and average cluster mean AOT value. Beside the maximum AOT of the 9 April 2007, the observed AOT values were close to the means for the clusters to which they belonged or were lower than the means.

P15425, l23: "Kamchatka Peninsula is listed as an Arctic source, but its latitude, _55N, is well outside the Arctic Circle (_66.6N)."

It will be corrected

P15428, l15: "The discussion of AERONET data should refer to Fig. 1."

It will be added.

P15430, l14: "The reference to Fig. 1 belongs in Section 2.1, not here."

Fig. 1 is referred to in Section 2.3 to justify separate cluster analysis for spring and summer and to give a reader a general impression on AOT variability.

P15431, ll6-9: "Needs to be restated to improve clarity and refer to Fig. 1. The Julian day of key dates needs to be stated, so the reader can find the corresponding data points in Fig. 1."

The paragraph will be rewritten as follows:

For variance calculations cases of AOT values most deviated from the seasonal average been rejected, e.g. 2 and 3 May 2006 (respective Julian days 122 and 123) and 5 July and 29 August 2008 (respective Julian days 187 and 241; compare Fig. 1). Inclusion of these cases into particular clusters would have strong impact on the value of the AOT relative variance, which would mask the contribution of other cases. Exceptionally high AOT cases of 2 and 3 May 2006 caused by agricultural fires in Eastern Europe were discussed by Lund Myhre et al. (2007).

P15431, ll23-24: "at least 8-day long air mass history" could be more clearly stated as "air mass history of 8 days or longer".

It will be corrected.

P15432, ll4-6: "Small drop of a relative variance along with an increase of trajectory length may be attributed to an impact of long-range transport on AOT variability" needs rewording for clarity."

Both local factors and a long-range transport influence the AOT variability. The relative variance is the smallest with one-day long trajectory clustering, which suggests that local factors are dominant, namely cleaning processes. With an increase of trajectory length the AOT variance increases and then slightly decreases. Such decrease may suggest the impact of the source area on the AOT variability – secondary effect versus the cleaning processes.

P15432, ll17-20: "Most probably the cluster analysis of longer "single-level" trajectories is not representative anymore for a total (i.e. for all altitudes above the station) advection to the Hornsund station." Needs to be restated for clarity."

If the AOT value is affected by the direction of air mass advection at all analyzed altitudes and the clustering is made for air mass advections at one given altitude then ignoring the other advection levels adds to the calculation error. The authors suspect that in clustering for one level there is some trajectory length, clustering for which is most representative for advection in the entire atmosphere column.

P15433, ll2-4: "This is an artifact of using the same number of clusters with growing number of altitude levels employed in the cluster analysis." Needs a better explanation.

The more parameters ("degrees of freedom", e.g. number of levels at which air masses arrive) are used in the clustering algorithm the wider the ranges of particular parameters within a given cluster at the same number of clusters. This may cause the increase in the AOT variance.

P15434, ll12-13: "In this section all cases have been used, including the extreme ones, which were rejected during the rel VAR(AOT) analyses." The reason for this different treatment needs to be explained."

All AOT values should be included since they are part of the data set, however, in case of the relative variance analysis the "outliers" with very high AOT values very strongly influence AOT relative variance. They may mask the impact of the distribution of other

days/cases in clusters. Thus they would dominate the dependences given in Figures 2 and 3 (AOT relative variance in function of a trajectory length). While discussing particular cases of trajectory division in clusters high AOT cases were included since they influence the mean AOT and variance values only for their own clusters. It is not very drastic. Moreover, their placement in clusters is discussed in the text.

P15439, l3: Norilsk needs some explanation for why it is mentioned.

The copper/nickel mining and smelting complex near Norilsk, is a strong source of pollution, including sulphur dioxide.

Kashulina, G., Reimann, C., and Banks, D.: Sulphur in the Arctic environment (3): environmental impact, Environ. Pollut., 124, 151–171, 2003.

"Fig. 6: Far too small to be legible. Caption refers to solid and dotted trajectories, which can't be distinguished."

The figure will be enlarged

Other points:

"The paper should state how the trajectory arrival time input to HYSPLIT was chosen relative to the start & end times of each day's AERONET data set (used to compute daily mean AOT & Angstroem exponent). Table 2 shows these times can vary significantly from day to day."

The following sentence will be added to the final manuscript:

The middle time of the aerosol measuring period at a given day was selected as the trajectory arrival time input to HYSPLIT at that day.

"The paper could be greatly strengthened by giving more physical explanation of likely reasons for the observed changes of relative variance."

The final version of the paper will include the following information

Figures 2 and 3 (numbering from original manuscript) show that long-range advection is responsible for AOT variability in spring, which is in accordance with the present knowledge. It results from the location of the main pollution sources, mainly outside the Polar Circle and easier advection of air masses from lower latitudes. This on the other hand is connected with the southerly location of the Arctic front. Besides, the relatively low cloud cover and small precipitation decrease wet deposition and make the long-range transport more effective in spring. The fact that the variability may be connected mainly with higher trajectories is likely concerned with longer ranges of such trajectories and lower chances for particles to deposit from high altitudes. In spring local production of aerosols is relatively small since vast areas of Spitsbergen are covered with ice and snow. Sea ice reduces marine aerosol production. In spring advections from NW-E-S are most frequent , which causes that the trajectories cross over rather uniform surface – mainly snow and ice.

In summer the AOT variance is several times lower than in spring. The Arctic front moves northerly, which makes the air mass advections from lower latitudes more difficult. The air mass trajectories have thus shorter ranges than in spring.

Long-range advections occur but they are much less common than in spring and either have insignificant impact on AOT values or it is much smaller than in spring. This is connected with an increase of wet deposition due to greater cloud cover and precipitation. While in spring advection comes mainly from northern and eastern sectors, in summer the air inflow from the western sector (S-W-N) is dominating. In summer air masses cross over ice free (to a great extent) ocean surface, and significant cloud cover is present (http://modis-atmos.gsfc.nasa.gov/MYD08_M3/browse_c5.html). Ice moves northerly which facilitates greater production of marine aerosols. They contribute to AOT. However, such generation of mainly coarse mode particles due to wave

breaking also causes the creation of additional deposition fluxes of smaller particles from the boundary layer. Simultaneously life is intensified in the tundra and the sea, which aerosol production.

The authors think that in summer, similarly to spring conditions long-range advection from Europe and Asia is mainly responsible for the AOT variability. However, unlike in spring the trajectory of the advection is important (direct advection from over Spitsbergen or from western and southern sectors over the sea). The importance of the source is masked by variability in the cleaning intensity on the way to the station. In cases of the highest average AOT air masses advect directly from over Siberia through the Arctic Ocean and the Spitsbergen. In general the Spitsbergen island has lower cloud cover in summer than warm sea in the southern and western parts (in August also from the east).

In cases of advection from the North America and Eurasia from over the ocean the AOT values are significantly lower than in cases of such advections via the island (see also the response to # 1_2) while such differentiation is not observed for the trajectories without any contact with continents. The summer AOT variability is influences by local processes in a sense of cleaning processes rather then by local aerosol sources.

The comparison given in #1_2 confirms the conclusions drawn from the cluster analysis which show that in summer, unlike in spring, the AOT variability is mainly caused by local processes of aerosol cleaning which are more effective while crossing over the ocean, due to increased cloud coverage and marine aerosol cleaning potential (boundary layer).

Due to a relatively small number of data these are rather assumptions and the further discussion on this issue will be given in a separate paper.

Interactive comment on Atmos. Chem. Phys. Discuss., 9, 15423, 2009.