An Analysis of the Global Climatology of Ice Cloud Effective Radius using PATMOS-x

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1. INTRODUCTION

Satellite observations of thunderstorms have been documented since the advent of the Geostationary Operational Environmental Satellites (GOES) in the 1970’s. Since the 1980’s, polar orbiting satellites have been providing high resolution imagery, twice each day data over the entire globe, beginning with the NOAA-6 and 7 in 1981. The high resolution data has continued through the present time with the launch of the NASA EOS satellites in 1999 and 2002, as well as NOAA-18 in 2005. Through the use of each of these satellites, there have been several studies on both the near storm environment and storm-top characteristics of severe storms (e.g., Adler and Mack, 1986; Setvák and Doswell, 1991).

There are several major processes which can affect the microphysical properties of clouds. One of the effects that are thought to affect the properties of clouds is the presence of giant and ultragiant particles (i.e. particles greater than 10 microns). There are several direct and indirect effects of giant and ultragiant particles. The direct effects are well understood while the indirect effects are not. In addition to these large particles, ice nuclei can have an effect on the microphysical properties of clouds. The major sources of both large and small aerosols are the deserts in the world. It is widely accepted that Mongolia and the Sahara are the major sources of desert dust in the world. Statistically, though, the two sources of dust act differently, either enhancing or reducing the potential for high cloud (ice) formation (Mahowald and Kiehl, 2003).

Currently, most in situ measurements have been of Asian dust and not Saharan dust events. The ice nucleating behavior has been observed in the atmosphere in the presence of modestly supercooled water with Asian dust, (Sassen, 2002). An increase in ice nuclei concentrations has been observed during dust storms (Levi and Rosenfeld, 1996). However, there have been relatively few measurement studies of how Saharan dust acts as ice nuclei.

In addition to aerosols having an effect on the size of ice water particles at cloud top, a climatological study was performed by Lindsey et al. (2006) using GOES data over the continental U.S. during the summer months. It was shown that thunderstorms over the mountains and High Plains tend to generate smaller cloud-top ice crystals than those which were further east. It was hypothesized that the low-level thermodynamic environment plays an important role in the associated mechanism. Small cloud droplets forming at cold temperatures in high-based thunderstorms can be lofted to the homogeneous freezing level where they nucleate as very small ice crystals. This idea also suggests that cloud condensation nuclei (CCN) may play a role in the cloud-top ice crystal size, and is supported by recent work by Rosenfeld et al. (2006). When storms form in areas with abundant CCN, their cloud droplets are small and numerous and are easily lofted to the upper portions of the storm.

The new AVHRR Pathfinder Atmospheres - Extended (PATMOS-x) dataset includes 25 years of cloud products from the Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA polar orbiting satellites, beginning with NOAA-7 in the fall of 1981 (Heidinger et al., 2006). This study will seek to extend the analysis presented in Lindsey et al. (2006), which was solely applied to the continental United States, and extend it to a global analysis for the years encompassing the PATMOS-x dataset. The use of a 25 year dataset will allow for long term patterns to become evident. Thus, if there are significant geographical features, they should emerge, especially if they are large features, as the analysis from the GOES imagery suggests. This study will seek to investigate the spatial patterns in ice cloud effective radius between the tropics, subtropics, and midlatitudes, as well as between ocean and land. In addition to the PATMOS-x dataset, we will also be using the average monthly data from AQUA. The MOD08 dataset, while shorter, will...
be used to look at how aerosol optical depth is related to the ice effective radius over land. In addition, both datasets will be compared to observe to see if both climatologies are consistent.

2. SPATIAL ANALYSIS

2.1. Comparison of PATMOS-x vs GOES

Because this study is extending the analysis presented in Lindsey et al. (2006), we first compare the average AVHRR ice cloud effective radius spatial field for June, July and August to the same spatial analysis using the GOES imagery that was used in Lindsey et al. (2006). Figure 1 is the average cloud top ice effective radius analysis using GOES data from the summers of 2000, 2003, and 2004 using the Cooperative Institute for Research in the Atmosphere (CIRA) ice effective radius algorithm. Figure 2 is the average cloud top ice effective radius from the PATMOS-x climatology, using AVHRR data averaged into 2x2 degree lat/lon boxes for this analysis. This was done to reduce the noise in the data and to focus on the larger scale features. As can be seen in Figs. 1 and 2, the effective radius minimum is present over eastern Colorado in both datasets. The averaged MOD08 data (not shown) for the similar months over JJA and averaged into 2x2 degree bins, shows the same gradients as the other two datasets.

![Figure 1: Ice effective radius for MJJA 2000, 2003, and 2004 from GOES East using the CIRA ice effective radius algorithm.](image1)

![Figure 2: Ice effective radius, averaged for JJA from 1981-2006 from the PATMOS-x dataset](image2)

As can be seen from the previous three figures, the orientation and location of the ice effective radii minimum, as well as the east-west gradient across the central Plains, are the same for all three datasets. Previous work has shown that the difference in the magnitude of the effective radius is due to differences in algorithms used to calculate the ice effective radius. Because they are similar in location and orientation, we can use the PATMOS-x and MOD08 datasets to analyze data for trends in ice effective radius on a global basis. This study will use the PATMOS-x and MOD08 datasets to study the spatial analysis of ice effective radius across the world. While the images from the MOD08 dataset are not shown, the each of the patterns discussed in this study are those present in both datasets.
2.2. Patterns in other parts of the world

Using the PATMOS-x dataset, similar features to those in Figs. 1 and 2 can be found in other parts of the world. Data from June through August were averaged to look for patterns in the northern hemisphere summer, while December through February was averaged to look at patterns in the southern hemisphere summer. These months were chosen so that convectively generated ice clouds could be focused on.

2.2.1 Northern Hemisphere

Similar to the local minimum of effective radius located over eastern Colorado, additional minima can be found in other parts of the Northern Hemisphere. Figure 3 shows contours of ice effective radius over northern Africa, the Middle East and Europe. For this study, we restricted the data to the ice effective radius of clouds that had a cloud top temperature of less than 234K, and the data were averaged into 5x5 degree lat/lon boxes.

![Figure 3: Contours of ice effective radius from the PATMOS-x climatology (1981-2006), centered over northern African and Europe for JJA.](image)

The breaks in the contours indicate areas where there was insufficient data, where there was less than 6 years of data, or there was little or no convection during the summer months. The presence of a minimum of ice effective radius in the African desert is suggested when looking at the MOD08 analysis. Using the MODIS monthly data as a proxy in this location, we see that a minimum appears over Israel and Syria. While more analysis is needed, it is possible that the minimum over Chad in central Africa and the minima over Spain and Portugal can be explained by the fact that their summers are fairly hot and dry, suggesting that thunderstorms with high cloud bases are common, similar to that over the eastern part of Colorado in the United States. These parts of Spain and Portugal experience the Viento Sur in the Cantabrian region, which is a wind similar to the Chinook on the eastern Rockies, making the area south of the mountains hot and dry.

The suggestion of a minimum in the northern portion of Middle East is possibly due to a combination of reasons. Again, as is the case in Spain and Chad, the Middle East is hot and extremely dry. In addition, the areas on the eastern Mediterranean are highly mountainous. Both of these factors could lead to the formation of higher based clouds. Due to the limitations of the aerosol detection algorithms in MODIS, which was used to look at the aerosol optical depth over land, it is impossible to quantify if there is any direct correlation directly over the desert regions.

In addition to the minima located over Africa, the Middle East and southwest Europe, there were two other local minimums found in the Northern Hemisphere. One over Thailand and Laos and the other over central India as shown in figure 4.
It is worthy to note that a minimum of ice effective radius appears over the Tibetan plateau during the winter months (not shown). There are a few possible reasons for the local minimum over the Tibetan plateau in the ice effective. If the storms are convective in nature, the high cloud bases would be responsible for the ice effective radius minimum. Another possibility for the local minimums in the ice effective radius is the presence of orographic wave clouds. These clouds are often generated by homogeneous nucleation and therefore are composed of very small ice crystals (Heymsfield and Miloshevich, 1993).

The minimum over central India has no obvious influence other than the intense convection that occurs over that region during the summer monsoon months. The local minimum over Southeastern Asia, however, is not meteorologically similar to eastern Colorado or other areas with hot, dry, mountainous regions. In addition, the effective radius is similar to the eastern United States or the Brazilian rainforest. That does not, however, mean that the causes for the low ice effective radius are the same. Because the local minimum is quite large, compared to much of the world, and the surrounding area is generally low lying and extremely warm and humid, there is no obvious meteorological explanation for the local minima of ice effective radius. The presence of anthropogenic aerosols makes it a candidate to investigate the relation to the aerosol optical depth, which will be discussed in Section 3.

2.2.2 Southern Hemisphere

As was mentioned previously, the PATMOS-x data was averaged over December through February to look at convection during the summer months in the Southern Hemisphere. In South America, there were two minima of ice effective radius, as can be seen in figure 5.

*Figure 4: Contours of ice effective radius from the PATMOS-x climatology (1981-2006) over southern Asia for JJA.*

*Figure 5: Contours of ice effective radius from the PATMOS-x climatology (1981-2006) over South America.*
The first is most similar meteorologically to the eastern slopes of Colorado, and is located just to the east of the Andes. The area just to the east of the Andes is where the Zonda wind, similar to Chinook winds in Colorado, is located. The Zonda has been observed to be a dry wind, often carries dust from the Peruvian desert. It is created as polar maritime air is carried northeastward by polar fronts. As is the case with the Chinook, the low-lands east of the Andes are warm and dry, which create similar meteorological situations as eastern Colorado. The Zonda has been observed to be stronger than the Chinook wind, with winds over 200 km/h winds recorded in some cases. However, the local minimum in ice effective radius is larger than the one in eastern Colorado, suggesting some other mechanism may have an influence here.

The final area in the Southern Hemisphere that was observed to have a local minimum of ice effective radius was located just south of Darwin, Australia (not shown). This area has a similar climatology as the eastern Mediterranean, with maritime convection flowing to the south over the land. The area just to the south of the minima is the Great Sandy Desert, which is a potential source of aerosols, similar to that of the deserts just inland along the Mediterranean. This was one area that was looked at for the possible correlation with the aerosol optical depth and the minimum in ice effective radius.

2.2.3 Oceans

There were a couple of areas of low effective radius located over the oceanic regions of the world when not filtering any of the data for average cloud top temperatures. However, by looking at the MODIS and PATMOS-x data, we were able to see that most of these regions had either very few pixels which were computed as ice cloud pixels or were located just off the coasts of the continents, in such locations that would indicated blow off from continental convection. It should be noted that there were widespread areas of decreased effective radii in the northern Pacific and off the desert coasts of the Middle East and Africa. These are the subject of a future investigation, as this study focuses on the ice effective radius minimums over land.

3. THE EFFECT OF AEROSOLS ON OPTICAL DEPTH

As was mentioned above, previous studies have shown a link between aerosols and particle size. This study did a limited correlation analysis between the ice effective radius and aerosol optical depth (AOD). Because the PATMOS-x dataset does not contain aerosol information over land, MODIS monthly data was used as a proxy.

Correlation analysis showed that of the areas of low ice effective radius, only two areas had any significant correlation (areas of greater than .5) with AOD. These were Southeast Asia, during both the summer and winter months, and parts of Africa. Other areas that were investigated, such as Australia, did not show a significant correlation.

The area of correlation in Southeast Asia is associated with the area of high aerosol optical depth (not shown), is primarily located over Laos and Thailand do not have high aerosol optical depths. The temporal correlation for the month of July is shown in figure 8. Areas of 0 correlation and missing data are dark grey, areas of positive linear correlations are warm (red) colors and negative linear correlation are cooler (blue) colors. A positive correlation is associated with higher (lower) than normal ice effective radius and higher (lower) than normal AOD.
As can be seen, the area of highest correlation between the two is in the same area as the local effective radius minimum, shown in figure 4. This area of high correlation is also not the area with the highest AOD. This suggests that the source region is not necessarily the same area to have an ice effective radius minimum. It should also be noted that the strongest correlation occurs during the peak summer months rather than the beginning of summer. In addition to the summer months, there is a strong negative correlation during the winter months, (not shown). This time, though, the strong negative correlations were located over the industrial areas of China. This correlation between the AOD and effective radius, in addition to the small values of AOD suggest that the type of aerosol over that area might be more effective at reducing the ice effective radius than over dust regions.

The other area of interest for this study was over the African continent. The AOD data averaged over June through August (not shown) shows there are two maxima of AOD in Africa. The first is over Chad and Central Africa, and the other west of the Sahara. Because the MOD08 aerosol product masks out deserts, correlation analysis was not done over the Sahara. The area to the west of the Sahara suggests that dust from the Sahara might be injected into the mid-atmosphere, thus decreasing the effective radius in convective storms at these locations. The temporal correlation for AOD and ice effective radius for July is shown in figure 9.
The temporal correlations analysis shows that for the majority of Africa, where there is data, has 0 linear correlation between the AOD and ice effective radius shows that there is at least one region, the area off the Western Sahara that has a weak temporal correlation for June, July and August (June and August are not shown)\nThe other area of high correlation is the central Congo Basin, an area of future investigation.

4. CONCLUSIONS AND FUTURE WORK

The analysis first presented in Lindsey et al. (2006), which was solely applied to the continental United States, was extended to a global analysis through the use of the 25-year PATMOS-x dataset. In order to test the robustness of the datasets, the area over the continental United States was chosen. It was found that, while the minimum located in southern Colorado existed in all three datasets, the value of the minimum was different. These differences are likely due to differences in lookup tables for each dataset. After confirming that the feature was located in all three datasets, it was found that there were other minima located in other parts of the world. There were several locations, such as the eastern Andes and parts of Spain and Portugal, which may experience similar meteorological conditions as eastern Colorado. These areas of low effective radius seem to be as a result of meteorological conditions rather than aerosols influencing the change in cloud properties, especially when looking at the correlation analysis of these areas.

There were some areas of high correlation between aerosol optical depth and ice effective radius. Some of these occurred where there was a moderate to low aerosol optical depth and a local minimum in the ice effective radius. Two such areas are Southeast Asia and the western edge of Africa. These regions have locally low ice effective radii, the aerosol optical depth is half or less than that of the areas over desert regions nearby. This is perhaps due to the fact that instead of a strong source of aerosol, the aerosol mass is spread over a larger region, thus weakening its effect for each convective storm. While it is true that Saharan dust does reach the United States, such episodes are not on a persistent basis and would not necessarily show up in the long term trend. However, the effects of dust in these periodic events have been shown in recent field campaigns (DeMott et al., 2003)

The final areas that this study looked at were areas of locally low effective radius are places that had no obvious mechanism for their presence. One such area is the northern part of Australia, near Darwin. Because the aerosol optical depth of this region is quite low, it is possible that a metrological influence is responsible for the minimum located in this area. During the Southern Hemisphere summer, reanalysis data shows a dryline is often in the vicinity of the effective radius minimum in the northern Australia. It surges north and retreats back south just about daily. While this is not really the same meteorological setup as in eastern CO, both areas have a source of low and mid-level dry air nearby. However, there is a large desert near this area, suggesting that aerosols could play a role in affecting the cloud top ice particle size. However, without a more detailed analysis, this local minimum of ice effective radius cannot be completely explained.

DeMott et al. (2003) and other studies have shown that aerosols can play an important role in affecting cloud top properties. A recent study by Ramanathan et al (2007) showed that the Asian Brown Cloud, the area of high aerosol optical depth over southeast Asia, not only effects cloud properties, but can also enhance low level atmospheric warming. Thus, it is important to understand the impacts aerosols have on cloud properties and the atmosphere. Future work will include looking more in depth at the areas of locally low effective radius, especially in areas such as northern Australia. However, as was seen in the analysis, aerosols are not necessarily the primary reason for changes in ice effective radius. Metrological factors, such as if there is a location of low and mid-level dry air is present. Winds, such as the Chinook of the Front Range in Colorado, can be a source of this air. A more in depth look at the potential reasons for the influence in to the areas that aerosols seem to play an important role will help determine how important they are to changing the cloud top ice effective radius.

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6. REFERENCES


