ENHANCED ICE GENERATION AND SUPPRESSED DRIZZLE FORMATION BY DUST PARTICLES IN STRATIFORM CLOUDS OBSERVED FROM CALIPSO AND CLOUDSAT MEASUREMENTS

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ABSTRACT

Two years collocated CALIPSO/CloudSat measurements were employed to investigate the impacts of dust particles on ice generation in mid-level stratiform clouds (cloud top higher than 2.5 km above the surface and cloud top temperature - CCT warmer than -40 ^{0}C) and drizzle formation in warm stratiform clouds (CTT warmer than ^{0}C) in a global view. The results showed that not only do the dusty mid-level stratiform clouds have higher mixed-phase fraction compared with that of the non-dusty cases at given CTT (colder than -6 ^{0}C) and layer maximum lidar total attenuated backscattering (TAB, which has a positive correlation with the cloud liquid water path - LWP at given CTT) in the same geographical region, but also the dusty mixed-phase mid-level stratiform clouds have larger layer maximum radar reflectivity (which indicate higher ice particle concentration) compared with that of the non-dusty case at given CTT and layer maximum TAB. Our studies also showed that there was obvious drizzle suppression for dusty warm stratiform clouds compared with that of the non-dusty warm stratiform clouds at give CTT and layer maximum TAB in the same geographical region.

1. INTRODUCTION

Dust is one of the major sources for atmospheric aerosols and plays an important role in the Earth's radiation budget [Tegen et al., 1996], directly by scattering and absorbing solar and Earth infrared radiation and indirectly by modifying cloud properties through acting as cloud condensation nuclei (CCN) or ice nuclei (IN). Heterogeneous ice generation in atmospheric clouds is still poorly understood and parameterized because of the largely unknown properties of ice nuclei (IN). Although dust particles are widely regarded as effective IN and are able to initiate ice nucleation at relatively warm temperatures and dry environments from both laboratory experiments [Field et al., 2006; Koehler et al., 2007] and field observations [Sassen, 2002, 2005; DeMott et al., 2003; Sassen et al., 2003; Toon, 2003], there still are large uncertainties on its effectiveness as IN at relatively warm temperature as highlighted by recent field observations. For example, Ansmann et al. (2008) presented results from lidar measurements in dust region showing that no ice formation were observed with cloud top temperatures of -8 ^{0}C to -18 ^{0}C. Long term observations will provide more reliable information on dust impacts on supercooled stratiform clouds. On the other hand, large dust particle that coated with small fraction of soluble material can act as effective cloud condensation nuclei (CCN), and suppress warm precipitation [Rosenfeld et al., 2001; Min et al., 2009].

CALIPSO lidar and CloudSat radar measurements provide unique datasets for studying dust impacts on stratiform clouds. The Cloud - Aerosol lidar with Orthogonal Polarization (CALIOP) lidar on CALIPSO satellite is capable of detecting dense dust layers and cloud tops, while CloudSat CPR radar are used to detect the appearance of ice particles in/below the stratiform clouds. Combined CALIPSO/CloudSat measurements provide useful information of dust impacts on the stratiform cloud properties, especially the ice particle and hydrometeor appearance in/below the stratiform clouds. In this study, two years combined CALIPSO/CloudSat (from June 2006 to May 2008) measurements were used to investigate the impacts of dust on stratiform clouds.

2. IDENTIFICATION OF DUSTY STRATIFORM CLOUDS FROM COMBINED CALIPSO/CLOUDSAT MEASUREMENTS

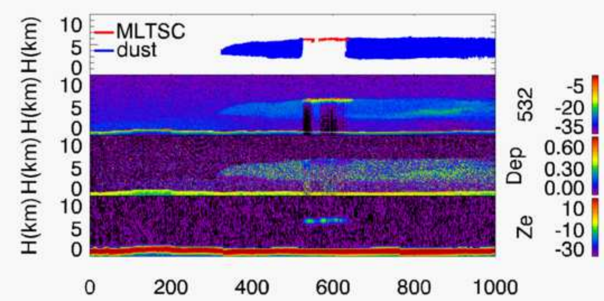

Figure 1: An example of identified dusty mid-level stratiform clouds. Plots from top to bottom are identified dust layers and mid-level stratiform clouds, CALIOP 532nm TAB, CALIOP 532nm depolarization, CloudSat CPR radar reflectivity separately .

The CALIOP on CALIPSO satellite is the first space-borne polarization lidar, providing backscattering coefficient at 532 nm and 1064 nm, and also linear depolarization measurements at 532 nm [Winker et al., 2003, 2007]. The vertical and horizontal resolutions of the CALIOP are 30 and 333 m below 8.2 km, and 60 and 1000 m between 8.2 and 20.2 km, respectively. CloudSat carried the first space-borne cloud radar - a 94.05 GHz Cloud Profiling Radar (CPR) with sensitivity of -30 dBZ [Stephens et al., 2002, 2008]. The CPR measurements provide radar reflectivity (Ze) profiles with a vertical resolution of 240 m and a footprint of 1.4 km 1.8 km (cross- and along-track). The formation flying of CloudSat and CALIPSO ensures that the CALIOP footprint overlaps with the CPR footprint more than 90% of the time [Stephens et al., 2008]. The CloudSat and CALIPSO measurements were then collocated by averaging CALIOP profiles within a given CPR footprint.

Zhang et al., [2010] developed algorithms to identify mid-level liquid layer topped stratiform clouds (MLTSC) from collocated CALIPSO/CloudSat measurements. Strong lidar backscattering at the top and strong attenuation of lidar signal at 532 nm after the peak indicates the existence of liquid layer at the top; while the horizontal cloud top variations were used identify stratiform clouds. In addition, radar measurements were used to exclude strong precipitation cases. Identifying dust layer for cloud free granules from collocated CALIPSO/CloudSat measurements were developed by Liu et al., [2008]. Dust layer is detected if the layer integrated TAB and depolarization at 532 nm are larger than pre-selected thresholds (detailed in Liu et al., 2008). Since the signal to noise ratio is pretty low, and thus the depolarization ratio is much noisy during daytime measurements, only night time measurements were used to identify dusty layers in this study. Since CALIPSO lidar generally are not able to penetrate the liquid layer at the top of stratiform cloud to provide depolarization ratio for detecting dusty layer below the cloud, we defined dusty stratiform clouds as stratiform clouds with dusty layer closely on one or both sides. To be simple, we only consider the single layer cloud cases to avoid seeding from the upper level clouds. Fig 1 shows a case of identified dusty stratiform clouds from collocated CALIPSO/CloudSat measurements. Plots from top to bottom in Fig 1 are identified dust layers and stratiform clouds, CALIOP 532nm TAB, CALIOP 532nm depolarization, and CloudSat CPR radar reflectivity separately. Obvious ice particle appearances were observed below the liquid water layer from the radar measurements in fig 1.

3. DUST IMPACTS ON ICE GENERATION IN SUPERCOOLED MLTSCS

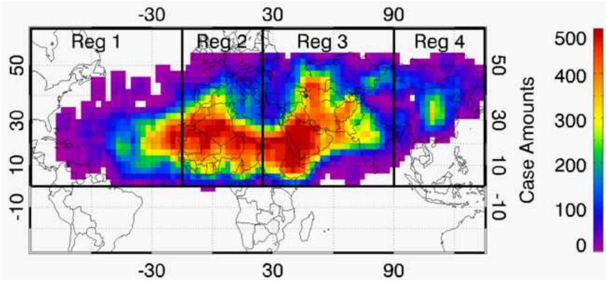

Figure 2: The global distribution of dusty mid-level stratiform clouds. The distribution is separated into four regions to investigate the regional variations.

Collocated CALIPSO/CloudSat measurements provide good opportunity to study dust impacts on ice generation in mid-level stratiform clouds in a global scale. Fig 2 shows the global distribution of dusty mid-level stratiform clouds in a $2.5^0 \times 2.5^0$ box identified from collocated CALIPSO/CloudSat measurements. From the figure, the dusty mid-level stratiform clouds are mainly located over the northern Africa and Saudi Arabian regions, and also northern China regions. Dust particles in deferent regions may have different ice nucleating abilities. Therefore, to study the dust impacts on ice generation in mid-level stratiform clouds in different geological regions, the global dusty mid-level stratiform cloud distribution is separated into four small regions as labeled in Fig 1. Region 1 is from west coast of northern Africa to deep Atlantic Ocean. Dust particles in this region are generally far from the source region, and may interact with sea salt, which will reduce its ability to act as effective IN as suggested by previous studies [Archuleta et al., 2005]. Dust particles in region 2 and region 3 are close to the source regions. While dusty particles in regions 4 are also far from the source regions, and interact with eastern Asian pollutant aerosols, which may change its ability to act as effective IN.

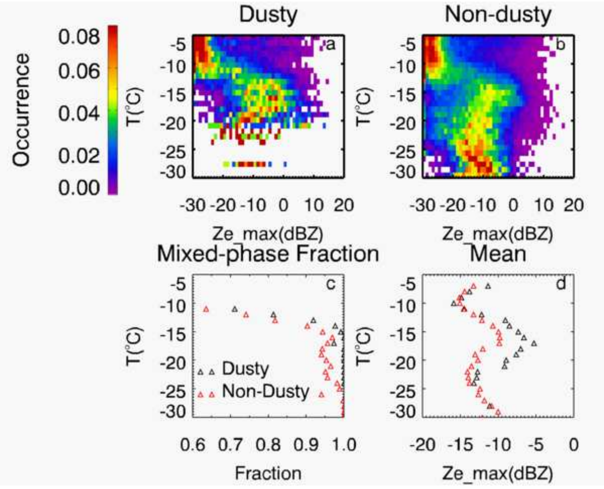

Figure 3: Supercooled stratiform clouds occurrence as a function of CTT and layer maximum radar reflectivity (Ze_max) for dusty and non-dusty cases at a narrow lidar TAB range of 0.37-0.51 km^{-1} sr^{-1} (a, b); c) mixed-phase stratiform cloud fractions and d) mean Ze_max at each CTT for dusty and non-dusty MLTSCs.

The liquid water path (LWP) has a great impact on the ice generation in supercooled stratiform clouds. To isolate the dust impacts on ice generation in supercooled stratiform clouds, we compare ice generation in supercooled stratiform clouds for dusty and nod-dusty cases under similar meteorological conditions, i.e., the clouds have similar LWP and CTT. However, the collocated MODIS data only provide day time LWP measurements. Since the max lidar TAB at the cloud top has a positive correlation with LWP at given CTT, we used max lidar TAB as a substitute of cloud LWP. To ensure enough data points, we choose a narrow lidar TAB range around the lidar TAB peak distribution of dusty MLTSCs (0.37 - 0.51 $km^{-1}sr^{-1}$). The dust impacts on ice generation in supercooled stratiform clouds are shown in fig 3. Fig 3 a) and b) are the supercooled stratiform clouds occurrences as a function of CTT and Ze_max for dusty and non-dusty cases at a narrow lidar TAB range of 0.37 - 0.51 $km^{-1}sr^{-1}$. From fig 3 we can seet that dusty supercooled stratiform clouds are fully glaciated at about -20^0C, and generally have larger portion at the large Ze_max, which indicates that dusty supercooled stratiform cloud are more likely to produce ice particles. This is also seen in Fig 3c, the dusty cases have larger mixed-phase fraction at each temperature colder than -6^0C. From Fig 3d, the dusty mixed-phase stratiform clouds also have larger mean Ze_max at each CTT. At given CTT and similar max lidar TAB, the ice particle growth is similar in supercooled stratiform clouds. Thus larger mean Ze_max for dusty mixed-phase stratiform clouds indicates that they have higher ice particle concentrations. This is consistent with field experiments which showed strong IN enhancement when dust storms passing over [DeMott et al., 2003].

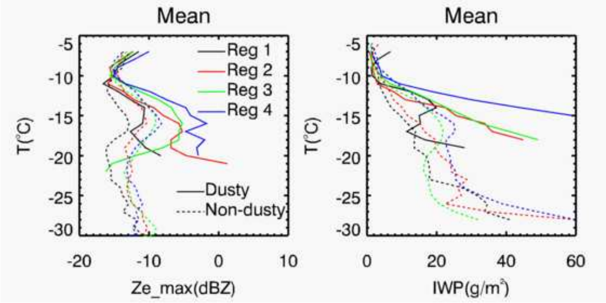

Figure 4: Regional dependence of dust impact on ice generating in mixed-phase MLTSCs (TAB within 0.37-0.51 $km^{-1}sr^{-1}$) in terms of Mean Ze_max and IWP.

Dusty particles that originated in different regions may exhibit different ice nucleating abilities. Fig 4 shows the regional dependence of dust impact on ice generation in mixed-phase stratiform clouds for max lidar TAB within 0.37-0.51 $km^{-1}sr^{-1}$. For all the four regions, dusty mixed-phase stratiform clouds have larger mean Ze_max and IWP at each CTT. Mixed-phase MLTSCs in Region 1 have the smallest mean Ze_max and IWP at each CTT, while the largest mean Ze_max and IWP in region 4. There are multiple mechanisms possible to explain this, such as different dust number concentrations, different chemical components, and thus different ice nucleating abilities. More detailed works are needed to confirm the statements.

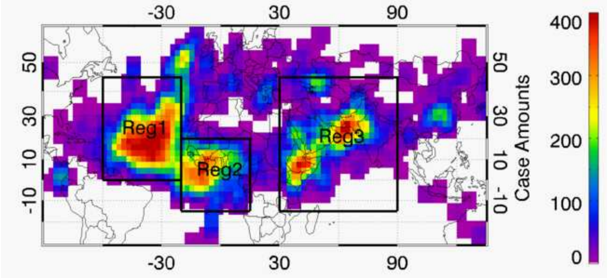

Figure 5: Global distribution of dusty warm stratiform clouds.

4. DUST SUPPRESSION OF DRIZZLE FORMATION IN WARM STRATIFORM CLOUDS

Aerosol indirect effect still represents the greatest uncertainty of model forecasts of climate change [IPCC, 2007]. Dust as one of the major aerosol sources has the potential to impact global cloud and precipitation processes. Model simulations predict that dust particles coated with sulfate when passed over the polluted regions can act as giant CCN, which will then enhance the collision and coalescence between droplets and therefore increase the warm precipitation [Teller and Levin, 2006]. However, observations from satellite measurements and field campaign suggested that dust suppress warm precipitation by changing the CCN concentration. Similar as in section 3, dust layer and warm stratiform clouds were also identified to study the dusty impacts on the drizzle formation in warm stratiform clouds. Fig 5 shows the global distribution of dusty warm stratiform clouds. It is clearly that the dusty warm stratiform clouds mainly located over the coast of northern Africa and Saudi Arabia. Again, to study the regional differences, we separated the distribution into three small regions as labeled in Fig 5.

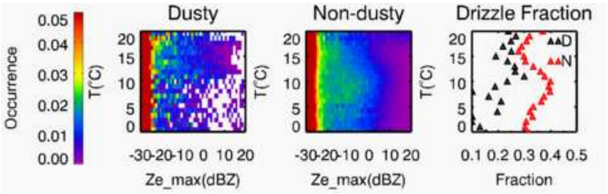

Figure 6: Warm stratiform clouds occurrence as a function of CTT and Ze_max and mean drizzle fraction (Ze > -15 dBZ) for dusty and non-dusty cases with TAB within range of 0.27-0.39 $km^{-1}sr^{-1}$.

To ensure enough data points and similar LWPs, we choose a narrow TAB range around the max lidar TAB peak distribution of dusty warm stratiform clouds (0.27 - 0.39 $km^{-1}sr^{-1}$). Drizzle appearance in warm stratiform clouds will dominate the radar reflectivity signal. Threshold of - 15dBZ were widely used to discriminates between drizzling and nondrizzling warm clouds [Kubar et al., 2009]. Fig 6 shows the warm stratiform clouds occurrence as a function of CTT and Ze_max and the mean drizzle fraction for dusty and non-dusty cases. Obviously that dusty warm stratiform clouds have less portion of larger Ze_max, and smaller drizzle fraction than than of non-dusty cases at each CTT. The regional differences of dust impact on drizzle formation are shown Fig 7. For all the three small regions, dusty warm stratiform clouds have smaller drizzle fractions. One exception is that in the region 1 which is over the west coast of northern Africa, the drizzle fraction differences between dusty and non-dusty warm stratiform clouds are much smaller than that over the other two regions.

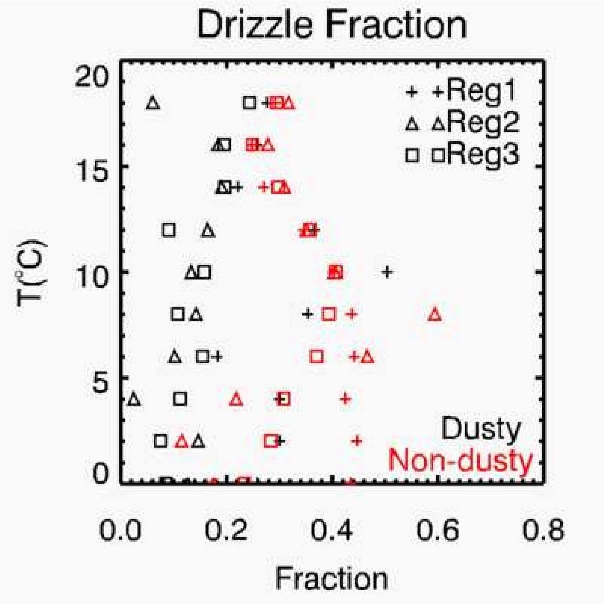

Figure 7: Mean drizzle fractions at each CTT for dusty and non-dusty over three different regions at a narrow TAB range of 0.27-0.39 $km^{-1}sr^{-1}$.

5. CONCLUSIONS

In this study, two years collocated CALIPSO/CloudSat measurements were investigated to study the dust impact on ice generation in supercooled stratiform clouds and drizzle formation in warm stratiform clouds, and their regional differences. Dusty mid-level stratiform clouds not only have higher mixed-phase fraction but also have larger layer maximum radar reflectivity than non-dusty similar cases at given CTT (colder than -6^0C) in the same geographical region. Dust particles originated from different source regions also showed different ice nucleation abilities. Dusty warm stratiform clouds have smaller drizzle fraction than that of non-dusty case under similar condition, which indicate that dust particles can noticeably suppress drizzle formation in warm stratiform clouds.

ACKNOWLEDGMENTS

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REFERENCES

1. Ansmann, A., et al. (2008), Influence of Saharan dust on cloud glaciation in southern Morocco during the Saharan Mineral Dust Experiment, *J. Geophys. Res.*, **113**, D04210, doi:10.1029/2007JD008785.
2. Archulet, C.M., P.J.DeMott, and S.M.Kreidenweis (2005), Ice nucleation by surrogates for atmospheric mineral dust and mineral dust/sulfate particles at cirrus temperatures. *Atmos. Chem. Phys.,* **5,** 2617-2634.
3. DeMott, P. J., K. Sassen, M. R. Poellot, D. Baumgardner, D. C. Rogers, S. D. Brooks, A. J. Prenni, and S. M. Kreidenweis (2003), African dust aerosols as atmospheric ice nuclei, *Geophys. Res. Lett.*, **30(14)**, 1732, doi:10.1029/2003GL017410.
4. Field, P. R., O.Mhler, P. Connolly, M. Krmer, R. Cotton, A. J. Heymsfield, H. Saathoff, and M. Schnaiter (2006), Some ice nucleation characteristics of Asian and Saharan desert dust, *Atmos. Chem. Phys.,* **6,** 2991- 3006.
5. IPCC (2007), Climate Change 2007: The Physical Science Basis. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
6. Koehler, K. A., S. M. Kreidenweis, P. J. DeMott, A. J. Prenni, and M. D. Petters (2007), Potential impact of Owens (dry) Lake dust on warm and cold cloud formation, *J. Geophys. Res.*, **112**, D12210, doi:10.1029/2007JD008413.
7. Kubar, T.L., D.L.Hartmann, and R. Wood (2009), Understanding the Importance of Microphysics and Macrophysics for Warm Rain in Marine Low Clouds. Part I: Satellite Observations. J. Atmos.Sci, 66, 2953-2972.
8. Min, Q.-L., Li, R., Lin, B., Joseph, E., Wang, S., Hu, Y., Morris, V., and Chang, F.(2009), Evidence of mineral dust altering cloud microphysics and precipitation, *Atmos. Chem. Phys.*, **9**, 3223-3231, doi:10.5194/acp-9-3223-2009.
9. Rosenfeld, D., Y.Rudich, and R. Lahav (2001), Desert dust suppressing precipitation: Apossible desertification feedback loop, *Proc. Natl. Acad. Sci. U.S.A*, **98**, 5975-5980.
10. Sassen, K. (2002), Indirect climate forcing over the western US from Asian dust storms, *Geophys. Res. Lett.*, **29(10)**, 1465, doi:10.1029/2001GL014051.
11. Sassen, K. (2005), Dusty ice clouds over Alaska, *Nature*, **434**, 456.
12. Sassen, K., P. J. DeMott, J. M. Prospero, and M. R. Poellot (2003), Saharan dust storms and indirect aerosol effects on clouds: CRYSTAL-FACE results, *Geophys. Res. Lett.*, **30(12)**, 1633, doi:10.1029/2003GL017371.
13. Tegen, I., A.A.Lacis and I. Fung (1996): The influence on climate forcing of mineral aerosols from disturbed soils. *Nature*, Vol **380**, 419 - 422.

14. Teller, A. and Levin, Z. (2006), The effects of aerosols on precipitation and dimensions of subtropical clouds; a sensitivity study using a numerical cloud model. Atmos.Chem.Phys., 6, 67-80.
15. Toon, O. B. (2003), African dust in Florida clouds, *Nature*, **424**, 623- 624.