Distribution of Upper Tropical Cirrus in Relation to Tropical Easterly Jet

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Abstract

The role of redistribution of the tropical upper tropospheric humidity (UTH) in the formation of tropical cirrus (TC) is studied using three years (2006-2008) of data from the CALIOP, MLS and NCEP/NCAR reanalysis. Results show that the redistribution of UTH from a highly convective zone to the Indian peninsular region leads to the formation of the TC. Advection of upper layer humidity is caused by the tropical easterly jet (TEJ) associated with the Asian Summer Monsoon. Thus for the first time, the role of TEJ in redistribution of UTH and consequently in the formation of TC is investigated.

1. Introduction

Cirrus clouds are believed to have a profound effect upon the planetary energy budget due to their radiative properties [1]. Critical parameters in understanding the radiative effects of cirrus clouds are their geometrical and optical thickness along with occurrence height and other microphysical properties such as the shape and size of the ice crystals. However, the processes involved in the formation of cirrus clouds are not well understood, and thus they are poorly represented in global climate models [2]. Realizing the importance of the global distribution of UTH in the formation of the TC, we attempt for the first time to show the role of TEJ in this context. In this study, we analyze the monthly distribution of global UTH and TC, and reported their association with the TEJ.

2. Instruments and Data Base

Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instruments onboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) is the space-borne lidar system used to detect the clouds and aerosols. Details of CALIOP measurements and technical features can be found elsewhere (http://eosweb.larc.nasa.gov/PRODOCS/calipso/ table_calipso.html). The present study uses CALIPSO level-2, 5-km (horizontal resolution) cloud layer data product. This product provides information about the number of cloud layers detected along with the layer top and base altitudes. We have considered only those cloud layers for which the "cloud-aerosol discrimination score (CAD_Score)" parameter is between 80 and 100 to ensure the high level of confidence in the detection of clouds. For each cloud layer retrieved, an opacity flag parameter is also considered. Only those layers having an "Opacity_Flag" parameter equal to 0 are used in the present study to ensure the cloud layer is transparent. We defined the cirrus cloud using a cloud base height threshold of 8 km in the tropics (25^{o}S-25^{o}N), and 6 km in the mid-latitudes (25^{o}S-55^{o}S and 25^{o}N-55^{o}N) [3]. The calculation of cirrus cloud occurrence frequency is made by using a domain of 10^o latitude x 20^o longitude.

The Microwave Limb Sounder (MLS) onboard the Aura satellite measures thermal emissions in the millimeter and submillimeter wavelengths by scanning the Earth's atmospheric limb to determine humidity, temperature and profiles of the atmospheric constituents such as O_3, N_2O, HCL, HNO_3, CO among others. More details about the instrument, algorithms and science products can be in the MLS webpage (http://mls.jpl.nasa.gov). In this work, we use version 2, level 2 (V2.2) data products of relative humidity at 215, 146, 100 and 82 hPa (corresponding to the altitudes between 12-12.5, 14-14.5, 16-16.5 and 17.5-18 km, respectively) pressure levels.

The National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP/NCAR) reanalysis data are used to derive (i) zonal and meridonal wind pattern to study the TEJ, and (ii) outgoing longwave radiation (OLR) as a proxy for the intensity of convection. These data are available as the daily/monthly means, at a grid resolution of 2.5^o latitude $\times$ 2.5^o longitude. Details about the NCEP/NCAR reanalysis data could be found in the website (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html).

3. Results and discussions

In an attempt to understand the origin of the TC associated with the Asian Summer Monsoon (ASM), we have analyzed the occurrence of cirrus derived from the CALIOP and the wind characteristics from the NCEP/NCAR re-analysis, during the period from July 2006 to December 2008. Since we are interested in the role of the TEJ in the formation and/or transport of the TC, we restrict our analysis to the period ranging from June to September of 2006-2008. Figure 1 shows contour maps of monthly frequency distribution of cirrus clouds derived from the CALIOP from June to September 2006-2008. The thick dark closed contours in each panel indicate the locations of OLR < 220 watts

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m^{-2} for the corresponding month. The threshold of OLR <220 watts m^{-2} is considered as the proxy of convection. These contour maps clearly depict that the maximum occurrence of cirrus clouds is over the Indian tropical region (15°S-25°N and 30°E-170°E), i.e., the ASM region, and over some parts of the Central-west Africa. One striking feature to be noted is that in the initial phase of the ASM (June), the occurrence of cirrus is elongated along the longitude, and is confined to the Indian peninsular region by the end of the ASM (September). Figure 1 also reveals that the low values of OLR (<220 watts m^{-2}), are confined to a smaller area as compared with the occurrence of cirrus, which is extended over a much larger region. However, from Figure 1 one can find that the cirrus clouds occur in regions of high OLR (>220 watts m^{-2}). This can be attributed to slow advection taking place over these regions, and thus suggests that other factors besides convection also influence the formation and distribution of cirrus.

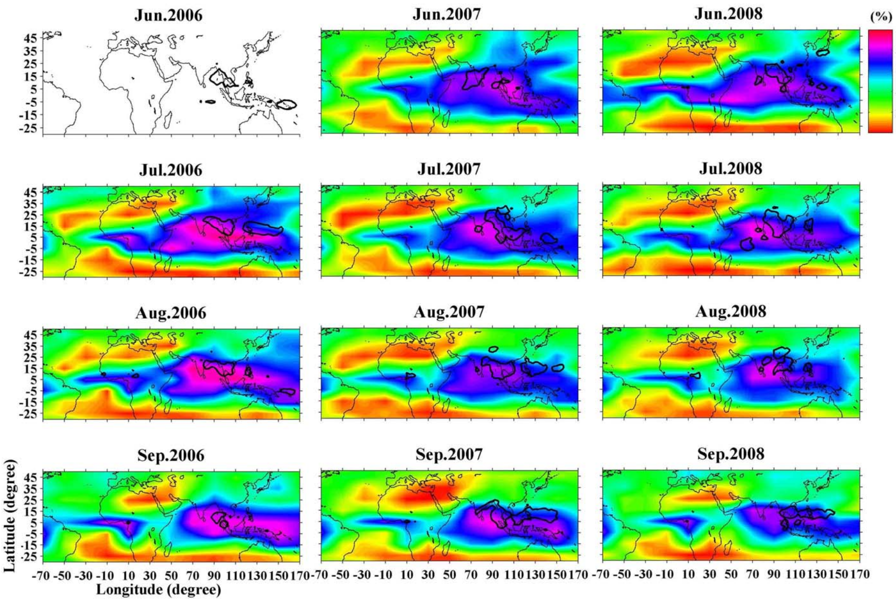

Figure 1: *Contour map of monthly distribution of cirrus occurrence derived from the CALIOP during June to September in the years 2006-2008. The closed thick contours in each panel indicate the outgoing long-wave radiation (OLR) < 220 watts m^{-2}. The OLR data is taken from the NCEP/NCAR reanalysis. The blank areas denote no data.*

Figures 2 show contour maps of monthly mean relative humidity with respect to ice (RHi) at different pressure levels (215, 146, 100 and 82 hPa) during June to September of 2006. These contour maps clearly indicate that the maximum amount of water vapor is available over the tropical areas around 15°S-25°N and 30°E-170°E, i.e., around the ASM region at 215 hPa pressure level. However, in the upper height levels, water vapor is confined to nearly 15°N-25°N and 30°E-110°E. It is possible that the overshooting convection plays a major role in the transport of water vapor into the upper troposphere. As mentioned earlier, since the intensity of convection (OLR<220 watts m^{-2}) is confined to smaller areas, it is believed that the convection is not the only process that governs the distribution of water vapor in the upper troposphere. It is also to be noted that at 925 hPa pressure level, the maximum amount of humidity is confined in the vicinity of low OLR, i.e. over the North Bay of Bengal, as revealed by the NCEP/NCAR reanalysis (figure not shown). Further investigation of monthly mean vertical velocity obtained from the NCEP/NCAR reveals strong updraft of the order >2 cm s^{-1} is observed over the ASM region (figure not shown). This indicates that due to convection, the moisture rises from the lower to the upper troposphere and reaches up to convective out flow from where it is transported over a larger area.

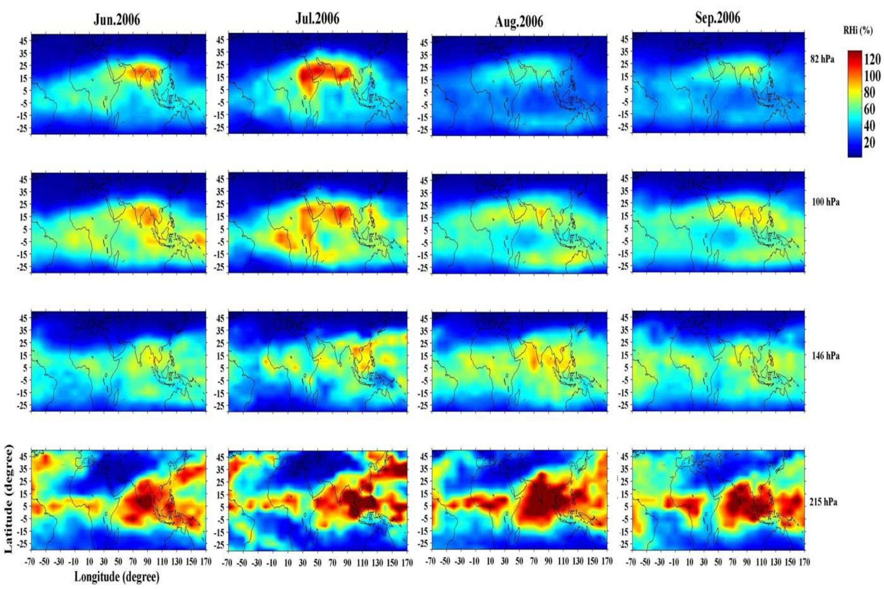

Figure 2: *Contour maps of monthly mean relative humidity w.r.t ice (RHi) for different pressure levels (215, 146, 100 and 82 hPa) obtained from the AURA-MLS during June to September of 2006.*

Figure 3 shows the contour maps of monthly mean zonal wind along with wind vectors at 150 hPa pressure level obtained from the NCEP/NCAR re-analysis during June to September of 2006-2008. The contour maps clearly indicate the existence of the TEJ over the Indian tropical region during the ASM. In the month of June with the onset of monsoon, a large amount of cirrus clouds are formed over the North Indian Ocean, Indian peninsular region, Bay of Bengal, some parts of the South China Sea, Philippine Sea and Central-east Africa, as seen in Figure 1. During this month, the easterly wind prevails over these areas with magnitudes greater than -20 m s^{-1} at 150 hPa pressure level, as shown in Figure 3. One can also note a closed circulation pattern from the Central Africa towards the Tibetan Plateau region. From July to September, the maximum occurrence of cirrus clouds is still observed over the North Indian Ocean, Bay of Bengal, South China Sea and Philippine Sea, but those over the Arabian Sea decrease by moving to the South. Moreover, though cirrus clouds are also observed over the Central America, there is no feature of such easterly jet in that region (not shown).

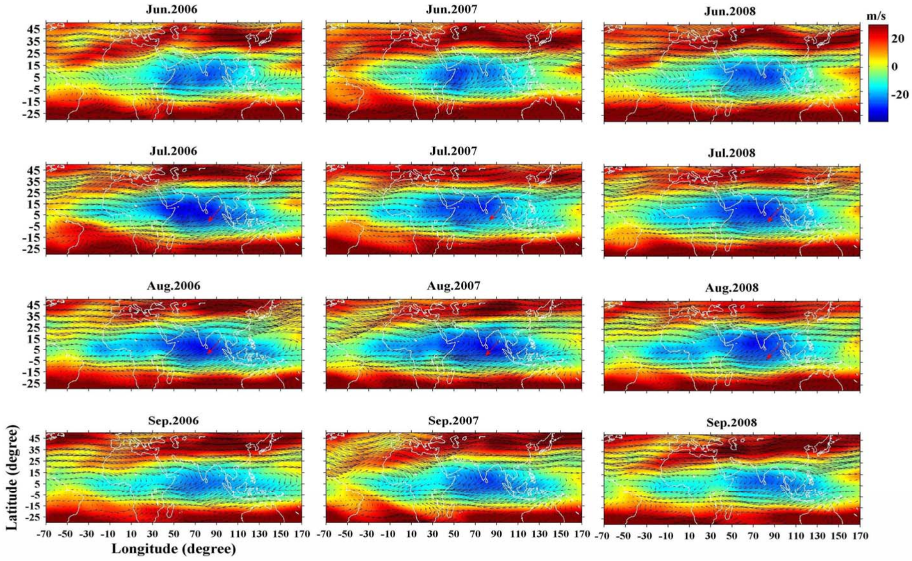

Figure 3: *Contour maps of monthly mean zonal velocity along with wind vectors derived from the NCEP/NCAR reanalysis at 150 hPa pressure level from June to September during 2006 to 2008. Red arrow indicates the movement of North-easterly winds.*

Figure 4 (i-iv) (left panel) shows the pressure level-latitude intensity (PLI) map of the cirrus occurrence frequency, averaged over 30°E-120°E, from July to September of 2006, respectively. Keeping in view of the TEJ band, this range of zonal mean is considered. These figures clearly show that the occurrence of cirrus is maximized between 5°S and 20°N at the height region of 200-100 hPa (12-16 km). To investigate further, we have analysed the corresponding zonally averaged (30°E-120°E) zonal winds as shown in Figures 4(i-iv) (right panel) as height-latitude intensity maps. It can be seen from these figures that the maximum intensity of zonal wind > |-20| m s^{-1} occurs in the vicinity of the tropical tropopause. This shows that the maximum occurrence of cirrus almost coincides with the location of the maximum intensity of the easterly wind, both in height and latitude and hence indicating the existence of the strong link between them.

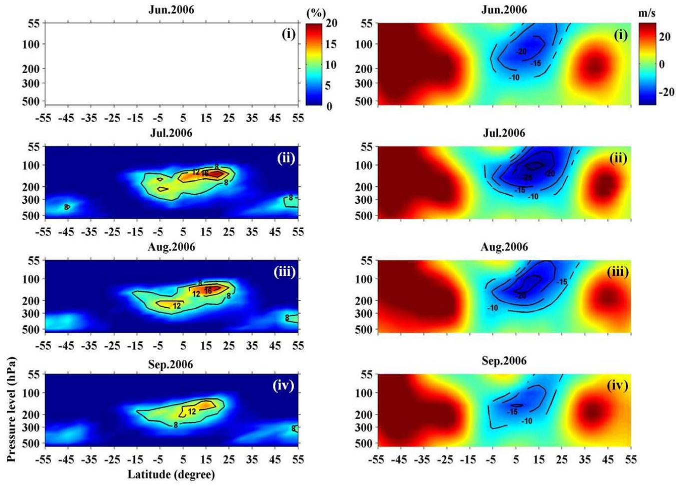

Figure 4 (i-iv). *Pressure level-latitude intensity maps of the percentage occurrence of cirrus (left panel) and zonal wind (right panel) averaged over 30°E-120°E from June to September in 2006, respectively. The blank areas denote no data.*

To examine the relationship between the TEJ and cirrus cloud formation, the longitudinal variation of the zonal wind at 150 hPa pressure level and the corresponding percentage of occurrence of cirrus clouds, averaged from June to September for 2006-2008 (except for June 2006) with the latitudinal average over 5°S-15°N are shown in Figure 5a. The occurrence of cirrus cloud shows the longitudinal variation with the maximum frequency over 60°E-90°E. It is noteworthy that the easterly jets are also well developed over the Indian and the Southeast Asian region, which can be seen in Figure 5a. The zonal winds at 150 hPa pressure level show a peak-to-peak relationship with the occurrence of cirrus clouds and thus indicate the close correlation between the TEJ and cirrus clouds. Thus, it can be considered that the high amount of cirrus clouds formed over the Indian and the Southeast Asian region during the NH summer is due to the advection associated with the TEJ. Figure 5b shows the longitudinal variation of RHi at 215, 142, 100 and 82 hPa pressure levels, averaged between June-September of 2006-2008 and over latitudes 5°S-15°N. The figure clearly shows that the maximum humidity is observed over 60°E-90°E, at 215 hPa pressure level. Similarly, Figure 5c gives the OLR and the vertical velocity at 250 hPa. The plot illustrates that less OLR (<220 watts m^{-2}) with relatively strong updraft is observed over the 60°E-90°E region. All these evidence clearly indicates that the convection over the North Bay of Bengal plays a major role in transporting the humidity from the surface to the middle and the upper troposphere up to ~215 hPa, and then the TEJ facilitates the transport or redistribution of the upper tropospheric humidity over the entire Indian peninsular region.

Figure 6 shows the normalized correlation coefficient of two-dimensional cross-correlation analysis between the cirrus occurrence frequency and magnitude of zonal wind. We have considered the data from 25°S to 45°N, and 70°W to 170°E. Both the cirrus occurrence frequency and zonal wind are averaged between June-September of 2006-2008 (except for the cirrus occurrence frequency of June 2006). The figure shows that the maximum correlation occurs with zero lags in both the longitudinal and latitudinal domains, which indicates that the maximum cirrus occurrence is well correlated with zonal wind maxima in the spatial domain.

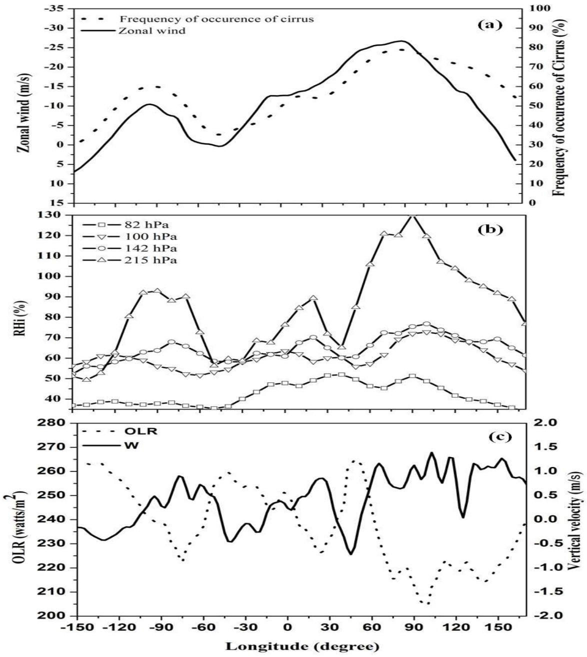

Figure 5: *Longitudinal variation of* ***(a)*** *zonal wind and percentage of occurrence of cirrus* ***(b)*** *RHi at different pressure levels and* ***(c)*** *OLR with vertical velocity (w) at 250 hPa. Data are averaged over 5°S-15°N from June to September during 2006 to 2008.*

4. Conclusion

The redistribution and transport of the UTH and then the formation mechanism of the TC clouds coupled with the TEJ are examined and discussed by using the CALIOP, AURA-MLS and NCEP/NCAR reanalysis data from 2006 to 2008. The observations clearly reveal low value of OLR (<220 watts m^{-2}) over the North Bay of Bengal during the South Asian Summer monsoon. It is also observed that maximum amount of UTH over the tropical Arabian Sea, Indian Ocean, Indian peninsular region, Bay of Bengal, South China Sea and Philippine Sea. The percentage of cirrus observations is higher over the regions where UTH is high. Observations show that there is a transport of humidity from the lower to the upper troposphere, as revealed from the vertical velocity, above the convective areas (e.g., low values of OLR over the North Bay of Bengal) and then further advected and redistributed over the maximum convective out flow. The advection taking place at the upper troposphere is attributed to North-easterly winds over the North Bay of Bengal and then due to the strong TEJ, it is elongated zonally. It is interpreted that the observed high frequency of cirrus occurrence over the South Asian Summer monsoon region is associated with the redistribution of upper tropospheric water vapor advected by the TEJ. Thus, the present study for the first time brings out the crucial role of the TEJ in the distribution of the UTH and subsequent formation of cirrus clouds during the ASM.

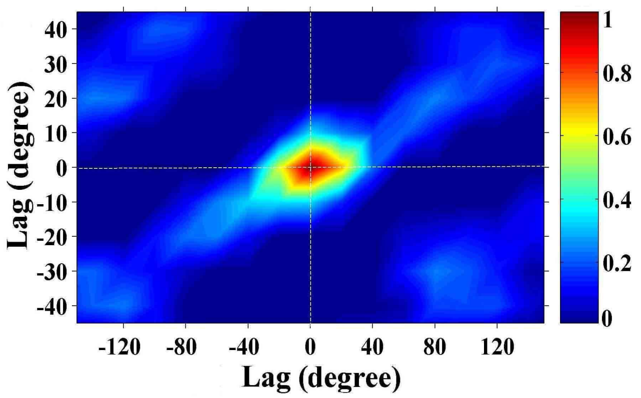

Figure 6: *The normalized correlation coefficient of two-dimensional cross-correlation analysis between cirrus occurrence frequency and magnitude of zonal wind.*

5. References

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6. Acknowledgments

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