ATMOSPHERIC SCIENCE LETTERS
Atmos. Sci. Let. **16**: 38–43 (2015)
Published online 4 July 2014 in Wiley Online Library
(wileyonlinelibrary.com) **DOI:** 10.1002/asl2.517

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Impact of monsoon-associated deep-penetrating clouds on the hydration of the tropical upper troposphere

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Received: 23 July 2013
Revised: 11 April 2014
Accepted: 5 June 2014

Abstract

This paper examines the relationship between water vapor mixing ratio (WVMR) and cloud top height (CTH) in the tropical upper troposphere. The region of high WVMR and CTH is collocated and observed over the core convective region. WVMR over South Asia shows significant correlation with CTH. Increase in CTH is observed during the moist phase of water vapor followed by a decrease in CTH during the dry phase. Daily CTH data show that some convective turrets reach above 150 hPa. Present analysis shows that moistening of upper troposphere occurs during the monsoon period when CTH is greater than 7 km.

Keywords: water vapor; convection; clouds; tropical upper troposphere; Aura MLS; ISCCP

1. Introduction

Water vapor (WV) is an important greenhouse which absorbs infrared outgoing longwave radiations (OLRs) emitted from the earth's surface and increases the temperature of the troposphere. It facilitates the stratospheric cooling and also affects the stratospheric chemistry leading to the enhanced ozone depletion (Forster and Shine, 1999). To understand the multifaceted roles of WV in the stratosphere and troposphere, the processes that affect the budget of WV in the upper troposphere and lower stratosphere (UTLS) region need to be understood. Thick clouds, associated with convective anvils, which reach up to the upper troposphere and sometimes penetrate into the lower stratosphere act as a radiative barrier for OLR and thus affect the radiative heat budget (Ramanathan *et al.*, 1989). The convective systems can also influence the temperature in the upper troposphere and tropopause region (Jain *et al.*, 2006, 2010, 2011) which, in turn, can influence the WV near the tropopause region and lower stratosphere, due to the so-called tape recorder effect (Mote *et al.*, 1996). Recent observations by several researchers (Dessler, 2002; Gettelman *et al.*, 2002; Dessler and Sherwood, 2004) have also shown that the convective mass transported directly to the lower stratospheric region can have a major influence on the stratospheric chemistry. Therefore, the relationship between WV in the upper tropospheric and lower stratospheric region, occurrence of deep convective events, height up to which convective clouds penetrates, i.e. top of convective clouds must be understood as they influence various dynamical and chemical processes in the tropical tropopause layer (Lelieveld and Crutzen, 1994; Thompson *et al.*, 1997; Gettelman *et al.*, 2002; Wang and Prinn, 2000).

Convection over the tropical region plays an important role in the transport of WV from sea surface level to the middle and upper tropospheric heights. Most of the WV present in the upper troposphere is transported via convection during the local monsoon period (Gettelman *et al.*, 2004). Folkins *et al.* (1999) suggested that large amount of WV is transported vertically or quasi vertically up to a height corresponding to ~150 hPa, i.e. top of Hadley cell. In this connection, it may be mentioned here that recent studies over the Tropics during Northern Hemisphere (NH) summer monsoon season have also suggested that the Asian monsoon plays an important role in hydrating the lower stratosphere (Bannister *et al.*, 2004; James *et al.*, 2008; Panwar *et al.*, 2012, Jain *et al.*, 2013).

Occurrence of convection and the possibility of convective transport are determined by various researchers (Corti *et al.*, 2006; Jain *et al.*, 2013 and references therein) using deep-penetrating convective cloud data. Convective clouds, which are optically thick and high-altitude clouds, penetrate into tropical tropopause layer more frequently over land area than the ocean region as shown by Hong *et al.* (2005). Deep-penetrating convective clouds are an indicator of convection, and enhanced WV is observed over the tropical region during the convective period. Therefore, the relation between convective clouds and WV must be understood in order to delineate the role of convection in the WV transport. This study, therefore, focuses on the following objectives:

- Identification of the regions containing deep-penetrating convective clouds and high WV content in the upper troposphere.
- Influence of monsoon-associated deep-penetrating convective clouds on WV content in the upper troposphere.

EOS Aura microwave limb sounder (MLS) water vapor mixing ratio (WVMR) data, ISCCP D1 (International Satellite Cloud Climatology Project) cloud top pressure data and tropopause height from National Centers for Environmental Prediction (NCEP) are used in this study to determine the relationship between the cloud occurrence and hydration in the upper troposphere.

2. Database and methodology

WVMR data are obtained from MLS, EOS AURA spacecraft. MLS Level 2, Version 3.3 Standard atmospheric product for WVMR is analyzed for the period from January 2005 to December 2010. Monthly mean data of WVMR is binned into 2° × 2° latitude–longitude grid to obtain the spatial distribution of WVMR at different pressure levels of the upper troposphere, viz. 261.0, 215.4, 177.8 and 146.8 hPa for June to September 2008. Validation of the WVMR data was carried out by Lambert *et al.* (2007).

ISCCP D1 daytime convective cloud top pressure data are used in order to examine the cloud occurrence in the upper troposphere. ISCCP Stage D1 3-Hourly Cloud Product provides the cloud top pressure binned over an equal-area grid with 280 × 280 km latitude–longitude at every 3-h interval. Local daytime (solar zenith angle ≤ 78.5°) and deep convective clouds (cloud optical thickness >23 and <379) are identified using ISCCP classification of the cloud system (Rossow *et al.*, 1996). The data points in the graphs are shown at the center latitude–longitude position of the equal-area grid.

Temporal variations in WVMR from Aura MLS and cloud top height (CTH) from ISCCP are examined for the period from January 2005 to December 2010 over the South Asian region (10–30°N, 60–120°E). A daily average of data values available in the grid bin (10–30°N, 60–120°E) is taken to form a time series. As mentioned above, ISCCP provides data after every 3-h interval. Therefore, the daily mean time series of CTH is obtained by taking an average of eight individual data sets.

Tropopause pressure data are retrieved from NCEP Daily Global analysis for the period from January 2005 to December 2009. NCEP provides daily data of tropopause pressure with grid dimension of 2.5° × 2.5° along latitude and longitude (Randel, 1987; Trenberth and Olson, 1988a, 1988b). The time series is obtained by taking the average of daily values over the South Asian region. Monthly mean values, if required, are obtained by averaging the daily values.

3. Results and discussion

3.1. Occurrence of hydration in the upper troposphere and deep-penetrating convective clouds

Figure 1 shows the spatial distribution of monthly mean WVMR (ppmv) at different pressure levels of the upper troposphere, viz. 261.0, 215.4, 177.8 and 146.8 hPa and the simultaneous observations of the monthly mean daytime convective cloud top pressure (hPa) for the period June to September 2008. It is clear from Figure 1 that during the NH monsoon period (June to September) maximum WVMR in the upper troposphere is observed over South Asia, particularly over India. The magnitude of WVMR over this region is ~500, ~250, ~50 and ~20 ppmv at 261.0, 215.4, 177.8 and 146.8 hPa respectively.

Figure 1 also shows the low cloud top pressure over the South Asian region during the same period. The region of high WVMR in the upper troposphere occurs in the vicinity of high-altitude cloud system indicating a close relationship between the two parameters. Around 22% of the total area over South Asia is covered with deep-penetrating convective clouds with a top pressure 100-–150 hPa (CTH: 13.9–16.9 km) for June 2008, whereas the area coverage decreases during July (4%), August (5%) and September (4%) 2008. Over the South Asian region, deep-penetrating convective clouds with a top pressure 150–200 hPa (CTH: 11.7–13.9 km) covers ~14, ~16, ~22 and ~23% area for June, July, August and September 2008, respectively. During the monsoon period, a wide area over this region is covered with convective clouds reaching ≤200 hPa, i.e. upper troposphere. Low OLR, which is a proxy for convective activities, is also observed during June to September over this region (Panwar *et al.,* 2012; Jain *et al.*, 2013). This confirms that the convection is active during the monsoon period and hydration of the upper troposphere and cloud occurrence in this region is associated with convection.

3.2. Comparison of CTH and WVMR over different convective regions

The relationship between WVMR and CTH is further examined over different convective regions. Figure 2 shows the longitudinal distribution of the WVMR at 177.8 hPa ($WVMR_{177}$) and daytime convective CTH for July 2008. The WVMR longitude series is obtained by taking an average of data over 10–20°N latitude sector with a resolution of 2° along longitude. Dashed line in Figure 2 indicates the 175 hPa pressure level (~12.7 km). It may be noted from Figure 2 that there are a large number of cases when CTH is much higher than the 175 hPa level. Three regions of high WVMR are observed at 177.8 hPa over the tropical region with the maximum moisture content over the Asian region as also suggested in Figure 1. Deep-penetrating daytime convective clouds with the top height ~10–15 km are observed only over the convective region, which is expected. The region of high WVMR and high-altitude cloud system is collocated and CTH is observed to be highest over the core convective region.

Another interesting feature which can be noted from Figure 2 is that the average CTH over all three regions, i.e. Asian, American and African regions is comparable for 10–20°N latitude sector, whereas the mean WVMR is highest over the Asian region. Figure 2 also shows the

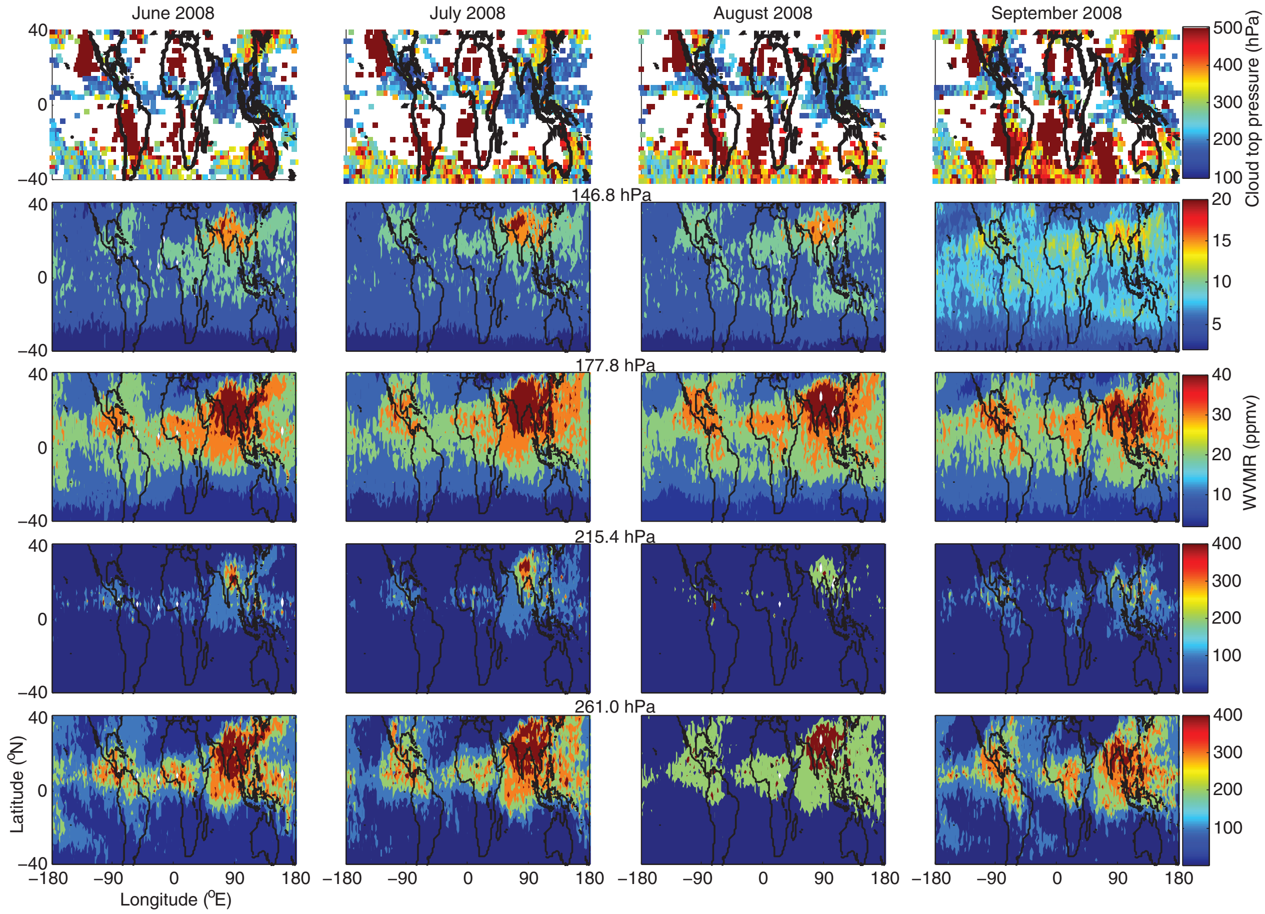

Figure 1. Monthly mean cloud top pressure and WVMR at 261.0, 215.4, 177.8 and 146.8 hPa for June to September 2008.

total number of cloud pixels with convective cloud top pressure < 175 hPa for different longitude sectors. Total number of cases are highest over the Asian region (~185 cases) followed by American (~93 cases) and African (~21 cases) regions. Also, the deep-penetrating convective clouds are organized and observed over a very large area over the Asian region in comparison with the other two regions, which is also depicted in Figure 1. Jain *et al.* (2013) have also shown that the cloud occurrence frequency (COF), i.e. the number of convective clouds reaching the upper troposphere (≤200 hPa) over the Asian region are more in comparison with American or African region (Figure 1(c) and (d) of Jain *et al.*, 2013). Therefore, more moisture content may be transported over the Asian region via convection, which can give rise to increase in WVMR over this region.

3.3. Simultaneous occurrence of convective clouds and high WVMR over South Asia

Figure 3 shows the daily CTH and WVMR time series over the South Asia at different pressure levels of the upper troposphere, viz. 261.0, 215.4, 177.8 and 146.8 for 1 January 2005 to 31 December 2009. Figure 3 shows that when convective CTH increases, the WVMR in upper troposphere also increases considerably. Over South Asia, increase in CTH is observed during the moist phase of WV followed by a decrease in CTH during the dry phase. WVMR time series at 261.0, 215.4, 177.8 and 146.8 hPa shows a good correlation, with correlation coefficient of ~0.71, ~0.71, ~0.70 and 0.65 respectively, with the CTH time series. This suggests that during the period of convection WVMR attains maxima and clouds reach higher altitudes and this phenomenon is repeated every year.

Figure 3 also shows the daily tropopause height (red line) obtained over the South Asian region obtained from NCEP reanalysis data as mentioned in Section 2 and the blue line shows the top of Hadley cell, i.e. 150 hPa. It can be observed from Figure 3 that, sometimes, daily convective CTH exceeds 13.9 km, i.e. 150 hPa during NH summer monsoon. This may be mentioned here that, as described in Section 2, the daily CTH over South Asian region is also a combination of individual data pixels. So, COF, which is defined as the ratio of the total number of cloudy pixels with pressure ≤150 hPa with respect to the total number of cloudy pixel over the South Asian region grid bin, calculated for each day using all available data pixels is shown in the bottom panel. The maximum CTH observed for each month during 2008 NH monsoon period (June to September) is shown in Table 1. It may be mentioned here that the same value of maximum CTH is observed twice during June 2008 and therefore both data values are given in Table 1. This confirms that there are events when CTH is more than the level of tropopause.

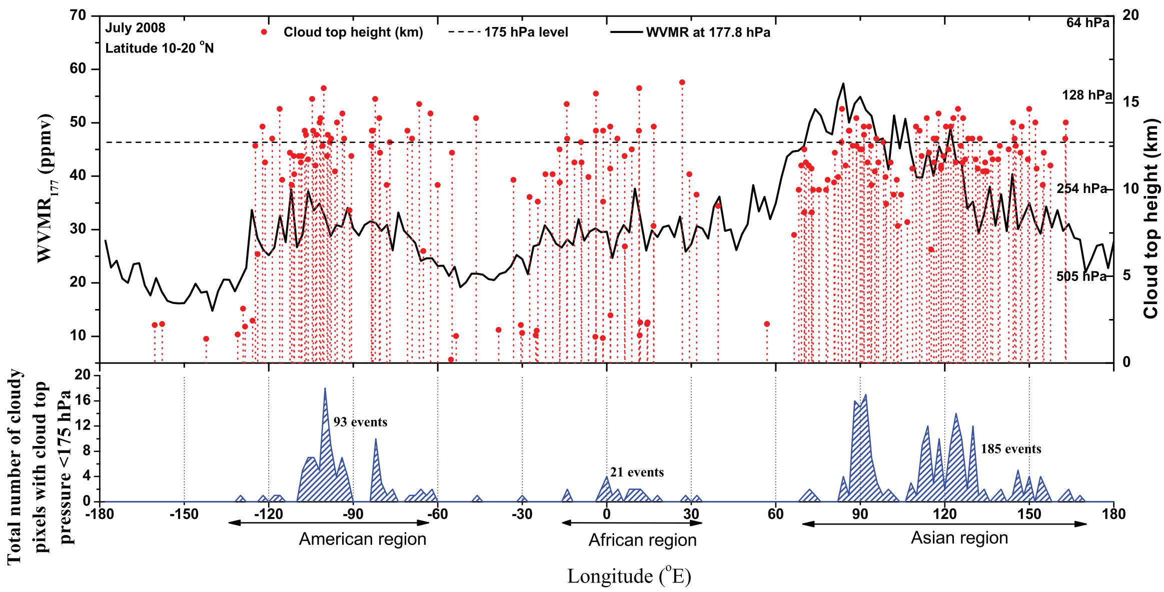

Figure 2. $WVMR_{177}$ and CTH as a function of longitude for 10–20°N latitude band for July 2008. The dashed line shows the 175 hPa level. The lower panel shows the total number of cloudy pixels for which cloud top pressure is <175 hPa over different longitudes.

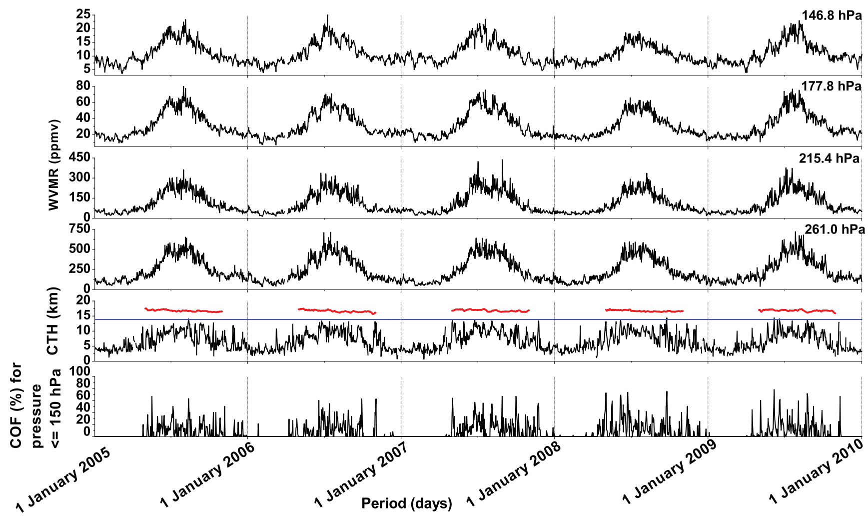

Figure 3. Daily mean CTH and WVMR at 261.0, 215.4, 177.8 and 146.8 hPa for 1 January 2005 to 31 December 2009 over the South Asian region (10–30°N, 60–°E). In the CTH panel, the blue line shows the 150 hPa level and the red line shows the tropopause height for May–October. The bottom panel shows the COF for pressure level ≤150 hPa (see text).

It is apparent from Figure 3 that some of the convective turrets reach above the top of Hadley cell (~150 hPa) over this region, and the occurrence of deep convective clouds for pressure level less than 150 hPa suggests the possibility of a direct convective transport of WV close to the tropopause level.

3.4. Influence of monsoon-associated deep-penetrating convective clouds on WVMR

WVMR and CTH daily data are used to study their seasonal pattern in the upper troposphere. Figure 4 shows the scatter plot between the daily CTH and daily $WVMR_{177}$ for the period from 1 January 2005 to 31 December 2009 over the South Asian region. December–March (NH winter period) and June–September (NH monsoon period) are shown in blue and red colors respectively. Pre-monsoon (April–May) and post-monsoon (October–November) data are also shown in the same figure. It is generally

Table 1. List of highest CTH and corresponding tropopause height for each month during 2008 NH monsoon over Asian region.

Month	Day	Maximum CTH (km)	Corresponding tropopause height (km)
June	6	18.5	17.2
June	27	18.5	16.9
July	7	17.3	16.7
August	23	17.6	16.6
September	23	16.9	16.6

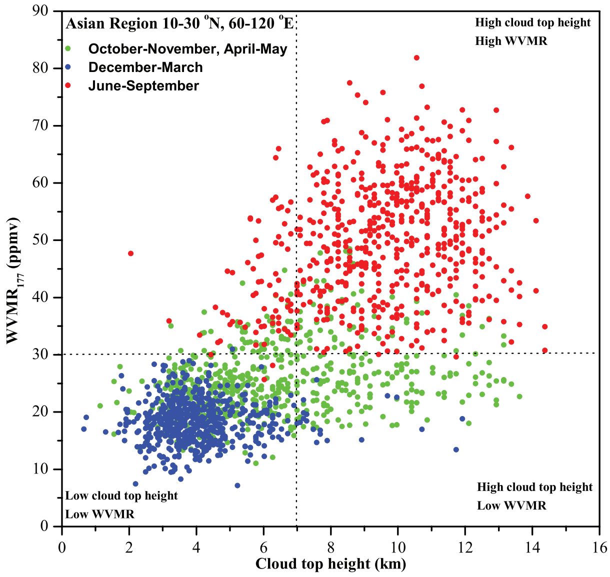

Figure 4. Scatter plot between daily mean $WVMR_{177}$ and CTH over South Asia for January 2005 to December 2009.

observed that during the monsoon season the convective CTH is higher than 7 km and the $WVMR_{177}$ is >30 ppmv. Figure 4 suggests that the monsoon-associated clouds play an important role in the hydration of the upper troposphere

During the winter season, the CTH is less than 7 km except some sporadic events and $WVMR_{177}$ is lower than 30 ppmv. Figure 4 shows that the convective clouds during the winter season do not affect upper tropospheric WV. This may be because of the fact that the winter-associated clouds are mainly observed in the lower and middle troposphere only. Therefore, the probability of these clouds influencing the upper tropospheric WV is substantially less. Figure 4 also depicts the characteristics of $WVMR_{177}$ and its dependence on CTH during pre- and the post-monsoon seasons. It shows the transition between the maximum and minimum phases of $WVMR_{177}$ and CTH in the upper tropospheric region.

The above analysis thus confirms that the moistening of the upper troposphere over this region occurs during the monsoon period when the CTH is greater than 7 km.

4. Conclusions

WVMR data retrieved from EOS Aura MLS show that over the tropical region, maximum moisture content in the upper troposphere is observed over South Asia, particularly India, during the monsoon period (June to September). Cloud top pressure data obtained from the ISCCP D1 show that the deep-penetrating convective clouds, with a top pressure of 100–200 hPa, also occur in the vicinity of the high WVMR region. Some deep-penetrating convective clouds reaching ≤175 hPa are also observed over the American and African regions, but the area coverage is comparatively less than the Asian region. One interesting feature noted in this study is that the average CTH over all three regions is comparable for 10–20°N latitude sector, whereas the mean WVMR is high only over the Asian region.

Daily cloud top pressure data show that some convective turrets reach above the top of the Hadley cell, which is at ~150 hPa. Some events with CTH greater than the tropopause level are observed during NH monsoon period over South Asia. This indicates the direct convective transport of WV close to the tropopause level (~100 hPa) as also suggested by Gettelman *et al.* (2002).

Increase in CTH is observed during the moist phase of WV followed by a decrease in CTH during the dry phase over the South Asian region and this phenomenon is observed every year. Convective clouds, which penetrate higher than ~7 km in the atmosphere during the monsoon period, are observed to strongly influence the WVMR in the upper troposphere over this region. Present studies thus confirm the influence of deep-penetrating convective clouds on upper tropospheric WV.

Acknowledgements

We gratefully acknowledge EOS AURA MLS and Goddard Earth Sciences Data and Information Services Centre for providing WV data. ISCCP D1 data were obtained from the International Satellite Cloud Climatology Project data archives at NASA Langley Research Center, Atmospheric Science Data Center. NCEP Daily Global Analyses data were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website. We would like to thank two anonymous reviewers for their helpful suggestions. This work is funded by ISRO/DOS under CAWSES India program. We are thankful to the Director, NPL and Head RASD, NPL for their support in carrying out this research work.

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