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# A Comparative Study of Cloud Liquid Water Content from Radiosonde Data at a Tropical Location

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## ABSTRACT

In this paper, some features of cloud liquid water content with respect to rain and water vapor are presented. Cloud liquid water density profile is obtained from radiosonde observation with Salonen's model and Karsten's model at Kolkata, a tropical location in the Indian region. Cloud liquid water contents (LWC) are obtained from these profiles which show a prominent seasonal variation. The monsoon months exhibit much higher values of LWC than in other months. However Salonen's model yields higher LWC values than that obtained with Karsten's model. The variation of daily total rainfall with LWC shows a positive relationship indicating the role of LWC in controlling the rainfall. Also the variation pattern of LWC with integrated water vapor (IWV) content of the atmosphere indicates that a threshold value of water vapor is required for cloud to form and once cloud is formed LWC increases with IWV.

**Keywords:** Cloud Liquid Water Contents (LWC); Integrated Water Vapor (IWV)

## 1. Introduction

The study of cloud properties is increasingly important in the context of climate research of troposphere. One of the sources of global warming is the cloud feedback and water vapour feedback. Again as relative humidity has a greater impact on cloud formation, knowledge of moisture distribution of troposphere is necessary to know the cloud process [1]. Parameterization of cloud component is very much necessary as cloud plays a dual role in affecting outgoing long wave radiation (OLR) as well as reflecting incoming solar radiation [2]. Cloud Liquid water content (LWC) plays also a dominant role in attenuating electromagnetic signal [3]. Stability of air is another important matter of concern as cloud development is associated with it. As air parcel is very large, it is realistically considered that it does not exchange any heat with surrounding as it rises and due to the expansion in volume it cools at a relatively constant rate. Depending on whether the air is saturated or unsaturated, the important parameter of cloud formation *i.e.* moist adiabatic lapse rate (MALR) or dry adiabatic lapse rate (DALR) comes into the picture. To know the profile of liquid water content and thereby total liquid water content for a particular day and also the amount of water vapour in the atmosphere the knowledge of humidity profile is also important. Water vapour can be related to low level humidity and low atmospheric humidity can be obtained as a function of surface temperature [4]. Retrieval of water vapour by Special Sensor Microwave Imager (SSMI) shows the dependence of water vapour is not only on humidity but also on atmospheric circulation [5]. Over the past two decades many retrieval methods have been obtained for water vapour and cloud LWC.

In case of water vapour no method is identified as the most accurate as there is a mismatch between satellite footprint and in situ measurement. In addition, for LWC cloud shape and structure causes the unreliability of the measured data.

Retrieval of the profile of cloud LWC by Radiometer shows the result in clear and cloudy condition. A comparison of radiometric profile is done with sounding from super cooled cloud liquid sensor carried by radiosonde. But not more than 50% agreement was observed between the two processes [6]. Though the profile of temperature and water vapour can be given by Laser radar (Lidar) and Fourier Transform Infrared Spectrometer (FTIR), but in presence of cloud neither the Lidar nor the FTIR will work. In a different approach, as cloud reflectivity is proportional to cloud drop radius and as cloud LWC is proportional to the volume of the cloud drops, LWC can be derived from reflectivity factor. But an error more than one order of magnitude of actual value is obtained as the relation is not linear. There are some other methods also for retrieving cloud LWC. For the methods using radiosonde data have to rely on a relative humidity (RH) threshold. When RH exceeds a threshold value cloud layers are supposed to be formed. In another approach it is assumed that each of the cloud layers satisfies the following equations.

$$\frac{d^2T}{dz^2} \geq 0 \tag{1}$$

$$\frac{d^2RH}{dz^2} \leq 0 \tag{2}$$

where T denotes temperature [7]. Here saturation region is taken as region of RH maximum and a region of weaker temperature decrease is considered for pseudo-adiabatic lapse rate within the cloud. Again there is another microphysical dynamic cloud model (DCM) where convection is initialized diabatically [8]. Here humidity and temperature profile are physically consistent with LWC profile but the clear sky condition can not be described by this model as the model always generates cloud. In the present study LWC profile obtained from Salonen's [9] model and Karsten's [10] model are compared. Integrated value of LWC is calculated throughout the year from the above two models and compared also for a tropical location, Kolkata (22˚C 34N, 88˚C 29E), for a period of three years.

## 2. Theoretical Basis

As cloud formation is associated with high relative humidity, radiosonde data can indicate the presence of cloud liquid water content depending on whether relative humidity exceeds a critical value. According to Karsten's model, cloud is formed when the relative humidity exceeds 95%. Again the phase of the water is determined by its temperature profile. If temperature is greater than 0°C liquid water is formed. From the adiabatic concept of thermodynamics, the cloud liquid water content (LWC) can be calculated at each height level by the relation

$$\mathrm{LWC}_{ad}(h)=\int \rho(z)\frac{Cp}{L}\left(\Gamma_d-\Gamma_s\right)dz \tag{3}$$

where $\rho(z)$ = air density, $C_p$ = specific heat at constant pressure, L=latent heat of vaporization, $\Gamma_d$ = dry adiabatic lapse rate, $\Gamma_s$ = moist adiabatic lapse rate. In the formula of LWC, $\Gamma_s$ varies from 4˚C/km to 9.8˚C/km depending on the seasonal variation of temperature. The air density is calculated from the ideal gas equation. Also considered is Cp = 1.0035 $J\cdot g^{-1}\cdot k^{-1}$, L = 80 cal/gm. The adiabatic condition gives maximum value of LWC which is reduced due to circulation of air mass accompanied by precipitation and freezing. The modified LWC is given by

$$\mathrm{LWC}=\mathrm{LWC}_{ad}\left(1.239-0.145\ln\Delta h\right)\ \mathrm{kg/m^3} \tag{4}$$

where $\Delta h$ = height above the cloud base. LWC is then calculated at each pressure level at a particular radiosonde ascent. Integrating the LWC profile over height, the total value of LWC is obtained at each ascent. According to Salonen's model also when relative humidity exceeds the critical humidity, cloud is formed. But critical humidity is calculated from Geleyn's formula

$$U_c=1-\alpha\sigma(1-\sigma)\left[1+\beta(\sigma-0.5)\right] \tag{5}$$

where $\alpha$ = 1.0, $\beta = \sqrt{3}$, σ is the ratio of pressure at the considered level and pressure at the surface level [11]. Again the phase of the liquid water is determined on the basis of temperature profile. When temperature is greater than 0˚C, contribution of liquid water content of cloud is significant. Liquid water content w ($g/m^3$) as a function of temperature t (˚C) and height $h_c$ from the base has been calculated by the relation

$$W=W_0(1+ct)\left(\frac{h_c}{h_r}\right)^a \rho_w(t) \tag{6}$$

where a = 1.4, c = 0.041/˚C, $W_0$ = 0.14 $gm/m^3$ for each radiosonde ascents at each pressure level. Integrating the profile of liquid water content over height, the value of cloud liquid water content (LWC) for each radiosonde ascents has been obtained. The total variation of LWC is observed throughout the year.

The temperature dependence of water vapour saturation pressure $e_{sw}$ (100% RH) is approximated and in turn, expressed as vapour concentration,

$$v=7.223e_w(\theta)=1.739\times10^9 u\theta^5\,\mathrm{gm/m^3} \tag{7}$$

where $\theta = 300/(T_t+273)$, $T_t$ = dry bulb temperature.

## 3. Data

Radiosonde balloon is released from a location over which characteristics of the troposphere are desired to be known. Radiosonde measurements are obtained twice a day at around 00 and 12 GMT (1830 and 0630 IST) by the Indian Meteorological Department at Kolkata, India (22˚C 34N, 88˚C 29E). The data from the period January to December of the year 2005 to 2007 have been used in this study. The data of temperature, pressure and dew point temperature at different height with a resolution of few tens of meters to few hundreds of meters up to a height of 15 km is measured. Temperature is measured by the carbon rod thermistor which measures the temperature from –90˚C to 60˚C with a resolution of 0.1˚C. Pressure is measured by an aneroid barometer with a resolution of 1 mb. Dew point temperature is obtained from relative humidity measured by a carbon hygristor with a resolution of 2% RH.

## 4. Results

Cloud LWC profiles of a particular day obtained using

Karsten's model and Salonen's model are shown in **Figure 1**. These two profiles show same nature; however the values of LWC are greater with the Salonen's model than with the Karsten's model as the adiabatic LWC is reduced due to circulation of air mass accompanied by precipitation and ice particles. Integrated value of LWC is obtained by integrating the profile of cloud LWC for each day of the year from Salonen's and Karsten's model. For a better comparison of LWC obtained by the above two methods, integrated value of LWC is plotted for the year 2005 to 2007 (**Figures 2-4**). **Figure 5** shows the variation in monthly mean value from the month of May to October of each year of cloud LWC obtained using Salonen's as well as Karsten's model from the year 2005 to the year 2007. It is obvious from these two figures that the two models are in good agreement in the tropical location with respect to the nature of variation but always Salonen's model gives a higher value. Variation of monthly mean value shows a strong seasonal variation of cloud LWC. Cloud LWC obtained from Karsten's model is plotted in **Figure 6** against cloud LWC obtained from Salonen's model. LWC obtained from Karsten's maintains a linear relation with that obtained from Salonen's model indicating again these two models are in good agreement regarding the nature of variation in tropical location. Difference of cloud LWC obtained from the models of Salonen and Karsten obtained for each day of the year of 2007 is plotted in **Figure 7**.

The variation of difference throughout the year shows, there is a difference between amounts of cloud LWC obtained from two models, but the difference is reduced by only 10% of the maximum value. The variation of daily total rain amount with cloud LWC is plotted for the year 2005-2007 in **Figures 8-10**. The figures show that the rain amount increases with the amount of cloud LWC. The variation of amount of cloud LWC in **Figures 11** and **12** along with water vapour indicates a threshold value of water vapour that is required for the formation of liquid water.

## 5. Conclusions

The two models, due to Salonen and Uppala [9] and Karsten *et al.* [10], have been used to obtain cloud LWC at temperature above 0˚C and also in the mixed layer in the temperature range from –20˚C to 0˚C. The result shows a strong seasonal pattern of cloud LWC which is a characteristic feature of tropical region. The analysis of data during the period 2005 to 2007 confirms that a threshold value of water vapour is required for the cloud to form. Once cloud is formed, daily total rain amount is found to increase with cloud LWC.

Salonen model gives an acceptable prediction of the amount of cloud LWC from Radiosonde data. As monsten model is more relevant than the Salonen model as it

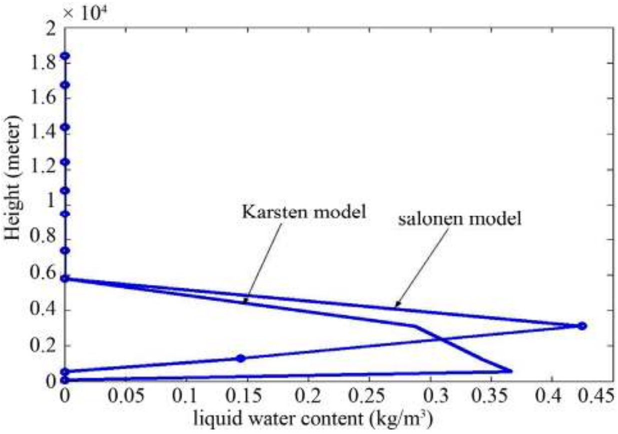

**Figure 1. A typical profile of cloud liquid water density obtained from radiosonde measurements using Salonen's model and Karsten's model of relative humidity and critical humidity at Kolkata on 4 July 2007.**

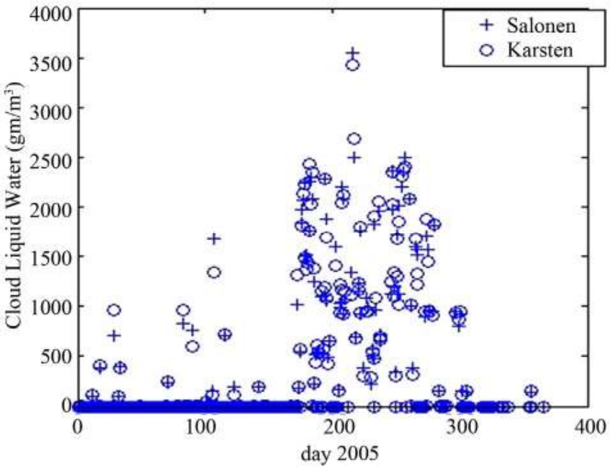

**Figure 2. Comparison between the values of cloud LWC obtained from Salonen's and Karsten's model at different days during 2005.**

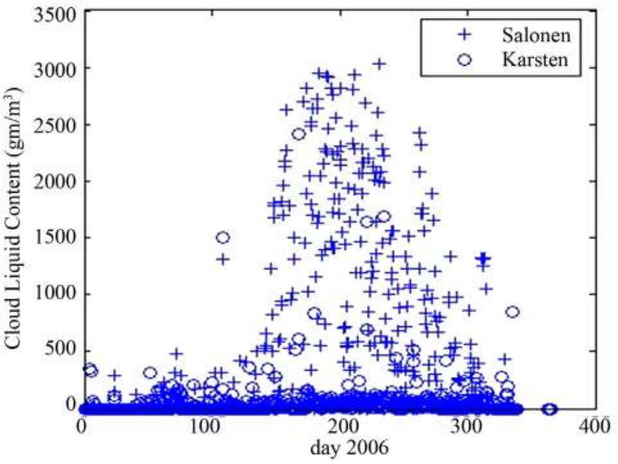

**Figure 3. Comparison between the values of cloud LWC obtained from Salonen's and Karsten's model at different days during 2006.**

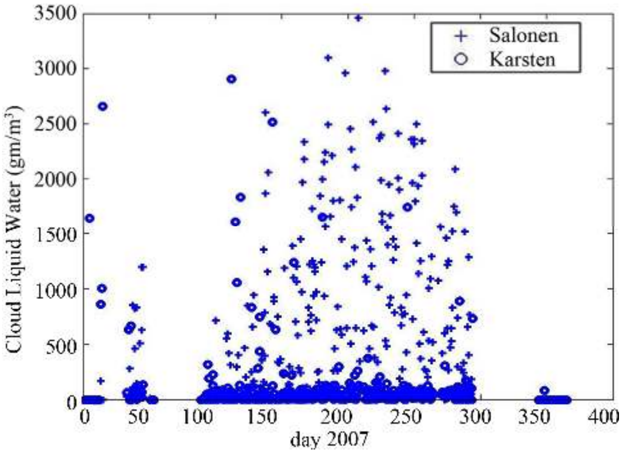

**Figure 4. Comparison between the values of cloud LWC obtained from Salonen's and Karsten's model at different days during 2007.**

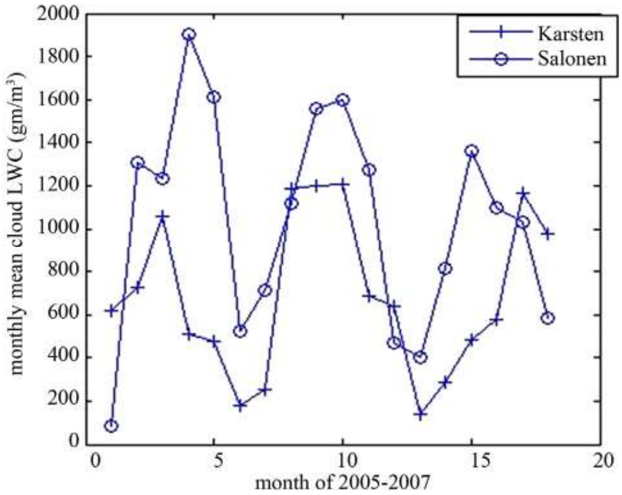

**Figure 5. Comparison of monsoonal variation of monthly mean value of Cloud LWC obtained from Salonen's and Karsten's model for a period of 2005 to 2007.**

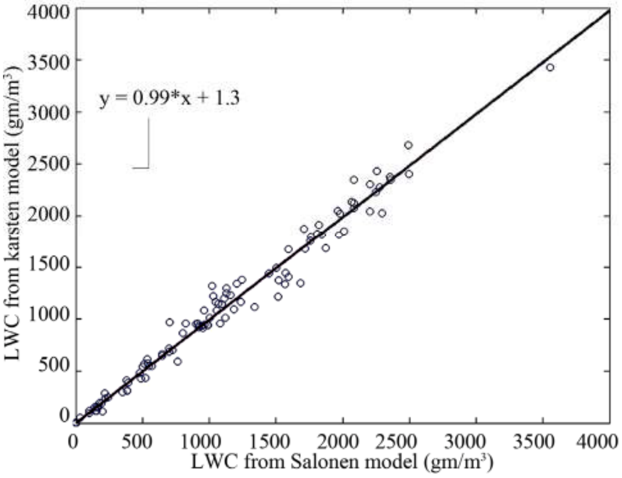

**Figure 6. A plot between LWC obtained from Salonen's and Karsten's model during 2005.**

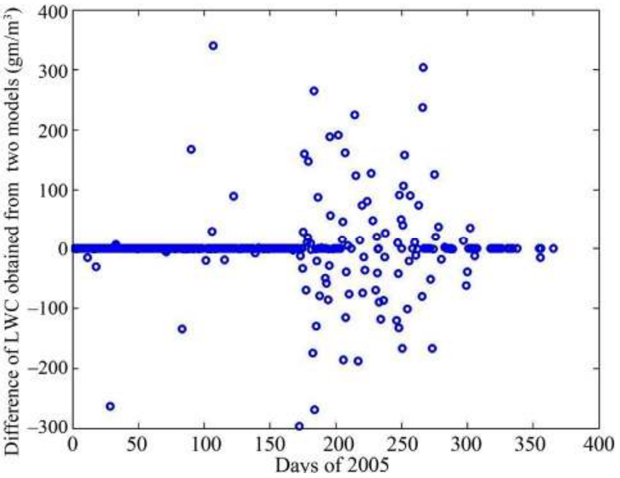

**Figure 7. A plot of difference in the values of LWC obtained with Salonen's and Karsten's model ($LWC_{sal}$ – $LWC_{kar}$) regarding integrated value of cloud LWC obtained per day.**

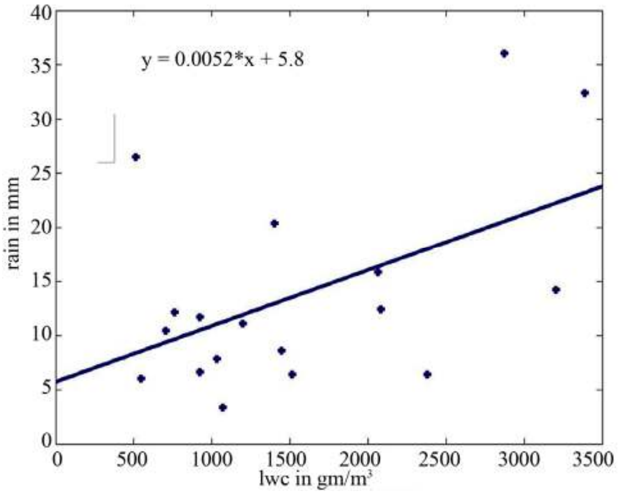

**Figure 8. Variation of rain amount with cloud LWC for the year 2005.**

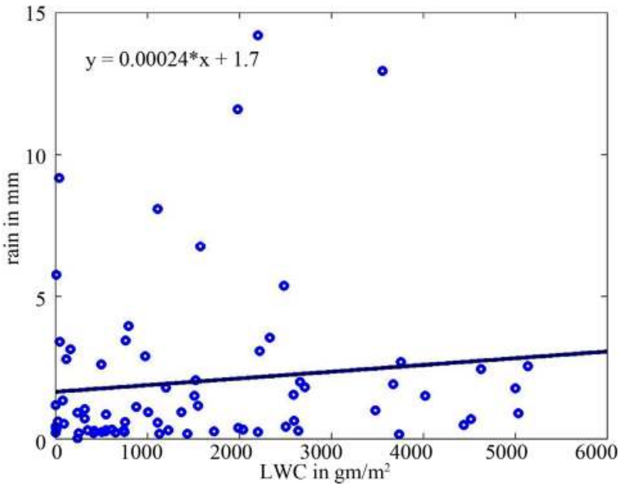

**Figure 9. Variation of rain amount with cloud LWC for the year 2006.**

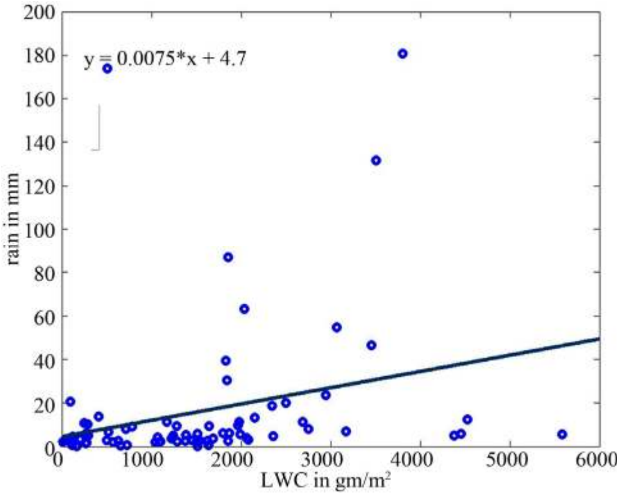

**Figure 10. Variation of rain amount with cloud LWC for the year 2007.**

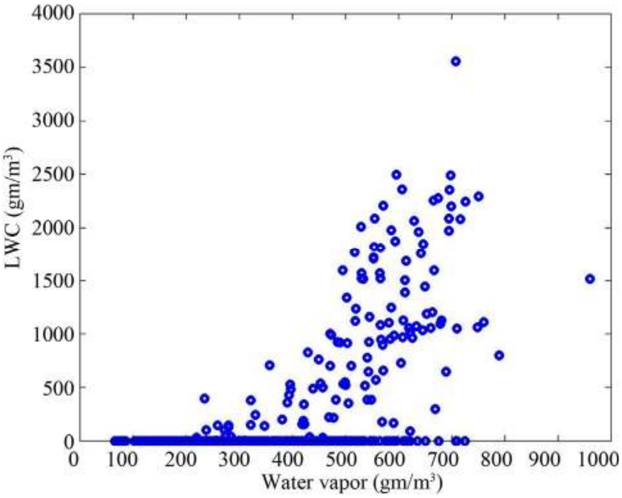

**Figure 11. Variation of liquid water content (LWC) and integrated water vapour (IWV) during 2005.**

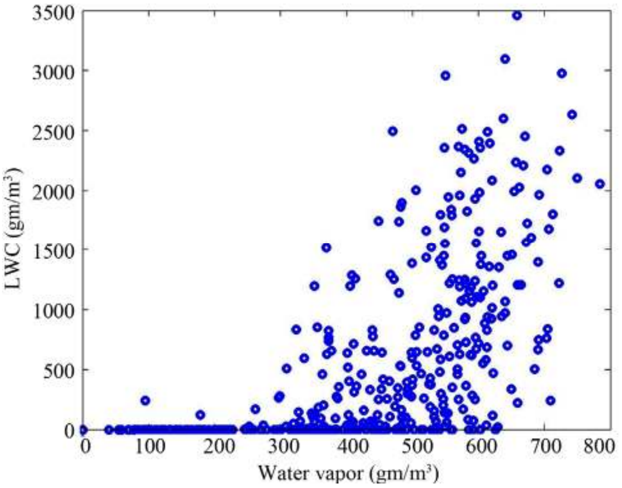

**Figure 12. Variation of liquid watered content (LWC) and integrat water vapour (IWV) during 2007.**

soon plays an important role in tropical atmosphere, Karsten model is more relevant than the Salonen model as it considers adiabatic LWC in addition to temperature profile while calculating LWC of cloud. It also considers circulation of air mass accompanied by precipitation and freezing to deliver a realistic picture of cloud LWC. Our further investigation will indicate if the picture is true for all other tropical location like Kolkata.

## 6. Acknowledgements

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