Retrieval of Slant Water Path, Liquid Water and Rain Events Using the Cloudy Sky Ratio from K-Band Brightness Temperature Measurements

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ABSTRACT

The Dynamics of the Madden-Julian Oscillation (DYNAMO) field campaign was conducted to improve understanding and modeling of the Madden-Julian oscillation (MJO). Observations during DYNAMO focused on atmospheric parameters important for understanding MJO initiation, including vertical moisture profiles, cloud structure, precipitation processes and the planetary boundary layer. These observations were performed using a variety of in-situ and remote sensing instruments, including the S-PolKa radar deployed by the National Center for Atmospheric Research (NCAR) and the collocated University of Miami (UM) microwave radiometer operating at 23.8 and 30.0 GHz. These instruments sampled approximately the same volumes of the atmosphere. A second microwave radiometer was deployed by the Atmospheric Radiation Measurement (ARM) Program approximately 8.5 km from the UM radiometer. These observations provided an opportunity to retrieve slant water path (SWP) and slant liquid water (SLW) from ground-based microwave radiometer measurements over a range of azimuth and elevation angles during both clear sky and cloudy conditions. The retrieved SWP and SLW will be compared to those from S-PolKa radar measurements. The goal of this study is to develop an algorithm to retrieve water vapor and liquid water from ground-based radiometer measurements.

1. INTRODUCTION

The Dynamics of the Madden-Julian Oscillation (DYNAMO) field campaign took place in the central equatorial Indian Ocean between September 1, 2011 and January 5, 2012 [1]. The experiment was primarily designed to improve understanding of the Madden-Julian oscillation (MJO) and its initiation in that region. Observations of vertical moisture profiles, cloud structure, precipitation processes and the planetary boundary layer were performed during DYNAMO. A number of remote sensing instruments, including the National Center for Atmospheric Research (NCAR)'s S-PolKa (dual-wavelength S- and Ka-band) radar [2] and the University of Miami's microwave radiometer, were deployed to estimate water vapor, liquid water and cloud structure. These instruments were collocated and scanned approximately the same volume of the troposphere over a range of both azimuth and elevation angles.

This work focuses on retrieval of water vapor and liquid water using ground-based brightness temperature measurements during DYNAMO. This work is organized into the following sections: Section 2 discusses the experiment setup for DYNAMO. The sensitivity of cloudy sky ratio (CSR) to water vapor and liquid water is analyzed in Section 3. The retrieval algorithm is described and results are shown in Section 4. Finally, the summary and future work are presented and discussed in Section 5.

2. EXPERIMENT DESCRIPTION

As part of the DYNAMO campaign, NCAR deployed the S-PolKa (dual-wavelength S and Ka-band) radar, and the University of Miami deployed a two channel microwave radiometer (UM-Radiometer) collocated on Gan Island in the Maldives in the Indian Ocean. A second microwave radiometer was deployed by the U.S. Department of Energy (DOE) at the Atmospheric Radiation Measurement (ARM) Site also on Gan Island, approximately 8.5 km from the UM-Radiometer. Figure 1 shows locations of the UM-Radiometer and the DOE ARM Site. In addition, radiosondes were launched eight (8) times daily from the DOE ARM site during DYNAMO to provide in-situ data on atmospheric conditions. The S-PolKa radar was deployed to monitor clouds and measure the intensity and types of precipitation. It performed 360º azimuth scans at a range of elevation angles, including 5º, 7º, 9º, and 11º. The UM-Radiometer was deployed to measure brightness temperatures, from which water vapor and cloud liquid water can be retrieved. The UM-Radiometer performed

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measurements at azimuth angles from -50º to +150º (referenced to north at 0º) and at elevation angles of 5º, 7º, 9º, and 11º.

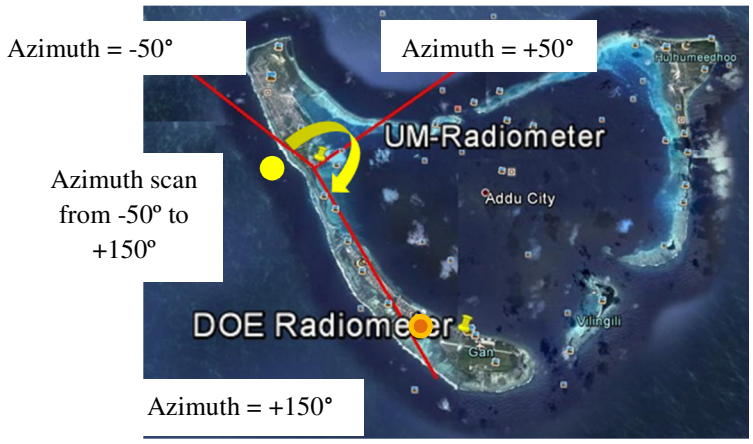

Figure 1. Map of the locations of the University of Miami microwave radiometer (shown by the yellow disk) and the DOE radiometer (shown by the orange disk) on Gan Island, Maldives. The azimuth angle scan range for the UM-Radiometer is from -50° to +150°, as shown.

The UM-radiometer's antenna beamwidth is 3.0º at 23.8 GHz and 3.3º at 30.0 GHz. Brightness temperature measurements were performed continuously to estimate slant water path (SWP, the slant version of integrated water vapor, IWV, where the two are equal at an elevation angle of 90°) and slant liquid water (SLW) during a variety of weather conditions, including clear and cloudy skies as well as precipitation of various intensities.

3. CLOUDY SKY RATIO AND SENSITIVITY TO WATER VAPOR AND LIQUID WATER

As already discussed, one of the main objectives of this study is to develop an algorithm to retrieve SWP and SLW from the UM-Radiometer measurements at low elevation angles, i.e. 5º, 7º, 9º, 11º, as well as for zenith-pointing measurements. To perform this retrieval, the cloudy sky ratio (CSR) is defined as the ratio of the 23.8 GHz brightness temperature to that at 30.0 GHz, as shown in Equation (1). Water vapor in the atmosphere strongly influences brightness temperatures at 23.8 GHz due to its proximity to the water vapor absorption line at 22.235 GHz. On the other hand, 30.0 GHz is a window frequency between the water vapor absorption line and the oxygen absorption complex near 60 GHz. So, under clear sky conditions, brightness temperatures at 23.8 GHz are significantly larger than those at 30.0 GHz, and the value of the cloud sky ratio varies, depending on the atmospheric water vapor density. However, as liquid water is added to the atmosphere, the cloudy sky ratio decreases to near unity since the brightness temperatures at 23.8 GHz and 30.0 GHz become similar in value under those conditions. This method is similar to that implemented by Bosisio et al. (2012) for precipitation events [3]. CSR is sensitive to variability in the amount of liquid water and to some extent to water vapor, as well as to the elevation angle of brightness temperature measurement. The sensitivity of CSR to these parameters allows retrieval of both integrated water vapor (IWV) and integrated liquid water (ILW) (both defined as total vertical column measurements) in the atmosphere.

$$\mathrm{CSR}=\frac{TB_{23.8}}{TB_{30.0}} \qquad (1)$$

To demonstrate the sensitivity of CSR to SWP, brightness temperatures were simulated for 23.8 and 30.0 GHz using measured radiosonde profiles during clear sky conditions for a number of elevation angles ranging from 5° to 90°. CSR was calculated from the simulated brightness temperatures, and the results are shown in Figure 2(a). CSR is approximately proportional to SWP for elevation angles from 20° to 90° while it is much less sensitive to changes in SWP for elevation angles from 15° to 20°. CSR is approximately inversely proportional to SWP for elevation angles from 5° to 11°.

To determine the sensitivity of CSR to liquid water, the liquid water density is calculated from radiosonde data [4] and then used to calculate absorption coefficients at 23.8 and 30.0 GHz using the latest commonly-accepted atmospheric absorption models in this frequency range [5] [6] [7]. The absorption coefficients for water vapor and liquid water are used to simulate brightness temperatures, and in this case the SWP was kept constant while the SLW varied depending on cloud liquid water content. Figure 2(b) shows that the CSR is approximately inversely proportional to SLW for all elevation angles

from 5° to 90°.

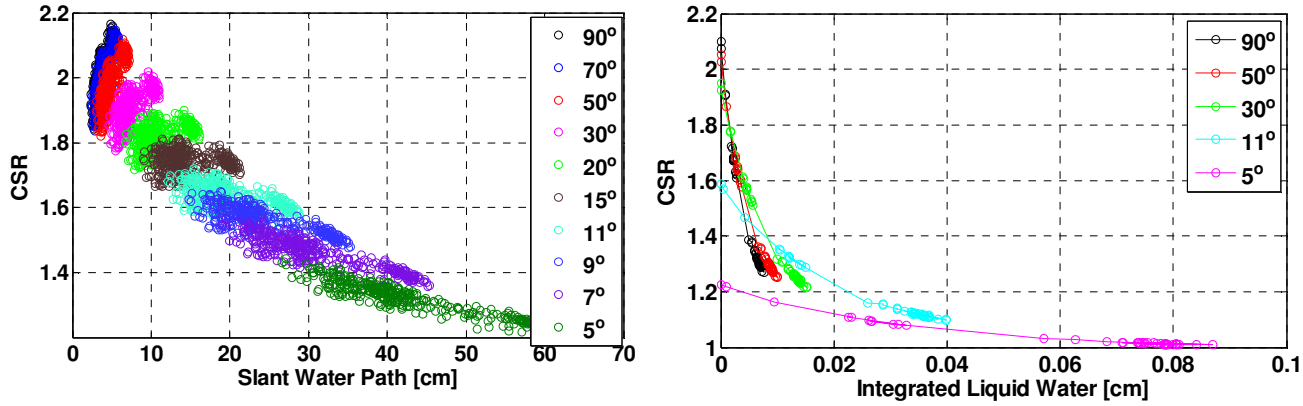

Figure 2. Cloudy sky ratio (CSR) measurements for various elevation angles as a function of (a) SWP and (b) SLW, with the other variable constant in each case.

4. IWV AND ILW RETRIEVAL ALGORITHM

Based on the results of the analysis of the sensitivity of CSR to water vapor and liquid water, a retrieval algorithm was developed to estimate IWV and ILW, as shown in Equation (2). This algorithm minimizes the squared differences between modeled and measured CSRs as well as that between modeled and measured brightness temperatures at 30.0 GHz.

$$\min_{\tau_{wv23.8},\,\tau_{lw30.0}} \chi^2 = |\mathrm{CSR}_{\mathrm{model}} - \mathrm{CSR}'|^2 + |\mathrm{T}_{\mathrm{B30.0}} - \mathrm{T}'_{\mathrm{B30.0}}|^2 \qquad (2)$$

where:

- $\mathrm{CSR}_{\mathrm{model}}$ is modeled CSR for the IWV range of 0 to 9 cm and ILW range of 0 to 0.6 mm,
- CSR' is the CSR calculated from the measured brightness temperatures at 23.8 GHz and 30.0 GHz,
- $\mathrm{T}_{\mathrm{B30.0}}$ and $\mathrm{T}'_{\mathrm{B30.0}}$ are the modeled and measured brightness temperatures at 30.0 GHz, respectively.
- The brightness temperatures at 23.8 and 30.0 GHz are modeled using IWV and ILW from 700 radiosonde profiles collected on Gan Island for the months of June, July and August 2011.

The results of the retrieval are shown in Figure 3. The curve starting near the y-axis and ending on the x-axis shows the locus of points where the measured CSR is equal to the modeled CSR, the minimum of the first term in Equation 2.

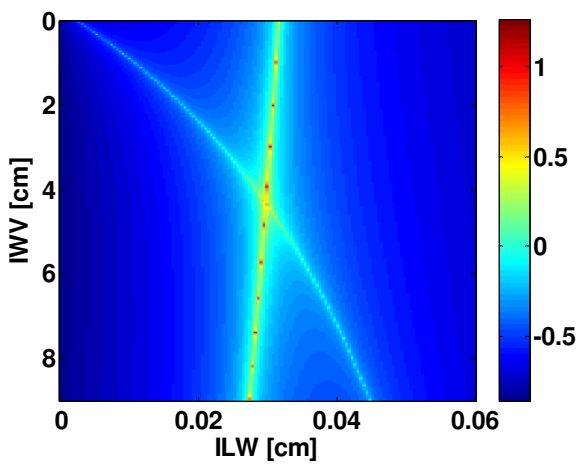

Figure 3. Intersection of the two loci representing the two terms in Equation 2.

From the first term, the CSR could be produced by a range of ILW from 0 to 0.042 cm and a range of IWV from 0 to 9 cm. The nearly-vertical curve in the figure shows the locus of points where the measured and modeled brightness temperatures at 30 GHz are equal, the minimum of the second term in Equation 2. From the second term, the measured brightness temperature at 30.0 GHz could be produced by a range of IWV from 0 to 9 cm but only by a narrow range of ILW, from 0.025 to 0.03 cm. The intersection of the two loci yields the region from which the IWV and ILW can be estimated. Using the retrieval algorithm, times series of IWV were estimated for December 15, 2011. A time series of estimated IWV is shown

in the blue points in Figure 4.

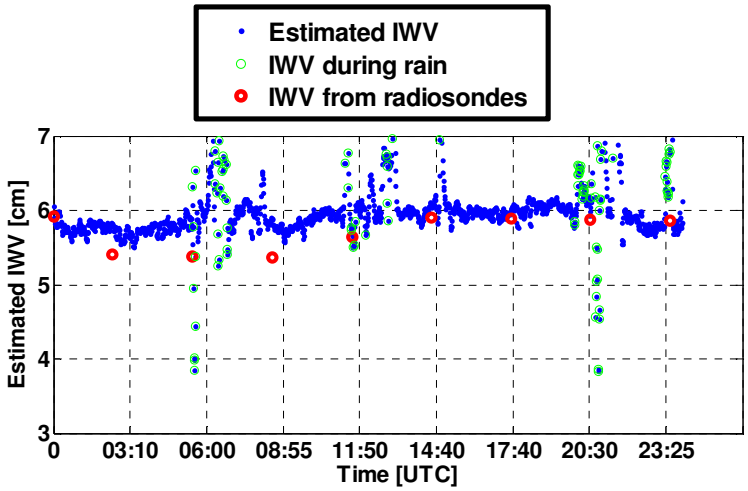

Figure 4. Time series of estimated integrated water vapor (IWV)

In Figure 4, IWV retrieved during rain events is shown by the blue dots with green circles while the red circles represent the IWV from radiosonde measurements. Rain events have been determined based on CSR values. Measurements which correspond to CSR values approximately equal to one are assumed to correspond to precipitating conditions.

5. SUMMARY AND FUTURE WORK

The analysis in this paper has shown that CSR is sensitive to both SWP and SLW and can be used for their retrieval. In this study, CSR and brightness temperature models (23.8 and 30.0 GHz) have been developed for a range of IWV and ILW. These models have been used along with measurements to retrieve IWV and ILW by minimizing the squared differences between models and measurements. The time series of estimated IWV agrees well with the IWV from radiosondes. Rain events have been detected when the CSR values are equal to or less than one. Future work will focus on determining the retrieval uncertainty and comparison of the detected rain events with those detected using the S-PolKa radar. It will also focus on retrieval of SWP and SLW and their comparison to the S-PolKa radar retrieved SWP [8] and SLW at various elevation and azimuth angles.

6. REFERENCES

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