Published in final edited form as:

Geophys Res Lett. 2018 January 28; 45(2): 1133–1140. doi:10.1002/2017GL076296.

Re-examining the Non-Linear Moisture-Precipitation Relationship over the Tropical Oceans

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Abstract

Bretherton et al. (2004) used the Special Sensor Microwave Imager (SSM/I) version 5 product to derive an exponential curve that describes the relationship between precipitation and column relative humidity (CRH) over the tropical oceans. The curve, which features a precipitation pickup at a CRH of about 0.75 and a rapid increase of precipitation with CRH after the pickup, has been widely used in the studies of the tropical atmosphere.

This study re-examines the moisture-precipitation relationship by using the version 7 SSM/I data, in which several biases in the previous version are corrected, and evaluates the relationship in the Coupled Model Intercomparison Project phase 5 (CMIP5) models. In the revised exponential curve derived using the updated satellite data, the precipitation pick-up occurs at a higher CRH (~0.8), and precipitation increases more slowly with CRH than in the previous curve. In most CMIP5 models, the precipitation pickup is too early due to the common model bias of overestimated (underestimated) precipitation in the dry (wet) regime.

1. Introduction

Important progress has been made in the last two decades on understanding the role of environmental humidity as a regulator of cumulus convection. Several observational studies (Brown & Zhang 1997; Sherwood 1999; Bretherton et al. 2004; Sherwood et al. 2004; Takayabu et al. 2006; Raymond 2007; Holloway & Neelin 2009; Ahmed & Schumacher 2015) have shown that tropical convection is strongly coupled to column-integrated humidity on various time scales ranging from hourly to monthly. When the relationship to convection is examined at individual levels, low-to-mid free tropospheric moisture shows the highest correlation and leads the onset of convection (Sherwood 1999; Takayabu et al. 2006; Holloway & Neelin 2009).

The coupling between environmental moisture and convection occurs through the entrainment of environmental air into convective plumes (e.g., Brown & Zhang 1997; Holloway & Neelin 2009), the argument that has been supported by cloud resolving model simulations in various configurations (Tompkins 2001; Grabowski 2003; Chaboureaud et al. 2004; Derbyshire et al. 2004; Kuang & Bretherton 2006; Bretherton & Khairoutdinov 2015).

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Microwave satellite retrievals of column water vapor and precipitation (e.g., Wentz & Spencer 1998) have served as the basis for quantifying the moisture-convection coupling over tropical ocean basins. Using the Special Sensor Microwave Imager (SSM/I) version 5 product, Bretherton et al. (2004) showed that the relationship of precipitation with column relative humidity (CRH) in the tropical oceans is characterized by a pickup of precipitation at a CRH value between 0.7 and 0.8 and a rapid increase of precipitation with CRH after the pickup. This exponential behavior in the moisture-precipitation relationship has repeatedly been found in the studies that used various types of observations of water vapor and precipitation (Raymond et al, 2007; Neelin et al., 2008; Raymond et al., 2011; Holloway & Neelin, 2009; Gilmore, 2015). It is worthwhile to note that recent studies have found that the moisture-convection coupling is the strongest over tropical oceans and it becomes weaker in coastal areas (Bergemann and Jakob 2016) and over land (Ahmed and Schumacher 2017) where the convection is typically forced by sea breeze or daytime surface heating.

The precipitation pickup and the rapid increase of precipitation with CRH after the pickup can be captured by an exponential curve of the form $P = P_r \exp(a_d \text{ CRH})$, where P is precipitation, and a_d and P_r are constant coefficients. Bretherton et al. (2004) obtained a_d and P_r by fitting an exponential curve to the observed joint distribution of precipitation and CRH. The resulting exponential curve (i.e., a_d and P_r) has been widely used in many studies. For example, a few recent theoretical studies of the Madden-Julian Oscillation (MJO) used the coefficients a_d and P_r obtained by Bretherton et al. (2004) (e.g., Sobel & Maloney, 2012; Adames & Kim, 2016; Liu & Wang, 2016). The Bretherton et al. (2004) exponential curve has also served as a constraint on numerical model simulations (e.g., Bretherton & Khairoutdinov, 2015; Daleu et al., 2016). In Daleu et al. (2016), the curve of Bretherton et al. (2004) was used as a reference against which the moisture-convection relationship in a series of single-column model simulations was evaluated.

The convective moisture adjustment time scale (Bretherton et al. 2004) is one way of characterizing or representing the moisture-convection relationship, which has been used in theoretical (Sobel & Maloney 2012, Adames & Kim 2016) and model evaluation (Jiang et al. 2016) studies of the MJO. It is a hypothetical e-folding time scale of moisture anomalies under the condition in which it is assumed that only convection is affecting the moisture anomalies. For example, a shorter convective moisture adjustment time scale indicates, for a given moisture anomaly, stronger anomalous convection occurs, restoring the initial moisture anomaly more quickly back to the mean state. In other words, a shorter (longer) time scale corresponds to a stronger (weaker) moisture sensitivity of convection.

In the moisture mode theories of the MJO (e.g., Adames & Kim 2016), the convective moisture adjustment time scale plays a critical role by determining the magnitude of diabatic heating (precipitation) and associated circulation anomalies for given moisture anomalies. Moreover, Jiang et al. (2016) found that models with a shorter convective moisture adjustment time scale – a stronger moisture-convection coupling – simulate a stronger MJO. Both examples suggest a strong need for an accurate estimation of the convective moisture adjustment time scale.

This study was motivated by an update of the SSM/I retrieval algorithm since Bretherton et al. (2004) examined the moisture-precipitation relationship. We find that the moisture-precipitation relationship in the upgraded dataset (version 7) is significantly changed from that of Bretherton et al. (2004), which was based on version 5. It will be shown that the change in the moisture-convection relationship is primarily due to the lower rain rate estimates in the version 7 products than those in that in the version 5 data. Note that it was reported by Bretherton et al. (2004) that the version 5 SSM/I rain rate was much higher than the estimates from the ground radar observations collected during the KWAJEX field campaign (see their Figure 11).

We also evaluate the moisture-precipitation relationship in the Coupled Model Intercomparison Project phase 5 (CMIP5) models against version 7 data.

2. Data and Methods

2.1 Microwave satellite observations of precipitation and column water vapor

We use precipitation and column water vapor observations obtained from two passive microwave radiometers – SSM/I and the Special Sensor Microwave Imager Sounder (SSMIS) that are carried onboard the Defense Meteorological Satellite Program satellites. These passive microwave radiometers observe atmospheric, ocean, and terrain microwave brightness temperature, which can be used to retrieve precipitation and column water vapor, among other variables (Wentz & Spencer, 1998; Hilburn & Wentz, 2008).

Two versions – version 5 and 7 – of precipitation and column water vapor retrievals from SSM/I and SSMIS observations are used in this study. Hilburn and Wentz (2008) document the version 7 algorithm, which improves the version 5 algorithm (Wentz & Spencer, 1998) by correcting errors caused by beam-filling overcorrection, resampling, and rain column height corrections. The updates improved the agreement of precipitation with other satellite observations and reduced inter-satellite differences (Hilburn & Wentz, 2008).

In order to investigate the impact of the algorithm updates on the moisture-precipitation relationship, results from the two versions are compared to each other for the period 1998–2001, the period examined by Bretherton et al. (2004). We then use the version 7 SSM/I and SSMIS overpasses over the period 1998–2016 for CMIP5 model evaluation.

Daily-averaged precipitation and column water vapor retrievals on a $2.5^{\circ} \times 2.5^{\circ}$ grid are obtained by averaging all available morning and evening overpasses (at a $0.25^{\circ} \times 0.25^{\circ}$ grid) on each day and in each $2.5^{\circ} \times 2.5^{\circ}$ grid box. The analysis is restricted to the tropical oceans between 20°N and 20°S and ocean basins are defined for the Atlantic Ocean, Indian Ocean, and the East and West Pacific Ocean, which is split along the 180° Meridian (see Bretherton et al. (2004)'s Figure 1).

2.2 ERA-Interim reanalysis

Daily-mean temperature data is obtained from the European Center for Medium Range Forecasts (ECMWF) interim reanalysis (ERA-Interim) four times daily data at a $2.5^{\circ} \times 2.5^{\circ}$ grid over the period 1998–2016 (Dee et al., 2011). The temperature is averaged over each

day and used to calculate the saturation vapor pressure (e_s) using the Clausius-Clapeyron Equation at each pressure level, p . The saturation specific humidity (q_s) at each pressure level and at the surface is then calculated using the approximation: $q_s \approx 0.622(e_s/p)$ (Wallace & Hobbs, 2006). Column integrated saturation specific humidity ($\langle q_s \rangle$) is obtained by vertically integrating the saturation specific humidity from the surface to the top of the free troposphere:

$$\langle q_s \rangle = \frac{1}{g} \int_{p_s}^{p_T} q_s dp, \quad (1)$$

where g is the acceleration due to gravity, p_s is the pressure at the surface and p_T is the pressure at the top of the free troposphere, here defined as 100 hPa.

2.3 CMIP5 models

We evaluate the moisture-precipitation relationship simulated in 28 climate models that participated in CMIP5 against that in the microwave satellite retrievals. Twenty years of daily mean temperature, specific humidity, and precipitation from the Historical simulation (Taylor et al. 2012) are used to assess their moisture-precipitation relationship. Model data are interpolated onto a $2.5^\circ \times 2.5^\circ$ grid and 8 vertical levels are selected (1000, 850, 700, 500, 250, 100, 50, 10 hPa). The model designation, host institution, and original horizontal resolution are given in Table S1. A more detailed description of CMIP5 models is given in Taylor et al. (2012) and the information of convection scheme and grid-scale cloud scheme of a subset of CMIP5 models are given in Ahn et al. (2017).

2.4 Moisture-Precipitation Relationship and Convective Moisture Adjustment Time Scale

We first calculate CRH by dividing column water vapor by column-integrated saturation specific humidity. We then calculate joint probability density function (PDF) of CRH and precipitation, from which the exponential curve of the form

$$P = P_r \exp(a_d \text{CRH}) \quad (2)$$

is obtained as a non-linear fit to the joint PDF.

The convective moisture adjustment timescale (τ_c) is derived as the inverse of the slope of the exponential curve at a reference CRH (CRH^*), scaled by the mean column-integrated saturation specific humidity:

$$\tau_c = \frac{\langle q_s \rangle}{a_d P_r \exp(a_d \text{CRH}^*)} \quad (3)$$

In this study, we define CRH^* as ‘reference’ CRH in the Eq. (2) that corresponds to the time and space mean precipitation over the warm pool region. Eq. (3) shows that the convective

moisture adjustment timescale is sensitive to the slope of the non-linear fit (a_d) as well as CRH*.

3. Results

3.1 Impacts of SSM/I Version Update on the Moisture-Precipitation Relationship

Figure 1 compares the two versions of SSM/I-derived precipitation and column water vapor. It is apparent that the rain rates are much lower in version 7 than in version 5 (Figure 1a), due to corrections made to beam-filling, resampling, and rain column height (Hilburn & Wentz, 2008). The difference between the two versions are more pronounced for higher rain rates. While the precipitable water comparison shows a nearly 1-to-1 relationship, retrieved water vapor path is slightly higher for the moistest columns in version 7 than in version 5 (see inset in Figure 1b). The increase in column water vapor from version 5 to 7 is presumably associated with the lower rain rate. Both retrieval algorithms reject pixels with heavy rain (rain rates $>15 \text{ mm hr}^{-1}$) because the radiative scattering is too high (Wentz & Spencer, 1998; Mears et al., 2015a), creating a possible retrieval bias. It is possible that due to the decrease of precipitation rate in version 7, fewer pixels with high precipitable water were rejected, leading to the apparent increase in the column water vapor. We also compared the version 7 rain rate and column water vapor estimates to independent observations collected during the DYNAMO field campaign (Yoneyama et al. 2013). Our results show that the version 7 product reasonably compares with the field campaign observations (Figure S1).

The systematic decrease in precipitation observations at high precipitation and the slight increase in column water vapor observations over the ocean significantly affect the relationship between CRH and precipitation (Figure 2). Figures 2a–b show the CRH-precipitation joint PDF for the two versions. Their difference, shown in Figure 2c, shows a large reduction in the frequency of rain rates greater than 50 mm day^{-1} in version 7 and a shift from CRH of 0.8 to 0.85 for rain rates lower than 50 mm day^{-1} . As a result, the tail on the end of higher precipitation rates is much less pronounced in the version 7 data.

The coefficients in the associated exponential fits of P vs. CRH (solid lines on Figures 2a and 2b) are:

$$\text{Version 5: } a_d=16.12, P_r=4.07 \times 10^{-5} \text{ mm day}^{-1}$$

$$\text{Version 7: } a_d=14.72, P_r=6.89 \times 10^{-5} \text{ mm day}^{-1} \quad (4)$$

Two factors combine to slightly reduce the slope of the fit in version 7 compared to version 5. The lower precipitation reduces the rate of increase of the exponential while the increase in CRH stretches the exponential laterally. It is worthwhile mentioning that the joint PDF shows notable deviations from the non-linear fit. This suggests that while the fit is able to describe the average relationship that precipitation has with CRH, CRH is not a single factor that governs precipitation over tropical oceans.

Our a_d and P_r derived from the version 5 data do not exactly match the coefficients $a_d = 15.6$, $P_r = 8.22 \times 10^{-5} \text{ mm day}^{-1}$ found by Bretherton et al. (2004). This difference is likely caused by small changes in the estimated CRH due to our use of ERA-Interim temperature data instead of the ECMWF forecast analysis used by Bretherton et al. (2004).

The changes in the non-linear fit can consistently be seen over all ocean basins (Figure 3). While the PDF of CRH is similar in both versions, the peak of the PDF is shifted toward higher values of CRH and is less pronounced in version 7. The inter-basin differences in the non-linear fit are reduced in version 7 compared to version 5.

The convective moisture adjustment timescale, τ_c , is influenced by the mean precipitation and the slope of the non-linear moisture-precipitation relationship (Eq. 3), both of which depend on the retrieval version. It is significantly lengthened from 13 hours in version 5 to 18 hours in version 7 (Figure 4c), again indicating that convection is less sensitive to moisture in the revised dataset than in the old one. This lengthening is mainly due to the decrease in mean precipitation and a_d .

3.2 Evaluation of CMIP5 Models with Updated Moisture-Precipitation Relationship

Figure 4a shows that while the exponential fits obtained from the CMIP5 models have a large spread among the models, many models show too much precipitation at low CRH and too little precipitation at higher CRH compared to the version 7 data (Figure 4b). For CRH bins of 0.7–0.75, for example, models tend to produce weak-to-moderate ($< 20 \text{ mm day}^{-1}$) rain rates too frequently, suggesting that the limiting effect of non-saturated columns on convection is too weak in the models. This is a well-known issue since Derbyshire et al. (2004), who showed that parameterized convection in global climate models is insensitive to environmental humidity. The insensitivity of convection to environmental moisture indicates that the fractional entrainment rate in the convection schemes used in the CMIP5 models are lower than what it should be (e.g., de Rooy et al. 2013). On the other hand, for CRH bins of values greater than 0.75, models underestimate the frequency of near zero rain rate ($< 5 \text{ mm day}^{-1}$). In other words, models have difficulty representing the suppressed condition with a large enough CRH.

The two pronounced biases in the CRH-precipitation joint PDF lead to the precipitation pickup in almost all CMIP5 models occurring at a drier regime than in observations. Given the nature of an exponential curve, the earlier precipitation pickup would lead to a shorter-than-observed convective moisture adjustment time scale, if the reference CRH remains the same. Despite the too-early precipitation pickup biases in the moisture-convection relationship, however, many CMIP5 models show a convective moisture adjustment timescale that is comparable to the value obtained from the version 7 data (Figure 4c). This is because the reference CRH, which is the CRH value that corresponds to the mean precipitation over the warm pool, is also systematically lower (pink dots in Figure 4a), making the convective moisture adjustment time scale longer than what it would be without the biases in the reference CRH. Our results suggest that in many CMIP5 models the two errors – too-early precipitation pickup and too-low reference CRH – are compensating each other to yield a reasonable convective moisture adjustment timescale.

4. Summary and Conclusions

In this study, we examined the moisture-precipitation relationship in two versions of SSM/I products to assess the impacts of the version update on the exponential relationship between CRH and precipitation. It was found that the CRH-precipitation relationship in the version 7 SSM/I data is significantly different from that in the version 5 product, which was used by Bretherton et al. (2004). Estimated precipitation is greatly reduced in the version 7 data compared to version 5 due to updates to the retrieval algorithm, while precipitable water is slightly increased in the moistest atmospheric columns. These changes led to an increase in the CRH value at which precipitation pickup occurs and a reduction of the slope of the exponential fit of precipitation to moisture, i.e. that the increase in precipitation with CRH is not as large in version 7 as in version 5. The corresponding convective moisture adjustment timescale is much longer in version 7 than version 5.

The considerable spread around the non-linear fit in the joint distribution of CRH and precipitation (e.g., Figure 2b) indicates that there are factors other than CRH that affect tropical oceanic convection. Whether the spread is from the stochastic nature of convection, or is deterministically caused by other processes (e.g., the degree of convective organization) remains to be explored. Utilizing the full CRH-precipitation joint PDF in addition to the non-linear fit in the model evaluations will also provide further insights into the model bias in the moisture-convection relationship (e.g., Figure 4b).

Representations of the moisture-precipitation relationship in 28 CMIP5 models is evaluated against that in the version 7 products. Compared to the observations, all CMIP5 models produce too much rain in the low moisture regime with CRH lower than 0.8, suggesting that the model convection schemes lack enough sensitivity to environmental moisture. Models also tend to be incapable of representing suppressed condition with high column moisture ($\text{CRH} > 0.8$). Due to these biases, the precipitation pickup in the CRH-precipitation relationship occurs too early in most CMIP5 models. Nonetheless, the CMIP5 models show a convective moisture adjustment timescale that is comparable to observations because the bias in the CRH-precipitation relationship is compensated by the low bias in the reference CRH value.

Many studies have used the exponential curve derived by Bretherton et al. (2004) from the version 5 SSM/I product as the simplified moisture-convection relationship in simple models of tropical atmosphere or as the basis of model evaluation (Sobel & Maloney, 2012; Bretherton & Khairoutdinov, 2015; Adames & Kim, 2016; Daleu et al., 2016; Liu & Wang, 2016; Adames, 2017). We strongly suggest that the exponential curve derived from the version 7 SSM/I and SSMIS products should be utilized for future studies. Our results also warrant further studies on the causes of the systematic biases in the moisture-precipitation relationship in the CMIP5 models.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

Acknowledgments, Samples, and Data

SSM/I and SSMIS data are produced by Remote Sensing Systems and are available at www.remss.com/missions/ssmi. CMIP5 model simulations are available at the CMIP5 archive. SSR and DK was supported by National Aeronautics and Space Administration Grant 80NSSC17K0227. DK was also supported by the startup grant from the University of Washington. MSA was supported by the Korean Meteorological Administration Research and Development Program under Grant KMIPA2015-2114.

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Key Points

- A revised exponential relationship between column relative humidity (CRH) and precipitation is obtained.
- The precipitation pickup occurs at a higher CRH and precipitation increases with CRH at a lower rate in the new relationship.
- Most CMIP5 models exhibit a too early precipitation pickup bias.

Figure 1.

Joint histogram of (a) precipitation and (b) precipitable water between the version 5 and version 7 SSM/I products. Red lines represent the best fit lines for the joint histogram. Dashed lines are the 1-to-1 line. The inset in panel (b) is a zoomed-in view of the version 5 and version 7 column water vapor, showing that the majority of points are off of the 1-to-1 fit.

Figure 2.

Joint PDF of precipitation rate and column relative humidity (shading) for the (a) version 5 and (b) version 7 SSM/I data over the period 1998–2001. The shading is the probability of the number of observations of a particular range of precipitation and CRH. The non-linear fit (solid) is shown for each version. (c) The difference between the version 7 and version 5 histograms.

Figure 3.

(a–b) Mean precipitation in 1% bins of column relative humidity for tropical ocean basins (Atlantic, East Pacific, West Pacific, and Indian Ocean) using the (a) version 5 and (b) version 7 SSM/I products over the period 1998–2001. (c–d) Number of observations per 1% CRH bins in the (c) version 5 and (d) version 7 SSM/I products.

Figure 4.

a) Exponential fits derived from the precipitation-CRH joint distributions representing the moisture-convection relationship in observations and models. Black dashed and solid line indicate the version 5 (1998–2001) and version 7 (1998–2016) product, respectively). Gray lines represent the CMIP5 models. Pink dots on the CMIP5 model fits and yellow stars on the observational fits indicate the reference CRH values used to calculate τ_c . b) Multi-model mean bias in the precipitation-CRH joint histogram against the version 7 products. c) τ_c of CMIP5 models (bars) compared to τ_c derived from the version 5 (solid black line) and version 7 (dashed black line) products.