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Influence of Sea Surface Temperature on the Columnar Water Vapor Content and Cloud Fraction, Based on Monthly-Averaged MODIS Data at 1° by 1° Resolution

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Abstract- Satellite data on global sea surface temperature (SST), water vapor and cloud fraction are analyzed to provide direct relationships on these parameters. Increase in SST elevates the water vapor pressure at the surface following the Clausius-Clayperon (exponential) form, and this effect persists to increase the columnar water vapor up to SST of approximately 300 K, at the 1^{o} by 1^{o}, monthly-averaged scale. Beyond SST of 300 K, a steeper slope for the columnar water vapor is observed. A similar transitional relationship is observed between cloud fraction (CF) and SST, except that a negative slope is found up to SST of 300 K. Then, a reversal occurs at SST of approximately 300K where CF increases quadratically as a function of SST. Parameterization of water vapor and CF is provided as a function of SST for 1^{o} by 1^{o} spatial resolution and monthly-averaged time scale.

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1. INTRODUCTION

The Earth climate system is arguably the most important scientific and engineering problem of our time, as it affects nearly all aspects of human existence and beyond. The cloud fraction (CF) and sea surface temperature (SST) are two of the fundamental parameters that affect the climate state. The cloud fraction is directly related to the atmospheric albedo, while SST and its lateral gradients are the drivers of the advection processes. The clouds are also attributed to trapping of the outgoing infrared radiation (Perkins, 2010; Wu et al., 2019). Water vapor equilibrium is set at the sea surface temperature, and convection of this vapor content leads to cloud fraction. Prior works analyze the cloud fraction as a key climate feedback parameter (Cess et al., 1996; Ingram, 2010; Houghton, 1990; and Stocker et al., 2001). The atmospheric optical depth and cloud fraction are close correlated (Engstrom and Ekman, 2010; Gryspeerdt et. al, 2014). For these reasons, inter-relationships between the basic climate variables such as SST, water vapor (WV), and cloud fractions are important in understanding of the Earth climate system. Thermodynamically, Clausius-Claperyon equation specifies the liquid-vapor equilibrium based on water temperature, e.g. SST. However, observational data for the columnar water vapor as a function of SST tend to deviate from this relationship, and modified constants are used depending on spatial locations (Zhang and Qiu, 2008; Stephens, 1990; Kanemaru and Masunaga, 2013). Stephens (1990), for example, examined the global relationships between SST and precipitable water vapor at the same coordinate, and showed that the Clausius-Claperyon form is applicable for SST > 15 C^o with less than 20% deviation potentially arising from large-scale flow effects. Constants in the SST-WV relationship have been obtained through least-square fit with passive microwave radiometry data (Stephens, 1990). Waliser (1996) investigated the SST-atmosphere interaction by examining thermodynamic and convection dynamic variables, suggesting that there is a feedback mechanism to suppress locally high SST. Ramanathan and Collins (1991) found that the net greenhouse effect increased as a function of the sea surface temperature, during 1987 El Nino event. However, this was offset by cirrus cloud reflection of incoming solar radiation at SST > 300 K. Kanemaru and Masunaga (2013) analyzed the surface moisture and vertical gradients, and found different moisture structure depending on latitude regions (e.g. sub-tropical, tropical). Yu and Weller (2007) found that the surface latent heat flux bears a great similarity to that of SST, leading to increased moisture-holding capacity of the atmosphere in line with SST.

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Analyses and computations of the Earth climate system typically include detailed spatio-temporal developments of climate variables including turbulent convection (Larson and Hartmann, 2003; Randall et al., 2007). For example, in a typical global circulation model (GCM) the ocean convection currents set the surface boundary conditions. Then, phase-equilibrium models need to be applied to compute the atmospheric water vapor and cloud formation leading to varying results which often are model-dependent (Cess et al., 1990, Randall et al., 2007; Yu et al., 2004). These GCM models are useful in assessing the interaction of local and surrounding environmental variables. However, detailed and accurate simulations of entire global circulation are intrinsically difficult and time-consuming. In addition, modeling of cloud formation at different altitudes adds a significant level of complexity in GCM simulations due to non-linear thermodynamics and multiple parameters in a typical cloud fraction model (Hu, 1997; Xu et al., 2010). Possibly for this reason, there have not been as much reported findings on relationship between SST with CF, compared to SST-WV analyses. Nair and Rajeev (2014) have considered SST and dynamical effects on vertical cloud distributions. Similar to WV, warmer SST is associated with increased upward convection (and turbulence), which affects the vertical distribution (Nair and Rajeev, 2014). Similar latitude (regional) differences are also expected.

Thus, the current approach is to first analyze the monthly averaged data, and seek fundamental first-order relationships between SST, WV and also CF, leading to some understanding of the global thermodynamic processes. A pre-cursor attempt was somewhat inconclusive (Lee and Park, 2022), and in the current work the analysis has been revised and re-examined to reveal some insight and succinct relationships for the fundamental climate variables, in particular directly between sea surface temperature and cloud fraction.

2. DATA ANALYSES

For understanding and predicting the Earth climate system, satellite-based, higher-level processed data sets are readily available including SST, WV and CF at various spatial and temporal resolutions. These data sets are often used during the key necessary step of validating and calibrating the computational models of the Earth climate system (Jiang et al., 2012). At a basic level, these data can be analyzed and examined from various perspectives (e.g., thermodynamic) to gain understanding of the important forcing functions, such as the relationship between the SST to columnar water vapor, cloud fraction, and others (Lee and Park, 2022). In this work, SST, WV and CF provided

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in the MODIS data products are used for analyses (Lee and Park, 2026). Detailed descriptions of the data and processing methods are discussed by various authors of the MODIS data set (https://modis.gsfc.nasa.gov/data/). We use the 1° by 1° resolution, monthly-averaged data in this work, for the time span of January 2000 to March of 2017. The unit for the columnar water vapor (WV) is in cm, which is the standard definition for the height of the water if the entire columnar water vapor condensed in that cell. These data are plotted in scattergrams (Figs. 1-5), while least-square fit regressions are attempted for quantitative correlations. Due to the large range of spatial and temporal scales, a fair amount of scatter exists in the plots, which is also discussed.

3. RESULTS AND DISCUSSION

Satellite data on global sea surface temperature (SST), water vapor and cloud fraction are analyzed, and inter-dependence of these parameters are attempted. As is well known, SST produces the water vapor in the atmosphere through the thermodynamics of saturation pressure and temperature. This is evident in SST vs. WV scattergrams (Figure 1), where a Clausius-Claperyon (CC) form of exponential dependence on SST is observed up to SST of approximately 300 K. With minor adjustments in the CC form, the columnar WV content can be tracked up to this transition point (T_c ~300 K). Beyond that, the slope increases substantially, above the typical CC-form. Other researchers have modified the constants in the CC equation to span the entire SST range (Zhang and Qiu, 2008; Stephens, 1990; Kanemaru and Masunaga, 2013). However, due to the above-noted transition near T_c of 300 K, SST-WV can be considered separately in two segments, SST < T_c and SST >T_c. The CC exponential form be effectively used up to T_c, but an alternate expression needs to be adopted to correlate WV with SST beyond that point. This transition is present in all of the data spanning 2000 to 2017 (a small sub-set is shown in Fig. 1), with minor month-to-month variations. During some months, the data are bifurcated for SST < 285 K, with upper branch exhibiting higher WV than the lower CC branch. These months are also associated with larger scatter in the data, in Figure 1.

We note that the CC-form equations are based on the sea-surface temperature, while the measured water vapor is for the entire columnar height above that location. Therefore, vertical convection can influence the WV (Kanemaru and Masunaga, 2013). In addition, low/high SST is mostly associated with high/low latitudes, and the two distinct behavior can arise from latitude effects. Other authors have also found such differences in SST-WV in subtropical and tropical regions (Kanemaru and Masunaga,

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2013; Stephens, 1990). At low to moderate temperatures (SST < 300 K), the water vapor content is dominated by the amount near the sea surface. At higher temperature (SST > 300 K), increased evaporation and SST leads to appreciable upward convection. Data plotted in Figure 1 indicate that the water vapor content is "over-saturated", higher than the water vapor pressure at the corresponding SST, SST of of approximately 300 K. This observation for SST > 300K is replicated for all of the monthly data set (Figure 1 is a representative subset of the entire data set). This bi-fold behavior appears to also have an effect on the cloud fraction, as discussed later. Dynamical effects can evidently influence SST-WV relations. As noted above Stephens (1990) also found that the Clausius-Claperyon form is applicable for SST > 15 C^o with less than 20% deviation potentially arising from large-scale flow effects. The scatter in the data increases progressively from SST ~ 275 K to 300 K. Stephens (1990) quantified the potential effects of large-scale flows to approximately 20%, and the amount of scatter in the data in Fig. 1 appears to reflect this convection variability.

A similar transition is observed in the SST vs. CF (cloud fraction) scattergram (Fig. 2). The transition to a different slope occurs at about the same SST (~300 K). We observe small month-to-month variations in this transition point of up to SST of +/- 2 K. For CF, the transition is more dramatic as the slope is completely reversed: CF *decreases* with respect to SST up to T_c, then steeply *increases* beyond it. The physical mechanism for this reversal and increase in CF above the threshold temperature (T_c) may again be attributed to the increased upward convection at high SST, distributing the water vapor to higher altitude resulting in more vapor available for condensation and cloud formation. We again note that the SST-WV correlation in Figure 1 is with respect to SST and thus representative of water vapor present near the sea surface. Any upward mobility in water vapor will increase the availability of WV at higher altitude/lower temperature, and condensation can occur leading to cloud formation. The decrease in CF with increasing SST below SST ~ 300K is apparently due to increasing saturation pressure (with SST) so that atmosphere is able to hold water vapor prior to condensation (cloud formation). These trends are consistently observed in all of the months in the data set, as will be shown later. There is a larger amount of scatter in the data, probably due to complex, multiple factors that can influence cloud formation (Nair and Rajeev, 2014). From the global thermodynamic perspective, the steep positive slope in CF with SST (SST > 300 K) provides a negative forcing of the global warming, as CF reflects a large portion of the incoming solar radiation.

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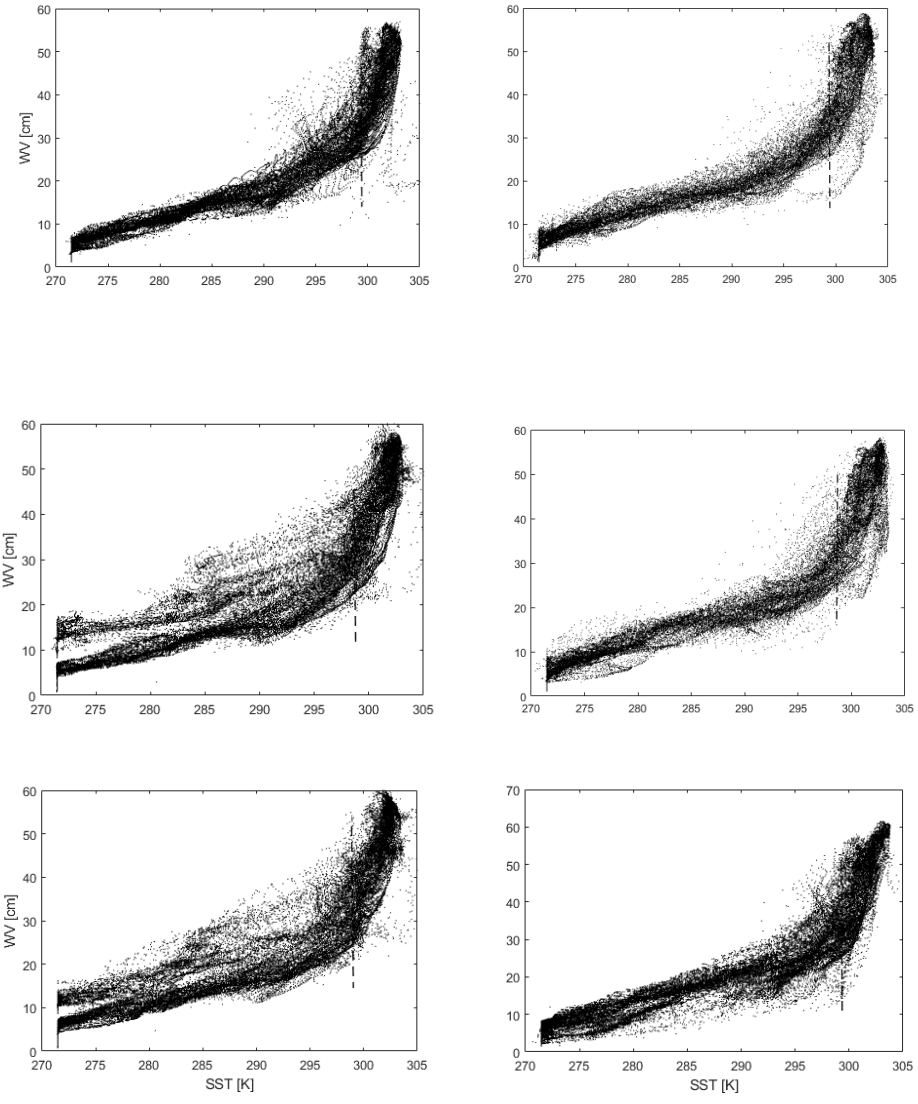

Figure 1. Water vapor (WV) vs. SST scattergram for various months (from top left: October, 2000; April, 2003; August, 2007; April, 2013; December, 2015; and December 2019).

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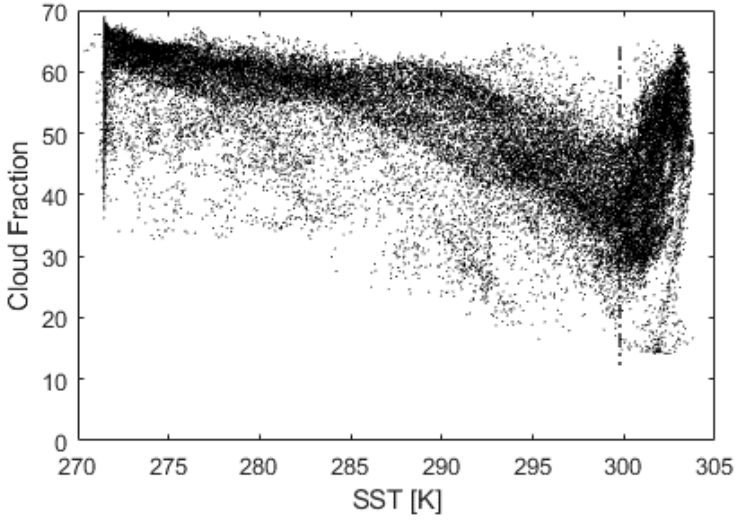

Figure 2. Cloud fraction (CF) vs. SST scattergram for May, 2007.

Above trends can be further examined by plotting shifted and/or inverted SST-CF data on top of the SST-WV (red), as shown in Figure 3. First, we use SST-WV correlational data (the same plots as in Figures 1 and 2, except plotted in red) as the reference. Then, we upward-shift the SST-CF data (black) on top of this reference data set, which results in overlap of WV and CF as a function of SST for SST>T_c (~300K) in Figure 3. This explains the over-saturation (large WV) at these SST's directly produces large cloud fraction (CF). Upward shifting is simply to match the vertical axis scale for WV and CF. Inversion of the same SST-CF data (blue) matches the SST-WV curve (red) for SST<T_c region. WV increased with SST, while CF decreased when SST<T_c, so that inverting CF results in an overlap for SST <T_c in Figure 3. This simply means that below SST <T_c the increase in saturation pressure withholds cloud formation in the atmosphere. Thus, the global data set strongly indicates that SST can be used as a single determinant for both WV and CF at 1^o by 1^o resolution, and with monthly time-averaging. The amount of scatter in the data is intrinsic at these scales, but the observed trends are consistent and clear. Considering that other models of cloud fraction are quite complex and incur deviations depending on the local conditions, the current correlational data for SST, WV and CF point to consistent and logical thermodynamic trends. Similar to SST-WV data, these trends are observed for all of the observed months during 2000 to 2017, as shown in Figure 4. However, there is an increasing data scatter as SST increases in the SST-CF

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plots. As noted above, cloud formation processes are quite complex starting from surface level moisture corresponding to SST, but involving upward and lateral convection, and altitude-dependent condensation (Nair and Rajeev, 2013). Nonetheless, as a first-order estimation of CF directly parameterized as a function of SST, current trends indicate a distinct two-fold CF behavior, below and above SST of approximately 300 K. In particular, a complete reversal in CF slope at high SST suggests that there may be an alleviating factor at this SST range.

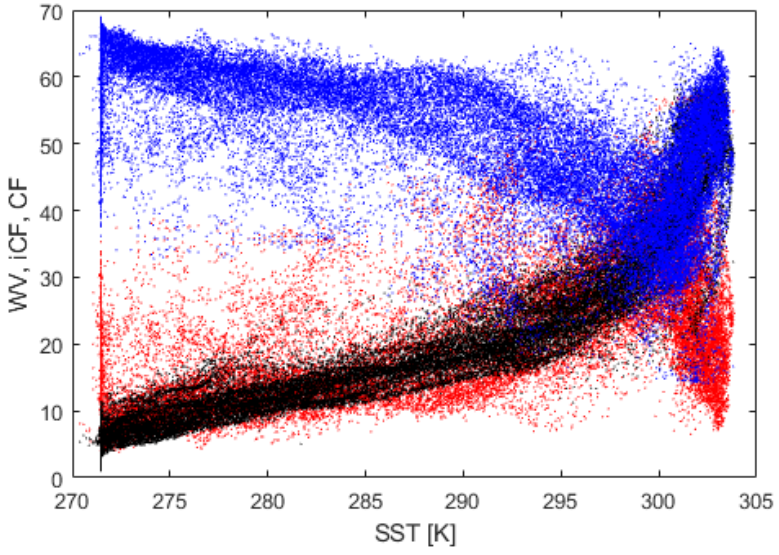

Figure 3. Relationship between WV (black), CF (blue) and inverted CF (red) vs. SST (May. 2007).

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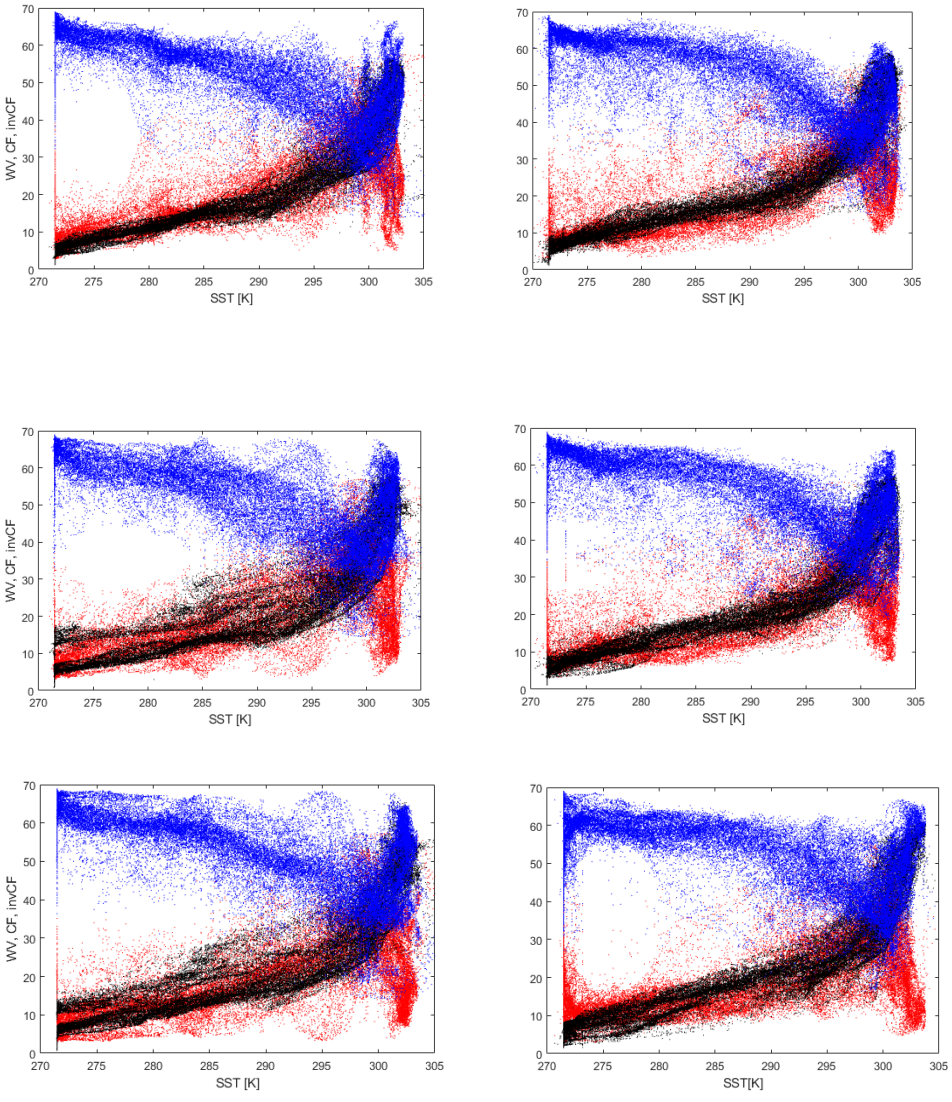

Figure 4. WV (black), CF (blue) and inverted CF (red) vs. SST scattergram for various months (from top left: October, 2000; April, 2003; August, 2007; April, 2013; December, 2015; and December 2019).

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In summary, when plotted as a function of SST, the cloud fraction is correlated with SST for SST > T_c due to over-saturation, but is anti-correlated when SST < T_c due to increasing saturation pressure. In spite of the fairly large scatter in the data, a set of quantitative correlations between SST [K] and WV [cm] or CF, as a first-order estimation, is attempted as follows:

$$WVa = 17.77 \times 10^{7} \exp(0.068 * (SST - 661.15)), \quad \text{for SST} < T_c \quad (1a)$$

$$WVb = -6.75 + 0.0215 (SST - 278.65)^2, \quad \text{for SST} > T_c \quad (1b)$$

$$CFa = 1.03125 - 2.22 \times 10^{7} * \exp(0.068 * (SST - 561.15)), \quad \text{for SST} < T_c \quad (2a)$$

$$CFb = -1 + 0.008125 (SST - 287.15)^2, \quad \text{for SST} > T_c \quad (2b)$$

T_c is taken as 300 K. The functionality of the correlation is demonstrated in Figure 5. The cloud fraction is an exact inversion of the water vapor trace for SST < T_c, and follows Clasius-Claperyon type of function (exponential, Eqs. 1a and 2a). However, for SST > T_c the steep increase in both WV and CF is better traced by quadratic curves (Eqs. 1b and 2b). As shown in Figure 4, these traces are replicated for most of the months in the data set. There is a fair amount of scatter in the data relative to the above correlations. At SST =285 K, the variances are +25/-9% for WVa and +6/-5% for CFa relative to the correlation functions (Ea. 1a and 2a). At SST=302K, the variances +11/-7% for WVb and +12/-20% for CFb, again relative to the correlations (Eqs. 1b and 2b). Stephens (1990) attributed approximately 20% to the large-scale flow effects, and the data variances are at about this level in the current observational data. Considerations of other variables have two facets of incorporating convection effects but also complicating the modeling process. Therefore, at this point we present the above correlations as a first-order modeling and analysis tool, while acknowledging the data variance to be considered in subsequent studies.

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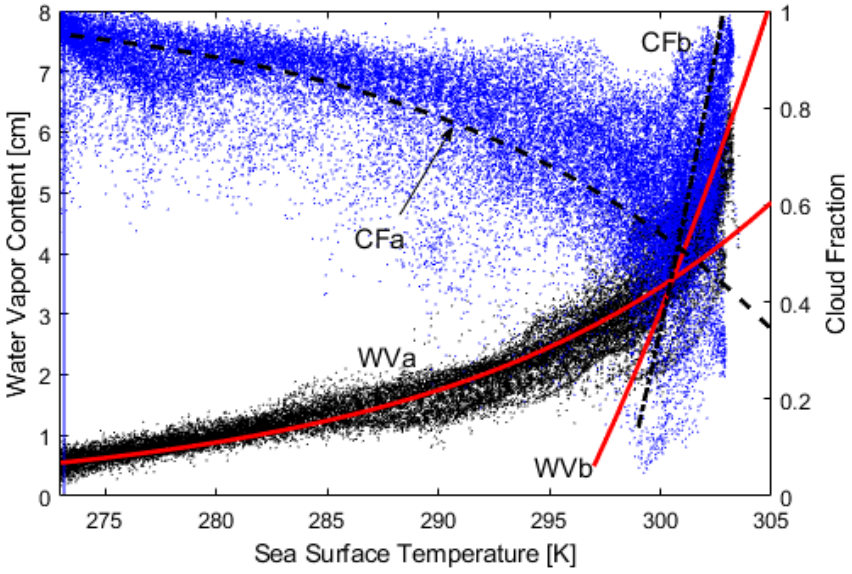

Figure 5. Correlational relationships (Eqs. 1 and 2) for WV [cm] and CF, as a function of SST.

4. CONCLUDING REMARKS

Water vapor content and cloud fraction both exhibit direct correlatability with the sea surface temperature, when averaged over 1° by 1° area on a monthly basis. A transition occurs at SST ~ 300 K, where the water vapor content sharply increases. Cloud fraction decreases with SST up to this transitional SST of 300 K. Then, it reverts to an increasing function of SST. These trends are quite repeatable over a fairly long time period, from 2000 to 2017, and parameterized as a function of SST (Eqs. 1 and 2). Thus, SST can be used as a primary determinant for the resulting atmospheric variables (WF and CF) at these spatial and temporal scales. There is a fair amount of scatter in the data (5 to 25%), relative to the mean relationships developed in this work, which is attributable to secondary effects such as convection and other local variations. Incorporation of these effects, using data sets at finer temporal and spatial scales, can be considered in future work.

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Preprint. Discussion started: 10 June 2026
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5. Data Availability

The data used in this work is available at https://doi.org/10.5281/zenodo.19389633 (Lee and Park, 2026).

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