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Short Contribution

Empirical Relationship between Sea Surface Temperature and Water Vapor: Improvement of the Physical Model with Remote Sensing Derived Data

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We have improved the previous model quantifying the bulk relationship between two key geophysical parameters, sea surface temperature (SST) and water vapor (WV) based on 14-year accumulated datasets. This improvement is achieved by the modification of the physical model derived by Stephens in 1990 and Gaffen *et al.* in 1992. With this improved model, we estimated WV between 2002 and 2004 using historical SST measurements. The estimated WV was compared with those derived from Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) observation and National Centers for Environmental Predictions (NCEP) reanalysis. Discrepancies of –1.16 mm and 3.19 mm with TMI- and NCEP-derived WV were obtained, respectively, suggesting a reliable retrieval of WV using the improved model. The improved model can potentially be used to calibrate and validate the WV measurements from other observations or model reanalyses, given that the accurate measurement of WV over a wide range of spatial and temporal scales has been a challenging task hitherto. Due to the limited time span of the current data, the temporal variation of WV in parts of the tropical oceans is not captured in this improved model, which we should study further with additional accumulation of SST and WV datasets in the future.

Keywords:
· SST,
· water vapor,
· empirical relationship.

1. Introduction

Water vapor (WV), one of the key geophysical parameters in the air-sea system, has attracted considerable interest during the past decades due to the critical role it plays in the climate. Two Chapman Conferences convened in 1994 and 1999 on WV in the climate system greatly stimulated WV related studies in the oceanic and atmospheric research community. The outstanding issues in WV research were summarized in a special report by the American Geophysical Union (AGU, 1995) as follows: 1) theoretical issue, including the role of WV in influencing the radiation budget of the Earth and the processes determining the distribution of WV and its changes over time; 2) observational issues, including the improvement of retrievals in WV profiles from satellites, and improvement and updating of radiosonde observations, as well as measurements in and around cloud systems; and 3) climate modeling issues, including improvements in the treatment of processes involving WV in climate models and the methods of testing the validity of climate models. During the past decade, the accumulation of WV data from a variety sources and sensors has provided opportunities to better address these issues. These data also allow further studies on WV acting as a major component of the global hydrological cycle and as a greenhouse gas, as well as the variability of WV at different spatio-temporal scales in the climate system.

The rich datasets accumulated make it possible to address another important issue, the relationship between WV and SST, an important topic related to the stability and sensitivity of the climate system (Sun and Held, 1996). To the best of our knowledge, the first systematic study of this relationship was carried out in 1990 by Stephens (1990, hereafter abbreviated S90) based on 52-month concurrent observations of SST and WV spanning May 1979 through September 1983, resulting in an equa-

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tion quantifying the bulk relationship in a purely physical sense. In 1992, Gaffen *et al.* (1992, hereafter abbreviated G92) further confirmed this relationship. Sudradjat *et al.* (2005) extended this work by comparing the spatiotemporal variability patterns between SST and WV. More recently, the study of this relationship was further advanced by Shie *et al.* (2006) using 11-month Goddard Earth Observing System (GEOS-3) data. All these papers supported a positive relationship between SST and WV in the troposphere in general. However, the estimation of WV from SST observations based on the purely physical equation between them proposed by S90 and G92 cannot be used to produce a result that is close to the observed measurement, because of the sensitivity of WV to atmospheric circulation (S90, G92).

The accumulation of data in records, improvements in resolution and quality, and the extended coverage both for WV and SST from numerous sources provide an unprecedented opportunity to improve this relationship. The purpose of this paper therefore is to improve the equation describing this relationship proposed by S90 and G92 making use of the accumulated datasets on the basis of an empirical study, in order to obtain an accurate estimate of WV using SST alone. To this end, we collected and compiled 14-year (1988–2001) simultaneous measurements of WV and SST to derive the spatial distributions of two parameters, which were considered constant by S90 and dependent on SST by G92. We then estimated 3-year WV over the oceans between 40°S and 40°N based on the two derived parameters. We hope our improvement on the physical equation will benefit our understanding of the systematic error observed in the atmospheric moisture fields in current general circulation models and help us to examine the past climate condition through estimation from historical SST datasets. The estimated WV provided by this improved model also has the potential to calibrate and validate the WV data derived from satellite observations and numerical reanalysis.

The paper is organized as follows. Data used in this study are presented in the next section. In Section 3 we improve the equation quantifying the bulk relationship suggested by S90 and apply it to estimate WV for 2002–2004. The estimated WV is then compared with those derived from the purely physical model, the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) observations, and the National Centers for Environmental Predictions (NCEP) reanalysis. Concluding remarks are given in Section 4.

2. Data

Four datasets from different sources have been used in this study. We describe them in detail as follows.

1) NVAP columnar WV dataset. National Aeronautics and Space Administration (NASA) Water Vapor Project (NAVP) (Randel *et al.*, 1996) datasets comprise a combination of radiosonde observations, Television and Infrared Operational Satellite (TIROS) Operational Vertical Sounders (TOVS), and Special Sensor Microwave/Imager (SSM/I) datasets. To date, these are the best observations available for WV. We first extracted 12-year (1988–1999) monthly $1° \times 1°$ gridded columnar WV data and 2-year (2000–2001) monthly $0.5° \times 0.5°$ next generation gridded WV data from the NVAP WV products. To obtain 14-year (1988–2001) monthly $1° \times 1°$ gridded WV data, the next generation data were resampled to a $1° \times 1°$ grid. Finally, the NVAP monthly gridded WV dataset over the ocean is compiled so that it can be collated with the SST observations during the same period.

2) Reynolds *et al.* (2002) SST dataset. Monthly SST data of the ocean at a $1° \times 1°$ grid are derived from Physical Oceanography Distributed Active Archive Center (PO DAAC), NASA. The NCEP Reynolds Optimally Interpolated SST Version 2 (OISST V2) products consist of weekly and monthly global SST fields, which blends both *in situ* and AVHRR satellite derived SSTs. The satellite-derived SSTs are from the Multichannel SST products, which have been constructed operationally from the five-channel Advanced Very High Resolution Radiometer by NOAA's Environmental Satellite. A 14-year dataset from January 1988 to December 2001 has been compiled in this study to collate with the simultaneous measurements of WV. Another 3-year dataset covering 2002–2004 has also been extracted and later used to estimate WV fields using our improved model quantifying the bulk relationship between SST and WV. Therefore, a total of 17 years of monthly SST data has been used in this study.

3) TMI-derived columnar WV dataset. Note that WV data from NVAP are available only for 1988–2001, with none existing after 2001. To evaluate the improvement of our new approach to estimating WV, a 3-year WV dataset spanning 2002 through 2004 from TMI (http://www.ssmi.com/tmi) at $1° \times 1°$ grid has been employed. The WV data from TMI are retrieved by the same algorithm as used in SSM/I (Wentz, 1997). Appropriate adjustments have been made to account for small differences in GHz between the TMI and SSM/I channels, due to the fact that TMI WV is measured at 21 GHz rather than 22.235 GHz as in all SSM/I.

4) NCEP reanalysis columnar WV dataset. The National Centers for Environmental Predictions (NCEP) reanalysis project utilizes a state-of-the-art analysis/forecast system to perform data assimilation using past data from 1948 to the present (Kistler *et al.*, 2001). Key geophysical parameters from this reanalysis project have been extensively used in the research community. It is worth noting that the surface WV derived from NCEP is not the surface WV value, but rather WV for the entire atmospheric column. Monthly WV values on a $2.5° \times 2.5°$ grid,

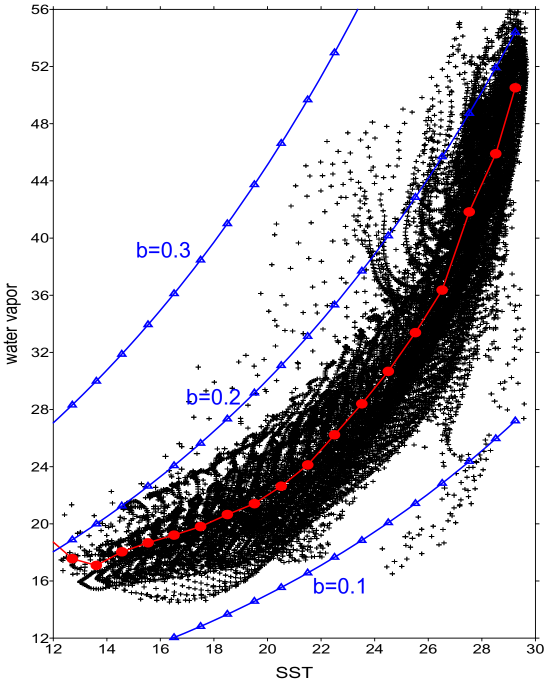

Fig. 1. Scatter plot of the relationship between SST (°C) and WV (mm) derived from 14-year climatologically collated data of SST and WV. The red curve with red dots presents the observed statistical relationship between them, while the blue curves with blue triangles show the statistical relationship between SST and WV derived from Eq. (1) for the stated values of $b = r/(1 + \lambda)$ and $a = 0.064k^{-1}$.

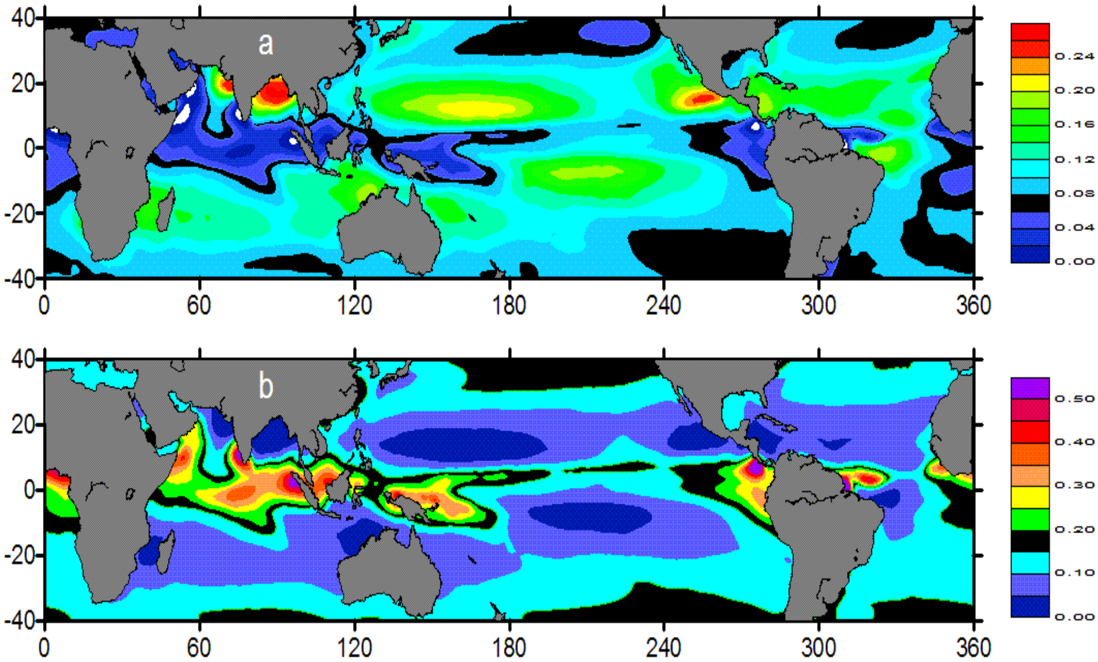

Fig. 2. The geographical distributions of variable (a) a, (b) $b = r/(1 + \lambda)$ for Eq. (2). The shaded black zones in (a) and (b) highlight the range $a = 0.06$~$0.08k^{-1}$and $b = 0.15$~0.20, where the values for $a = 0.064k^{-1}$ and $b = 0.162$ suggested by Stephens (1990) are located.

spanning 2002 through 2004, have been used in this study, serving a similar purpose as the TMI data so that they can be compared with the estimated WV from our improved model.

In summary, a 14-year simultaneous dataset of WV from NVAP and SST from OISST V2 covering 40°S–40°N, 0°E–360°E has been compiled from January 1988 to December 2001, which contains 168 monthly collated fields and 21739 grids at 1° × 1° level. This dataset is used to deduce the two parameters described in Section 3. Another 3-year (2001–2004) simultaneous dataset of SST, WV from TMI and NCEP is used to evaluate the improved model in terms of its capability to estimate WV using SST alone.

3. Improved Model

Studies on the relationship between WV and SST can be dated back to the 1960s (e.g., Reitan, 1963; Smith, 1966), but the first detailed investigation of the relationship was carried out by S90, who proposed the follow equation based simply on the well-known Clausius-Clapeyron relationship:

$$w = 10.82\left(\frac{r}{1+\lambda}\right)e^{a\left(T_s - 288\right)}, \tag{1}$$

where w (g/cm^2, 1 g/cm^2 = 10 mm WV) is the WV integrated from zero atmospheric pressure to the surface atmospheric pressure, and T_s is SST (Kelvin, 0°C = 273.15 K); r refers to the relative humidity, λ to a parameter describing the ratio between the atmospheric scale height and WV scale height, and a to a constant parameter ($a \approx 0.064$ K^{-1}). This relationship proposed by S90 was further confirmed by G92 in the form of an alternative equation, $\ln(w) = A + BT_s$, where A and B are two coefficients. According to S90, the value of $r/(1 + \lambda)$ should also be a constant (designated b hereafter). This constant, revealing a purely physical relationship between SST and WV, however, cannot be used to actually represent the observed relationship between SST and WV (S90). This statement is reconfirmed by the three examples based on our collated 21739 SST and WV grids over the ocean in climatological sense, with $b = 0.1$, $b = 0.2$ and $b = 0.3$ as presented in Fig. 1. By least squares fitting of 52-month WV and SST observation at a global level, S90 deduced a value for $b = 0.162$. Unlike S90, who indicated that $a = 0.064k^{-1}$, G92 suggested that coefficients A and B are dependent on T_s, which suggests that a in Eq. (1) is not constant either, because T_s varies spatially. Nevertheless, no detailed information on obtaining parameters A and B and how they change with T_s were provided by G92, due to the limitation of data availability at the time the research was conducted.

A number of phenomena might produce patterns at regional scale, resulting in departures from the gross purely physical relationship described in Eq. (1). Therefore, the use of two constant parameters, a and b, to estimate the WV field over large horizontal scale using SST observations may fail. For example, low-level moisture convergence tends to occur in the vicinity of the intertropical convergence zone (ITCZ), producing regions of above average moisture. Meanwhile, advection of moist air into a relatively dry region may also act to enhance the vapor content of that region. Taking advantage of the relatively high sensitivity of WV to large-scale circulation, S90 used the WV estimated from SST and the observed WV to produce a regional deviation, and highlighted the effects of large-scale motions on WV.

To achieve a relatively accurate estimation of WV using SST alone, we proposed an improved model based on the simple relationship embedded in Eq. (1), expressed as follows:

$$w = 10.82b(x,y)e^{a(x,y)\left(T_s - 288\right)}, \tag{2}$$

where w and T_s denote the same variables expressed in the same units as those in Eq. (1). However, a and b, the two previously constant parameters, now vary in space even though they still remain constant in time. x and y are the zonal and meridional locations of a grid, respectively, implying that a and b are spatially dependent over the oceans. We calculated the values of a and b at each grid using 168-month simultaneous measurements of WV and SST by the least squares fitting of these time series measurements for each grid. The horizontal distributions of a and b over the 21739 collated grids are shown in Fig. 2.

Both parameters exhibit heterogeneity throughout the entire study area, even though the values of SST for most of grids are above 15°C, a threshold given by S90 above which the bulk relationship in Eq. (1) was supposed to be more stable than that with a SST below it. The distribution of a and b presents a zonally banded structure in general. The values of a vary widely from $0k^{-1}$ to $0.26k^{-1}$, and only a small portion of the oceans lie within the range between 0.06~$0.08k^{-1}$ (shaded black in Fig. 2(a)), where the constant $a = 0.068k^{-1}$ suggested by S90 falls. High values are distributed in two zonal bands located between 10° and 20° in two hemispheres. A maximum is observed in the Bay of Bengal and part of the Arabian Sea, while a minimum is apparent mainly in the tropical Indian Ocean and western Pacific (Fig. 2(a)). As far as the distribution of b is concerned, a generally opposite structure to a is observed (Fig. 2(b)). The constant b value (0.162) suggested by S90 is within the range 0.15~0.20 and is highlighted in black; this also occupies only a small area of

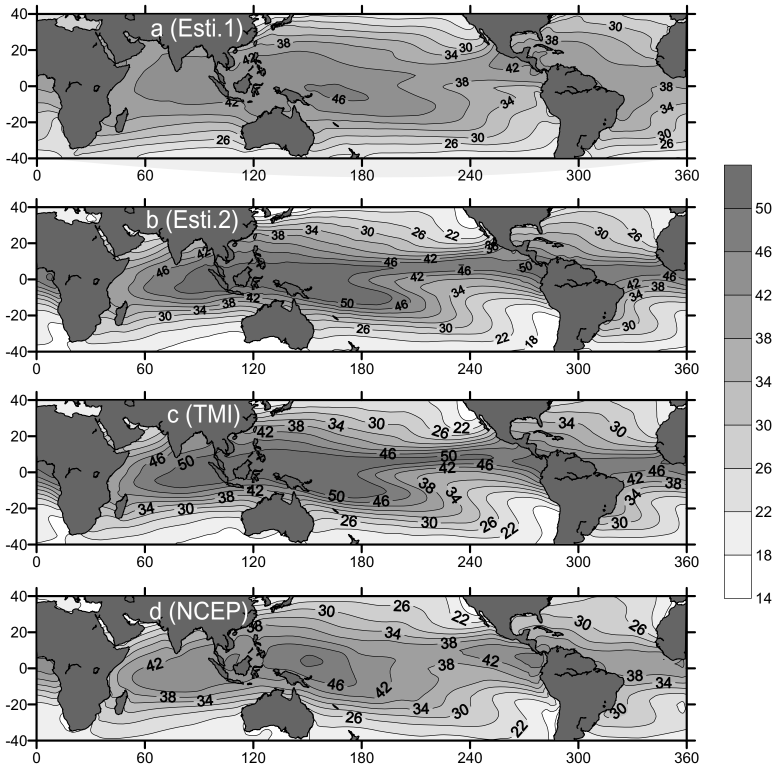

Fig. 3. Geographical distributions of WV (mm) for 3-year mean during 2002–2004 derived from (a) estimation using Eq. (1), (b) estimation using Eq. (2), (c) TMI observation, and (d) NCEP reanalysis. The contour interval is 4 mm.

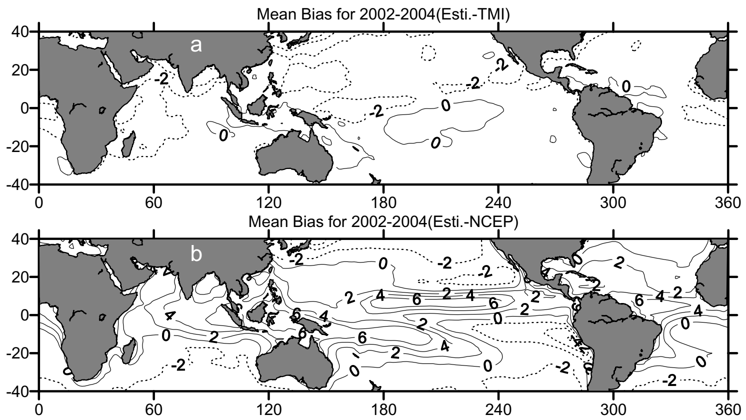

Fig. 4. Map of difference between (a) Figs. 3(b) and (c), and (b) Figs. 3(b) and (d). The thin solid and dotted curves denote the positive and negative contours, respectively. The contour interval is 2 mm.

the oceans. The interesting distributions of *a* and *b* have raised some challenging questions for future research in this field, such as what physical meaning these parameters *a* and *b* really represent, what forces have influenced the formation of their spatial patterns, and whether their distributions are associated with the composite effects of large-scale circulation and regional motion of vapor content.

To evaluate the accuracy of the improved model, the WV mean field estimated from SST by using Eq. (2) is compared with those derived from the original physical model (Eq. (1)), TMI, and NCEP for 2002–2004 (Fig. 3). It is observed that our estimated and TMI-derived WV fields are very similar in both spatial structure and value

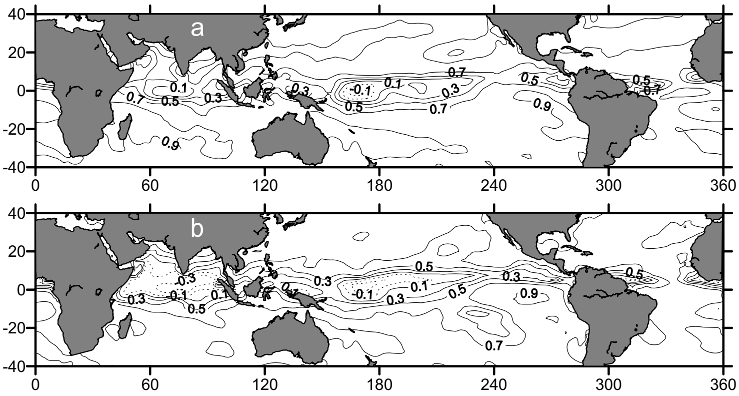

Fig. 5. Temporal correlation maps between (a) TMI-derived and estimated WV, and (b) NCEP-reanalyzed and estimated WV during 2002–2004. The estimated WV is derived from our improved model. The thin solid and dotted curves denote the positive and negative contours, respectively. The contour interval is 0.2.

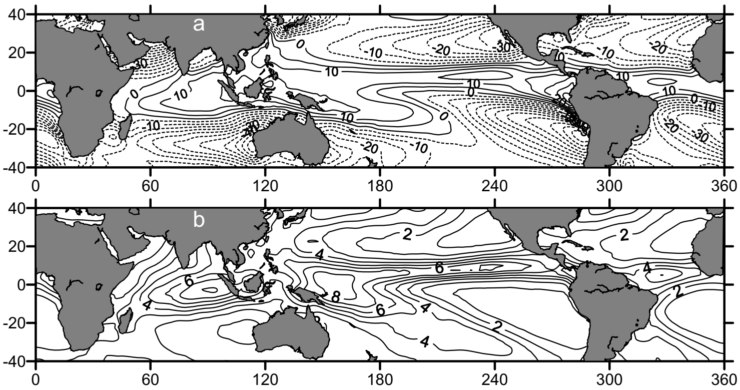

Fig. 6. Maps of (a) difference of estimations of WV between using Eq. (2) with variable a and b, and using Eq. (1) with constant $a = 0.057k^{-1}$, $b = 0.181$, and (b) precipitation (mm/day) derived from GPCP during 2002–2004. Values (in percent) in (a) is derived from $(W_v - W_c)/W_v \times 100$, where W_v and W_c denote the estimated WV with variable a and b, and constant a and b, respectively. The solid and dotted curves in (a) represent positive and negative contours, respectively. The contour intervals in (a) and (b) are 5% and 1 mm/day, respectively.

range (Figs. 3(b) and(c)), with a small discrepancy in the tropical Western Hemisphere region where the TMI derived WV is higher than the estimate. The difference between our estimated and NCEP derived WV is a little larger, with NCEP derived values usually lower, although they follow a similar general pattern of spatial distribution. From a visual comparison between WV estimation from the pure physical model (Fig. 3(a)) and our model (Fig. 3(b)), we can see that a significant improvement has been achieved with the new model in both spatial structure and value range. To quantify the discrepancy between our estimated and TMI and NCEP derived WV fields, the differences between Figs. 3(b) and (c), and between Figs. 3(b) and (d) are plotted respectively in Fig. 4. As can be seen, the bias of our estimated WV relative to TMI varies from –6 mm to 4 mm and our estimation are slightly drier (yellow) than TMI measurements over a majority of oceans and are wetter (orange) over the Indonesian Sea and the ocean east of Australian (Fig. 4(a)). A slightly larger estimation bias relative to NCEP is observed (Fig. 4(b)), with dryness in NCEP appearing in convective regions, probably due to the deficiencies in shortwave radiation and boundary layer parameterizations of the NCEP reanalysis model (Betts *et al.*, 1996; Bony *et al.*, 1997). The domain-averaged biases relative to the TMI and NCEP are –1.16 mm and 3.19 mm, respectively. The corresponding temporal correlation at the monthly level between TMI and our estimated WV (Fig. 5(a)), and between NCEP and our estimated WV (Fig. 5(b)) during 2002–2004 have also been calculated. As can be seen from both figures, the vast majority of the oceans are positively correlated with high correlation coefficients, while only a few small areas over the equatorial regions have low positive or negative values. This improved model is able to explain temporal variations for most of the regions, except in parts of the tropical oceans, maybe due to the limited time series involved. It is also observed that the regions with low correlation values have low value of a (Fig. 2(a)), suggestive of a weak dependence of WV on SST over these regions. This model may be further improved if a longer time span of SST and WV data accumulation is available in the future, so that both the spatial and temporal variation of these two parameters in Eq. (2) can be explored simultaneously.

S90 suggested that, by subtracting the SST-estimated WV using constant coefficients a and $b = r/(1 + \lambda)$ in Eq. (1) from the observed WV, one can reveal a spatial pattern of moist air convergence and/or advection zones in the tropical ocean. By least squares fitting of 52-month measurements of SST and WV, S90 deduced the values for coefficients a and b of $a = 0.0686k^{-1}$, $b = 0.162$ for T_s above 15°C. In the same manner, by treating a and b as constants, we derived $a = 0.057k^{-1}$ and $b = 0.181$ by fitting our 168-month simultaneous measurements for SST and WV at domain-averaged level for T_s above 15°C. To examine the capability of our improved model, which utilizes varying a and b, in its capability to resolve patterns of moist-air convergence and/or advection zones in the atmosphere, the difference between Fig. 3(b) (model with two varying parameters) and Fig. 3(a) (model with our newly derived constants) is obtained and presented in Fig. 6(a). Positive differences coincide with regions of enhanced upward moisture flux due to moist-air convergence and/or advection (see Prabhakara *et al.*, 1979). In contrast, the negative differences are associated with regions of subsidence and/or dry-air advection. This difference clearly demonstrates the pattern of "WV pool", ITCZ and SPCZ with the convective and wet-air advective zones, and it also better delineates the subsidence regions off the west coasts of North and South America and African continent. The pattern in Fig. 6(a) also matches well with the precipitation pattern (Fig. 6(b)) derived from Global Precipitation Climatology Project (Huffman *et al.*, 1997) during the same 3-year period. The convective zones are observed mainly in the rain pool region, where the highest rainfall is identified; and the subsidence regions are located in the marine deserts, where little rainfall occurs. Like NVAP and European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyzed WV, the newly estimated WV from our improved model can be used to detect the large-scale vapor motion in the atmosphere (Sudradjat *et al.*, 2005).

4. Concluding Remarks

The physical model describing the bulk relationship between SST and WV deduced from the Clausius-Clapeyron equation in S90 cannot be used to retrieve an accurate WV field using SST alone because of the motion of vapor in the atmosphere. In this study we took advantage of 14-year simultaneous measurements of SST derived from OISST V2 and WV from NVAP, which blend the best available observations of SST and WV from satellite sensors to date, to improve the physical model in order to achieve a better estimation of WV using SST. Two parameters a and b, considered as constant in S90 or dependent on SST range by G92, were treated as varying in space but constant in time in this study. These two parameters were derived on the basis of 168-month simultaneous measurements of SST and WV by least squares fitting for each grid. Based on the improved model utilizing spatially varying parameters, we estimated 3-year WV fields for 2002–2004 and compared the results with those retrieved from the purely physical model, TMI measurements and NCEP reanalyses. The results are encouraging, producing much better estimates than the traditional physical model. The improved model also demonstrated the capability to reflect the spatial pattern of moist air convergence and/or advection zones in the tropical oceans. Additionally, this new model provides an alternative approach to estimating the WV data over a wide spatial and temporal scale, and can be utilized to calibrate and validate the WV fields from satellites or reanalysis from other models.

A future improvement to our model will be the investigation of the temporal variation of a and b. Due to the limited availability of time series data for SST and WV at present, we were not able to examine the complete spatio-temporal variation of parameters a and b. We hope, with the accumulation of more SST and WV records in the future, to further improve our new model.

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