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Decadal changes in tropical convection suggest effects on stratospheric water vapor

George Tselioudis,[1,2] Eric Tromeur,[3] William B. Rossow,[3] and C. S. Zerefos[2]

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[1] Analysis of satellite observations of tropical Weather States derived from a cluster analysis of ISCCP cloud property retrievals, shows that the deep convection Weather State increased in frequency from 1983 to about 2000 and remained at a nearly constant level after that. The sharpest deep convection increase occurred between 1993 and 2000. This convection variability is driven by changes that occur in the Indian Ocean and the Western-Central Pacific regions, which are the regions where the majority of deep tropical convection occurs. Analysis modifications to account for satellite coverage changes during the period under examination do not alter these findings. Previous studies showed that stratospheric water vapor increased from 1980 to 2000 and dropped after that to lower levels that persist until today, and that this change could explain part of the recent global temperature variability. Since tropical deep convection is an important mechanism affecting stratospheric water vapor concentrations, the observed decadal changes in tropical deep convection could explain in part the stratospheric water vapor variability patterns. **Citation:** Tselioudis, G., E. Tromeur, W. B. Rossow, and C. S. Zerefos (2010), Decadal changes in tropical convection suggest effects on stratospheric water vapor, *Geophys. Res. Lett.*, *37*, L14806, doi:10.1029/2010GL044092.

1. Introduction

[2] In a recent study [*Solomon et al.*, 2010], satellite and balloon measurements were used to document stratospheric water vapor changes in the past 30 years. The study found that from 1980 to about 2000 stratospheric water vapor concentrations increased by about 1 part per million by volume (ppmv), while there was a drop of about 0.4 ppmv thereafter. The study then adopted these changes into a radiative-transfer model and concluded that changes of that magnitude could slow the rate of global surface temperature increase by 25% after 2000 and enhance the rate by 30% from 1980 to 2000.

[3] Stratospheric water vapor concentrations are affected by both radiative and dynamic processes. The basic balance in the lower stratosphere is between radiative heating and adiabatic cooling due to upwelling [e.g., *Rosenlof and Reid*, 2008; *Corti et al.*, 2005; *Gettelman et al.*, 2004]. This balance determines the temperature at which air enters the stratosphere and therefore the air's moisture content. The extreme cold of the tropical upper troposphere freezes out most of the water at the point of minimum temperature ("cold point") thus preventing it from entering the stratosphere [*Mote et al.*, 1996; *Rosenlof and Reid*, 2008]. Tropical deep convection significantly affects both tropical radiative heating as well as adiabatic cooling through it's impact on planetary wave activity [e.g., *Kerr-Munslow and Norton*, 2006]. At the same time, it constitutes the primary mechanism that supplies water to the tropical upper troposphere where it is in a position to rise to the lower stratosphere. It is clear, therefore, that tropical deep convection can significantly affect the distribution and variability of water within the lower stratosphere [e.g., *Solomon et al.*, 2010; *Rosenlof and Reid*, 2008].

[4] The International Satellite Cloud Climatology Project (ISCCP) provides a 25-year climatology of cloud properties [*Rossow and Schiffer*, 1999]. The ISCCP D1 dataset includes global retrievals of cloud optical thickness (TAU) and cloud top pressure (PC) starting in July 1983. Thresholds of TAU and PC are used in the dataset to define nine different cloud types, one of which is deep convective clouds. This method of definition of tropical convection introduces uncertainties into the study of global, long-term deep convection trends, as small shifts across the imposed TAU and PC thresholds would be interpreted as changes in deep convective cloud amounts. A recent study [*Rossow et al.*, 2005] applied a clustering algorithm to the daily ISCCP PC-TAU histograms and allowed the algorithm to define the major weather states from the morphology of the complete PC-TAU field. The cluster analysis found six major weather states (WS) for the global tropics (15S-15N). One of them is the deep convection WS that includes the larger mesoscale convective systems, which in turn encompass convective clouds that reach the Tropical Tropopause Layer or penetrate into the lower stratosphere [*Rossow and Pearl*, 2007]. The deep convection WS exhibits all the well-known tropical modes of variability such as EL Nino and the Madden-Julian Oscillation (MJO) [*Rossow et al.*, 2005; *Jakob and Tselioudis*, 2003; *Jakob et al.*, 2005; *Tromeur and Rossow*, 2010]. The deep convection WS lends itself better to the study of decadal convective activity changes, as it depends on the morphology of the full range of cloud optical properties and does not depend on pre-imposed cloud property thresholds. Therefore, time and space changes in the Weather State are less sensitive to satellite calibration, data sampling, and sample size issues.

[5] In this study, we examine the time series of the tropical deep convection WS for the period from July 1983 to June 2008. The primary objective is to document how tropical

[1]NASA Goddard Institute for Space Studies, Columbia University, New York, New York, USA.
[2]Centre for Atmospheric Physics and Climatology, Academy of Athens, Athens, Greece.
[3]CREST, NOAA, City University of New York, New York, New York, USA.

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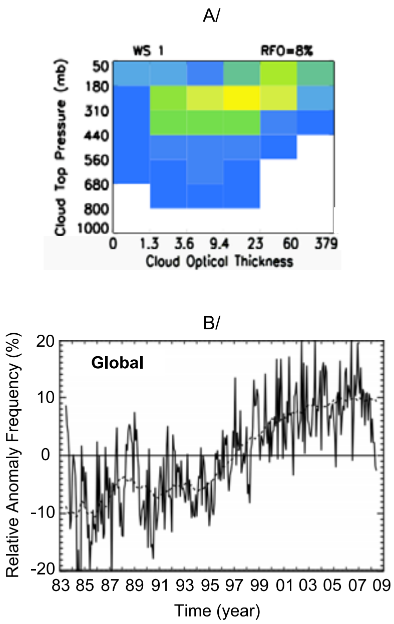

Figure 1. (a) Cloud top pressure (PC) – optical thickness (TAU) frequency histogram pattern for deep convection (called Weather State 1 - WS1), derived from 3-hourly variations of cloud properties in 2.5 latitude-longitude regions covering the whole tropics (±15 latitude) for 25 years (1983–2008) from ISCCP data [from *Rossow et al.*, 2005]. (b) Monthly-mean time series of WS1 for the global tropics and for the time period from July 1983 to December 2008. The time series is expressed as a percent relative deviation from the long-term mean occurrence of WS1 (8%), after the seasonal cycle is removed. The dashed line is a three- year running mean of the plotted data.

convective activity changed during that 25-year time period. Potential effects of those changes on the variability of lower stratospheric water vapor are discussed.

2. Results

[6] The cloud property distribution pattern of the deep convection WS (WS1) for the global tropics (15S-15N) is shown in Figure 1a by the TAU-PC frequency histogram. The histogram shows the dominance in WS1 of optically thick, high-top clouds, which represent organized mesoscale convection, and the presence of considerable amounts of optically thinner, high and middle top clouds. Note that the WS1 Relative Frequency of Occurrence is 8%. This implies that, in the 25-year time period, 8% of the time that a tropical ISCCP grid box (2.5 degrees in size) is occupied partially or totally by clouds the TAU-PC cloud structure is a deep convective one similar to WS1. The time series of WS1 for the global tropics and for the time period from July 1983 to June 2008 is shown in Figure 1b. The time series is expressed as a percent relative deviation from the long-term mean occurrence of WS1 (8%), after the seasonal cycle is removed. The plot shows a distinct pattern that consists of an increase in the occurrence of deep convection from 1983 to about 2000 followed by a reduction of the rate of increase from 2000 to 2008. The sharpest increase occurs in the period from 1994 to 2000. The overall difference in WS1 occurrence between the 1983–2000 and the 2000–2008 periods is about 20% relative (or 1.6% absolute), implying a significant change in the frequency of occurrence of deep convection in the tropics.

[7] The WS1 time series for seven tropical regions, namely Africa (0–45E), the Indian Ocean (45–105E), West Pacific (105–150E), Central Pacific (150–200E), East Pacific (200–280E), South America (280–315E), and the Atlantic (315–360E) were examined separately and are shown in Figure 2. Figure 2a shows the time series for the three regions (Indian Ocean, Western and Central Pacific) that show the largest frequency of occurrence of WS1 (17.37%, 18.28%, and 19.99% of the WS1 tropical mean respectively), while Figure 2b shows the four regions (East Pacific, South America, Atlantic, and Africa) with the smallest WS1 frequency of occurrence (14.54%, 12.32%, 7.29%, and 10.21% respectively). The time series are once again expressed as percent deviations from the long-term mean occurrence of WS1 (8%), after the seasonal cycle is removed. Inspection of the plots indicates that the three regions on Figure 2a include generally lower deep convection frequencies in the 1980s and 1990s and higher ones after 2000, showing a variability pattern similar to the one for the global tropics (Figure 1b). The four regions on Figure 2b show very weak variability patterns with no distinct features, with the exception of the Eastern Pacific which shows pronounced peaks in the El Nino years of 1988, 1992, and 1998. El Nino signals are also present in the Indian Ocean and the West and Central Pacific regions, but there the prevailing feature is one of overall lower values before 2000 and higher values after that. Linear correlation statisticss between the global tropics (Figure 1b) and the regional time series shows that the three regions in Figure 2a together explain 84% of the global tropical variability. In particular, the Indian Ocean explains 49%, the West Pacific 23%, and the Central Pacific 12% of that variability. The four time series on Figure 2b explain together 16% of the global tropical variability, with the highest one (South America) explaining about 7%. It must be noted that the three regions responsible for the majority of the global-tropics variability are also the regions where the maximum frequency of penetration of "cloud sized" particles into the stratosphere occurs [*Liu and Zipser*, 2005; *Rossow and Pearl*, 2007], while the Central Pacific is the region where the maximum correlation occurs between stratospheric entry values of water vapor and cold point temperatures [*Solomon et al.*, 2010].

[8] When examining time series of satellite retrievals, it is important to investigate potential uncertainty sources related to known changes in the satellite data input to the retrieval algorithm. One such change, known to be affecting significantly the Indian Ocean sector examined in this study, is the inclusion in 1998 of an additional geostationary satellite in the ISCCP input data stream that covers this particular sector. This addition changes the sampling in the region and may be responsible for the jump in 1998 of the WS1 global anomaly time series (Figure 1b). In order to test the sensitivity of the global tropics result to the satellite change, the analysis was repeated with the Indian Ocean sector data excluded. The global tropics WS1 time series with the Indian Ocean data removed is shown in Figure 3, expressed as percent deviations from the long-term mean of the modified WS1 after the seasonal cycle is removed. It can be seen that the curve exhibits the same main features as before, with the increasing trend from 1983 to 2000 and the flattening of the trend from 2000 to 2008, and with relative anomaly value differences of

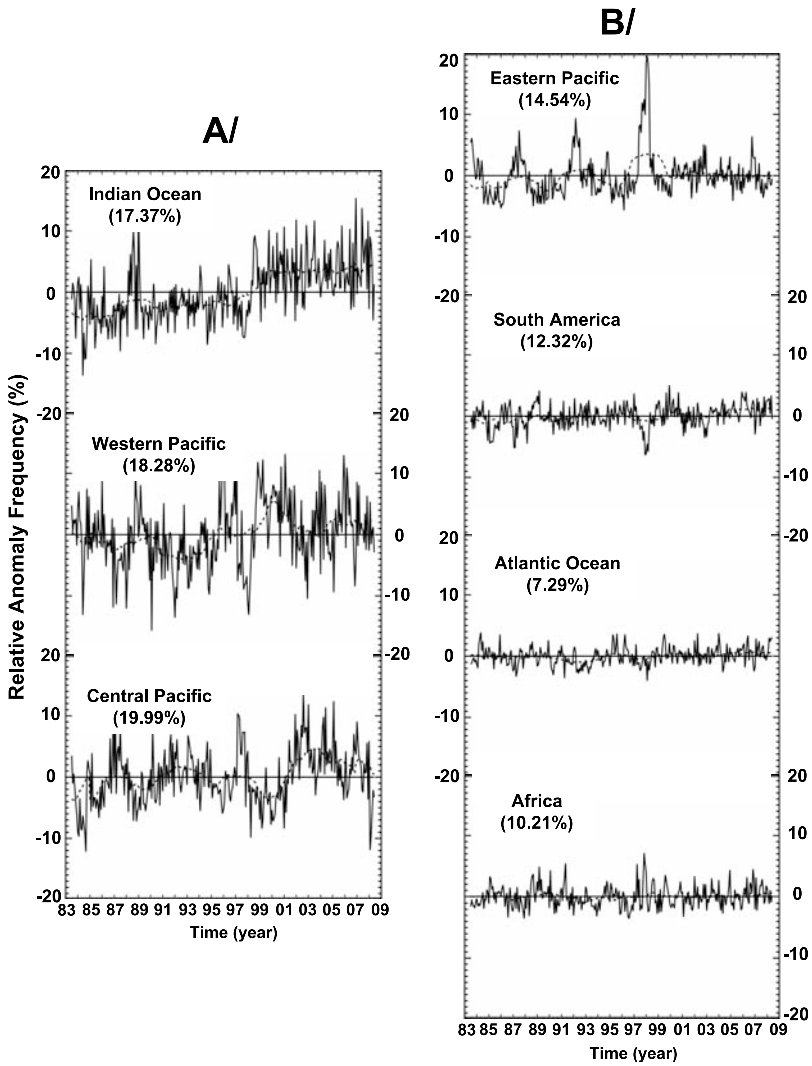

Figure 2. (A) Monthly-mean WS1 time series for the Indian Ocean (45–105E), West Pacific (105–150E), and Central Pacific (150–200E), and (b) the WS1 time series for East Pacific (200–280E), South America (280–315E), the Atlantic (315–360E), and Africa (0–45E). The time series are expressed as percent deviations from the long-term mean occurrence of WS1 (8%), after the seasonal cycle is removed. The fraction of the global WS1 occurrences covered by each region are noted on each plot. The dashed lines are three-year running means of the plotted data.

about 20% between the former and the latter periods. In this reworked time series, the Central Pacific is now the section explaining the largest part of the remaining global tropics variability (28%), while the West Pacific explains 22% of the variability.

3. Discussion

[9] The results presented in this study show that tropical convective activity increased from 1983 to about 2000 and remained at a nearly constant level after that, with the sharpest increase occurring between 1993 and 2000. At the same time, the results of *Solomon et al.* [2010] show an increase of stratospheric water vapor from 1980 to about 2000 and a drop after the year 2000 to lower levels that persist up to the present. Furthermore, an analysis of tropical radiosonde data showed that the tropical cold point temperature dropped significantly between 1993 and 2001 [*Rosenlof and Reid*, 2008]. A close similarity of patterns exists between the time series of cold point temperature and stratospheric water vapor on the one hand and tropical deep convection on the other, for the time period between 1983 and 2000 (the deep convection time series does not show a year-2000 drop but does show an end of the sharp increasing trend at about that year). Given the potential of convective activity to influence the processes that determine stratospheric water vapor amounts, the similarity of these patterns derived from completely independent data-sets suggests that deep convection changes could explain (at least part of) the recent stratospheric water vapor variability.

[10] The potential influences of tropical deep convection on stratospheric water vapor are complex, as the underlying processes can be both radiative and dynamical. Intensified convective activity would cause radiative cooling and thus would act to reduce the terrestrial infrared contribution to the stratospheric heat budget [*Rosenlof and Reid*, 2008]. Strato-spheric cooling can also be the result of upward motion associated with the Hadley or the Walker circulations [*Reed and Vleck*, 1969]. At the same time, deep convection is the

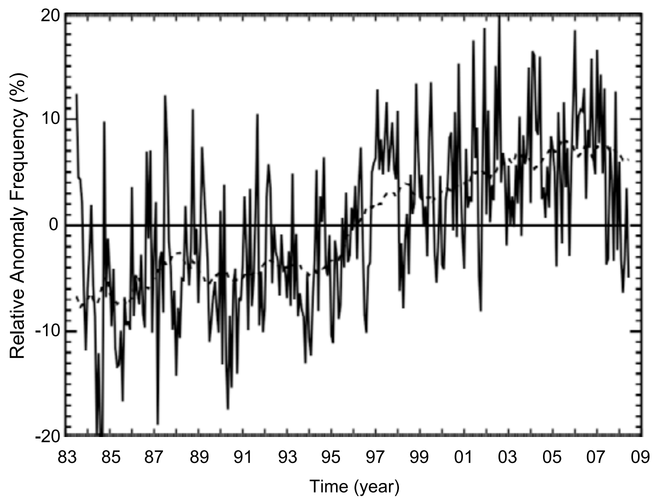

Figure 3. Monthly-mean global tropics WS1 time series with the Indian Ocean data removed, expressed as percent deviations from the long-term mean of the modified (by the removal of the Indian Ocean data) WS1 after the seasonal cycle is removed. The dashed line is a three-year running mean of the plotted data.

main source of tropical upper tropospheric moisture, and this moisture becomes available for transport into the lower stratosphere either through slow lifting processes or through the direct action of deep penetrating convective towers. Such deep penetrating convective towers occur as parts of the organized mesoscale convective systems that are included in the deep convection WS analyzed in this paper [*Rossow and Pearl*, 2007]. The majority of those deep convective systems occur in the Western Pacific – Indian Ocean sector [*Rossow and Pearl*, 2007]. However, an analysis of the time series of convective clouds penetrating into the lower stratosphere (results not shown) did not show any significant long term trends, indicating that potential convection influences on stratospheric water vapor trends come from the overall moistening of the tropical upper troposphere rather than from direct transport by convection penetrating in the lower stratosphere.

[11] The early period (1983–2000) upper tropospheric moisture increase suggested by the present study, is also supported by the study of *Chen et al.* [2002] which examined Reanalysis and High-Resolution Infrared Radiation Sounder (HIRS) data and found strengthening of the tropical Hadley and Walker circulations and increases in upper tropospheric moisture in the 1990s compared to the 1980s. The mechanisms through which the observed changes in convective activity influence the supply of moisture in the lower stratosphere remain to be examined. At the same time, the reasons for the increase in convective activity from 1983 to 2000 and the flattening of the upward trend after that need also to be understood, as those changes are a potential source of significant climate feedbacks both through stratospheric and tropospheric processes. The overall trend of tropical convective activity, with lower intensities in the 1980s and 90s and higher intensity after 2000 may be related to the phases of the Pacific Decadal Oscillation (PDO), which was in a mostly positive phase in the former period and in a mostly negative phase in the latter one. During the positive (warm) phase of the PDO the Western Pacific is cooler that normal, which may lead to reduced convective activity and reduced moistening of the upper troposphere. Direct PDO and WS1 correlations, however, do not show high significance levels, implying that the processes influencing tropical deep convection need to be explored in more detail, using the whole suite of available observations and examining the full range of scales of tropical variability.

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W. B. Rossow and E. Tromeur, CREST, NOAA, City University of New York, T-107, Steinman Hall, New York, NY 10031, USA.

G. Tselioudis, NASA Goddard Institute for Space Studies, Columbia University, 2880 Broadway, New York, NY 10025, USA. (gtselioudis@giss.nasa.gov)

C. S. Zerefos, Centre for Atmospheric Physics and Climatology, Academy of Athens, 131, 3rd September St., Athens 11251, Greece.