Seasonal and Interannual Variations of Upper Tropospheric Water Vapor Band Brightness Temperature over the Global Monsoon Regions①

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ABSTRACT

The upper-troposphere water vapor (UTWV) band brightness temperature (BT) dataset derived from the High-resolution Infrared Radiation Sounder (HIRS) channel 12 of the National Oceanic and Atmospheric Administration (NOAA) polar satellites from 1979 to 1995 is used to analyze the seasonal and interannual variations for the global monsoon regions. Results show that (i) there are three major regions where the UTWV band BT varies significantly with season, i.e., South Asia, the western coastal South-North America tropical region and the low-latitude African region; (ii) UTWV band BT clearly reveals the water vapor temporal / spatial features as well as the atmospheric circulation structure over the low-latitude during the monsoon onset; and (iii) there is a remarkable relationship between the interannual variation of the UTWV band BT over the monsoon regions and the sea surface temperature anomaly in the eastern equatorial Pacific.

Key words: Monsoon, Seasonal variation, Interannual variability, Upper tropospheric water vapor, Brightness temperature

I. INTRODUCTION

At the present time, over 60% of the world population lives in the monsoon regions. In these regions, monsoons bring most of water supply for the local agricultural and industrial sectors. The interannual variations of monsoon have direct impact on the local and global economic development. Unfortunately, with few of ground rainfall stations over the vast oceanic regions, it is almost impossible to determine the monsoon regions over the world and to compare the monsoon periods in different regions. Since the late 1970s, the space measuring technology has offered an alternative platform to monitor monsoon variations with much improved spatial coverage and horizontal resolution.

A set of High-resolution Infrared Radiation Sounders (HIRS) was mounted in the US NOAA operational polar-orbiting satellites to measure atmospheric water vapor. There are 20 channels on the HIRS. Many channels are sensitive to the variations of the upper-tropospheric water vapor. HIRS channel 12 (or HIRS12) was designed to sense the amount of water vapor in the upper troposphere. The higher HIRS12 value represents the less water vapor content in the atmosphere and the lower HIRS12 value represents the more water

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vapor content.

The previous studies on the HIRS12 data indicated that the air ascending or descending movements might affect total amount of water vapor in the upper troposphere (Wu and Bates et al., 1993; Bates and Wu et al., 1996). If the ascending movement occurs in the wet atmosphere, the water vapor will increase in the upper–troposphere. As a result, the brightness temperature (BT) measured by satellite and the value of the HIRS12 (water vapor band BT) will decrease. In the descending regions the air becomes dry and the value of the water vapor band BT will increase. Thus, the value of the water vapor band BT may be used as the indicator for vertical movement. Moreover, Wu and Bates et al. (1993) found that variations of HIRS12 values are much more sensitive to moisture than to temperature in the low–latitude regions. Generally, in the climatological sense, the high values of HIRS12 represent the dry upper–troposphere and the low values of HIRS12 represent the wet upper–troposphere. During the summer monsoon onset, the deep convection will develop in the monsoon region and the air will become wet. In the upper–troposphere, the amount of water vapor will quickly increase and the values of HIRS12 will decrease. So the change of the upper troposphere water vapor (UTWV) band BT can indirectly indicate the monsoon onset and its interannual variation.

In the applications of satellite measurement data, the outgoing longwave radiation (OLR) anomalies have been used extensively as a surrogate for the anomalous presence or absence of the deep convection in the tropics. However, as indicated by Bates et al.(1996) the UTWV band BT anomaly is a better surrogate for tracing circulation anomaly in the tropics than OLR anomaly. The UTWV band BT anomalies in the tropics and subtropics can be interpreted in terms of both the upper–tropospheric water vapor and circulation anomalies. In this paper, the seasonal and interannual variations of the UTWV band BT over the global monsoon regions are studied.

II. DATA

In this paper, the 5–day averaged upper troposphere water vapor (UTWV) band BT dataset derived from HIRS12 of the NOAA polar satellites from 1979 to 1995 is used to analyze the monsoon seasonal and interannual variations over the global low–latitude area. Only clear and cloud–cleared measurements from the operational sounding product are used to produce averages for bins of 2.5° latitude by 2.5° longitude and 5 days. Due to the operational constraint, some grid data were unavailable. Total unavailable data were about 5% in the tropical regions and up to 40% in the polar regions. Because the water vapor is continuous in space, the unavailable data can be obtained by applying the method of one order curved surface interpolation.

III. UTWV BAND BT VARIATIONS WITH TIME AT DIFFERENT LONGITUDES

The UTWV band BT variation with time has been calculated every 5° latitude. Only the UTWV band BTs along 20°S, 10°S, equator, 10°N, 20°N and 30°N latitude zones are shown in Fig. 1. Some basic features in Fig. 1 can be described as follows:

(1) Along the equator, the changes of the UTWV band BT with season are not clear besides the region between 30°W and 50°W. Along the equator, there are three wet (higher UTWV band BT) regions in Africa, South Asia (60°E~ 180°) and South America. The dry (lower UTWV band BT) regions are mostly over the Pacific, Atlantic and Indian Oceans.

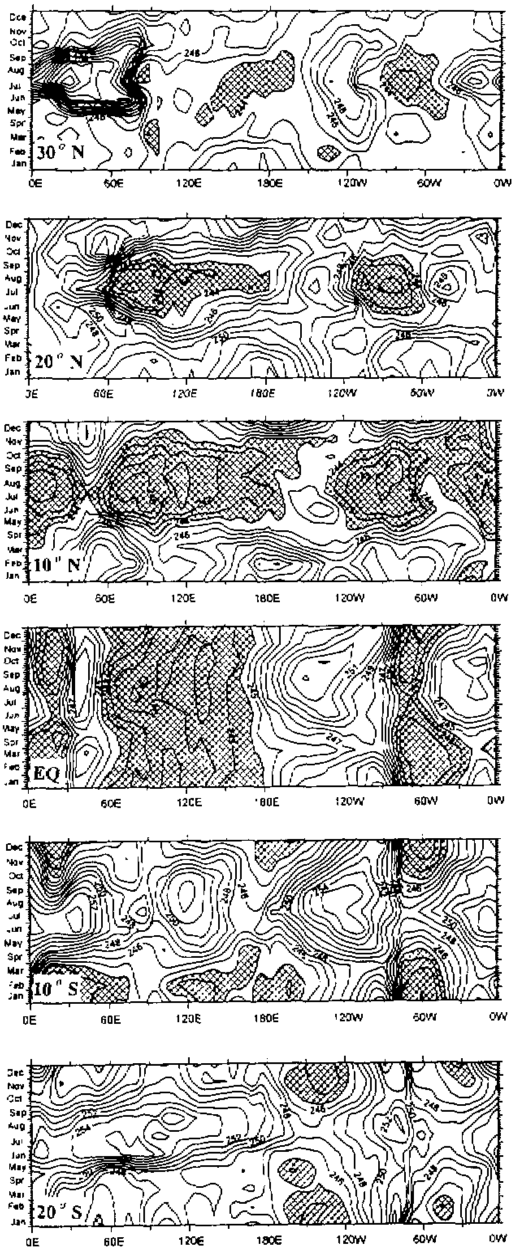

Fig. 1. The upper tropospheric water vapor (UTWV) band BT variations with time (pentad) along the latitude zones of 20°S, 10°S, equator, 10°N, 20°N and 30°N (unit: K).

Since the wet / dry regions are associated with the ascending / descending branches of the Walker cell, Fig. 1 indicates that in the seasonal scale, the Walker cell along the equator is quite stable and only its strength varies. During April to May, the Walker cell is weaker than that of other months. In July and August, two obvious ascending centers appear in Indian Ocean and the south of Filipino regions, respectively.

(2) To the south of the equator, the regions with large UTWV band BT seasonal change are in South America and Africa along 10°S. Along 20°S, the UTWV band BT seasonal changes are not so obvious.

(3) Along 10°N, there are three regions with large UTWV band BT in summer, i.e., Africa, South Asia (from the Arabian Sea to the Dateline) and North America. Among the three regions, the values of the UTWV band BT in the South Asian monsoon region are the highest and persistent for half a year. It also covers the largest region. However, along this latitude, the seasonal change of UTWV band BT is the earliest one over Africa. The seasonal change of UTWV band BT over the South Asian monsoon region starts between the eastern Bay of Bengal and Indo-China Peninsula. In the South Asian region, there are two centers, i.e., Indian Ocean and the South China Sea (SCS). Obviously, the Indian center is stronger than that over the SCS.

(4) Along 20°N there are two centers of the UTWV band BT seasonal changes that located in South Asia and North America. The one over India in summer is stronger than that over North America. The UTWV band BT changes mainly appear in June–August along this latitude. It should be pointed out that the rain season of India and the West Indian Islands is also in the same period.

(5) Along 30°N there is only one region with large UTWV band BT values in summer, i.e., the southern coastal region of the United States. The strong descending region locates in the Iran Plateau and the other two descending regions in the eastern Pacific and the Atlantic Oceans.

Three main points may be derived from the above analyses: 1) the regions with the large UTWV band BT seasonal changes mainly appear in the tropics; 2) the sea–land thermal contrast may contribute to the UTWV band BT seasonal changes; 3) the regions with large UTWV band BT seasonal changes seem to be associated with the global monsoon regions.

IV. UTWV BAND BT VARIATIONS WITH TIME AT DIFFERENT LATITUDES

From Fig. 1, four regions with the large UTWV band BT seasonal changes can be identified with centers along 15°E, 80°E, 115°E and 90°W. Fig. 2 plots the time–latitude cross-section of the UTWV band BT along Africa, India, the South China Sea and North America.

(1) African region. The large UTWV band BT in the Northern Hemisphere appears during the period of May to September and covers regions from 5°N to 15°N. In the Southern Hemisphere, the large UTWV band BT appears from the equator to 15°S during the period of September to the next April. In this region, the seasonal change of UTWV band BT along the equator is more significant than the other regions discussed below.

(2) Indian region. Along the same longitude, the relative large UTWV band BT is usually associated with the descending branch of the vertical circulation and the relative small UTWV band BT is associated with the ascending branch. In the Indian region, the ascending branch appears over the equator and the two descending branches appear over both hemispheres out of 16°N from December to the next April. The remarkable change occurs in the period of May to November. In this period the ascending branch appears in the region from the equa-

tor to 30°N. The corresponding descending branch, on the other hand, appears in the Southern Hemisphere. The seasonal changes of the UTWV band BT mainly occur in the region of 5 ~ 30°N. Moreover, these changes start near the equator in May and extend gradually to about 30°N in the middle of July.

(3) The South China Sea region. Along 115°E, the seasonal changes of the UTWV band BT mainly appear in the region from 5°N to 20°N. It has been shown (Xie et al., 1998) that the SCS monsoon onset is different from the Indian monsoon onset. Usually, the whole SCS monsoon region is rapidly developed from south to north in the third pentad of May. The withdrawal of summer monsoon in the SCS is from north to south in the period of September to the end of the year. During the SCS monsoon onset the strongest ascending branch occurs

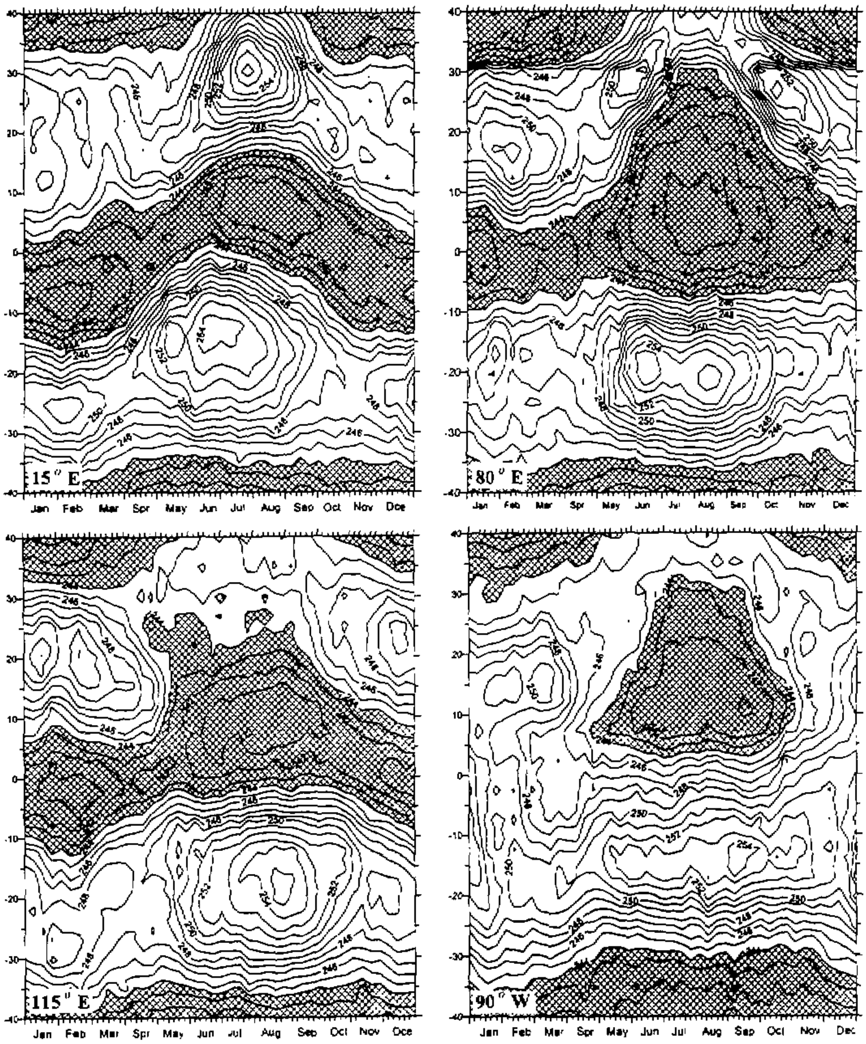

Fig. 2. The water vapor UTWV band BT variations with time (pentad) along the meridional lines of 15°E, 80°E, 115°E and 90°W (unit: K).

in the SCS, while the strongest descending branch occurs in the northwestern Australia. It is possible that the SCS summer monsoon onset links with the breaking of cold air in Australia.

(4) North American region. From Fig. 1, there are two regions with large UTWV band BT seasonal changes. One is along 90°W in the North America continent and another one is along 60°W in the South America continent. Only the North America region is shown here. In summer, the large UTWV band BT covers the region of 5 ~ 30°N. It increases from south to north in May–July. A quick withdrawal is observed in September.

From the above analyses, it can be seen that the increase of UTWV band BT in Africa, India and North America are gradually from south to north except in the SCS region where the UTWV band BT increases rapidly along the meridional direction. By observing all four panels in Fig. 2, it can be found that with the increases of UTWV band BT in the boreal summer there are four direct vertical cells developing across the two hemispheres. In the African region, there are two strong descending branches in both hemispheres.

V. UTWV BAND BT INTERANNUAL VARIATION AND SST ANOMALY IN THE EASTERN EQUATORIAL PACIFIC

The variations of UTWV band BT and its strength are directly related with the troposphere atmospheric circulation anomaly. The circulation anomaly, however, is the result of effect of the land–sea thermal contrast. Here, the study on the relationship between the UTWV band BT interannual variations and SST anomaly is conducted. First, the correlation coefficients between the global UTWV band BT anomalies and SST anomaly time series in NINO3 (5°N ~ 5°S, 150 ~ 90°W) region from 1979 to 1995 were calculated. Results are shown in Fig. 3. The dashed areas represent negative correlation. From Fig. 3, it can be seen that there are four negative correlation centers between the NINO3 SST anomaly and global UTWV band BT, i.e., the central eastern equatorial Pacific (CEEP), the continental region from India to South China, the subtropical regions in South America and North America. The negative correlation coefficients show that there is more water vapor in the upper troposphere during the ENSO events. The four positive correlation regions, including Maritime Continent in the western equatorial Pacific, the equatorial South America, the southern and northern Pacific subtropical regions, are also found around the CEEP in Fig. 3. It is drier in the upper troposphere than normal in these four regions when the SST anomaly is positive. Fig. 3 displays not only the relationship between the global UTWV band BT anomalies and the NINO3 region SST anomaly but also the global upper–troposphere water vapor

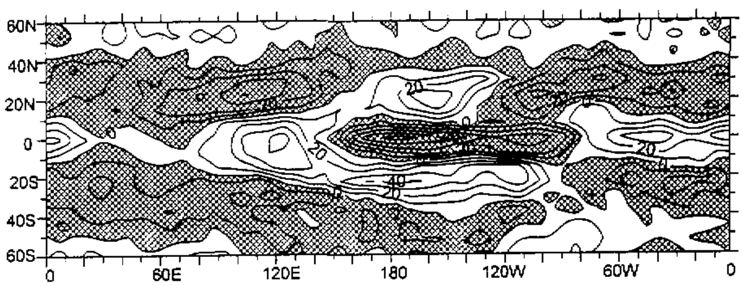

Fig. 3. The distribution of the correlation coefficients (value × 0.01) between the NINO3 region SST anomaly and the global UTWV band BT anomalies from 1979 to 1995.

oscillation pattern between the CEEP and its surrounding regions. In the tropical region, the negative departure of UTWV band BT represents relatively higher water vapor content than normal in the atmosphere and is associated with the strengthening of ascending movement. Conversely, the positive departure of UTWV band BT represents relatively less water vapor content in the atmosphere and is associated with the strengthening of descending movement. In the longitudinal direction, these variations of ascending and descending movements in the tropical region are the result of the strength changes of the Walker cell. In the subtropical region, since there is relatively less water vapor, the positive (negative) departure of the UTWV band BT directly reflects descending (ascending) movements in the atmosphere. In the meridional direction, the opposite fluctuation of UTWV band BT in different regions reflects the variation of the strength of the Hadley cell. Therefore, this oscillation is the reflection of the strength of atmospheric circulation around the central eastern equatorial Pacific. This oscillation differs from both the oscillation of the SST anomaly in the ocean basin and the oscillation of the Southern Oscillation that is restricted among mountain ranges (Qian and You, 1998). Since the regions covered by this oscillation are mainly associated with

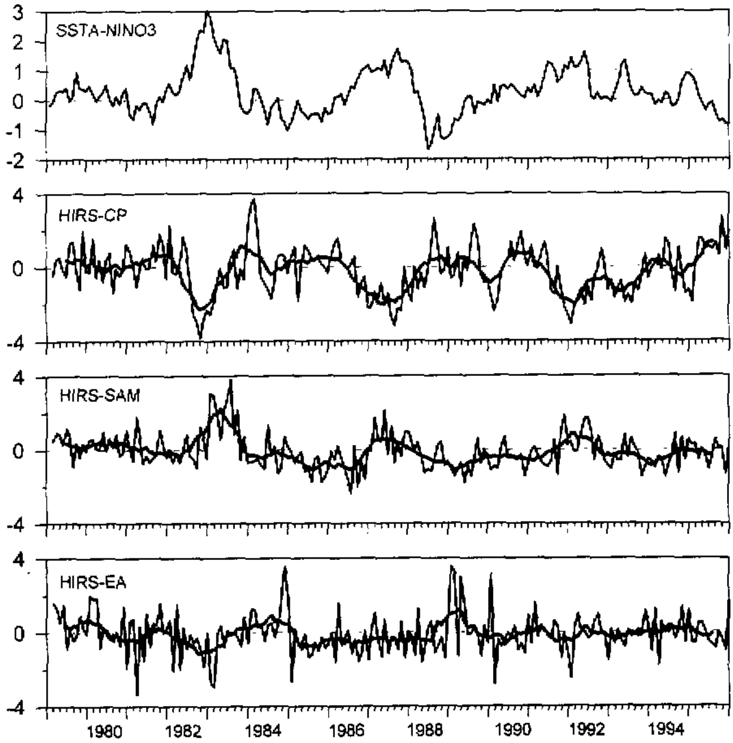

Fig. 4. The time-series of the SST anomaly (unit: °C) in the NINO3 region and the upper-troposphere water vapor band brightness temperature anomalies and 9-point running mean (heavy line, unit: K) in different regions. HIRS-CP, HIRS-SAM and HIRS-EA represent the water vapor band brightness temperature anomalies in the EEP (5°N ~ 5°S, 145°E ~ 135°W), South America (5°N ~ 5°S, 75 ~ 25°W) and East Asia (22.5 ~ 27.5°N, 92.5 ~ 127.5°E) respectively.

the global monsoon regions, we may call it "the monsoon oscillation". By using the method of the empirical orthogonal function (EOF) to analyze the HIRS12 data from 1981 to 1994, Bates et al.(1996) also found one mode that is similar to the monsoon oscillation.

The monsoon oscillation may reflect the interannual variability of the atmospheric circulation and its connection with the eastern equatorial Pacific SST anomaly. The three regions with high positive / negative correlation coefficients have been chosen to further reveal the spatial and temporal features of the monsoon oscillation, i.e., the central Pacific (CP), the South Asian Monsoon region (SAM) and the equatorial America (EA). Fig. 4 shows three UTWV band BT anomaly series and SST anomaly time-series in the NINO3 region.

From Fig. 4, it can be found that for the interannual UTWV band BT variations the strongest signal is in the CEEP. The strong UTWV band BT departure signal in the CEEP is opposite with that of the NINO3 region SST anomaly throughout the 1980s and the short warming events in the early 1990s. The UTWV band BT variations in South America are consistent with that of the NINO3 region SST anomaly, but the UTWV band BT variations in East Asia are opposite with that of the NINO3 region SST anomaly in phase. These results indicate that there is an interannual variation not only in the EEP SST anomaly but also in the upper-troposphere water vapor and OLR (Bates et al., 1996).

Since this oscillation occurs not only just in the Asian monsoon region (Webster and Yang, 1992) but also in the other major monsoon regions around the globe, here, we propose the concept of the Global Monsoon-ENSO System (GMES).

VI. CONCLUSIONS AND DISCUSSIONS

Some knowledge can be obtained from the above seasonal and interannual variation analyses of the upper-troposphere water vapor band brightness temperature dataset and NINO3 region SST anomaly series.

(1) The UTWV band BT can be used to reveal the seasonal and interannual variations of monsoon in the low-latitude region. It also reflects the variations of vertical circulation in different time-scales.

(2) The large seasonal changes of UTWV band BT mainly occur in the Northern Hemisphere, including Africa, South Asia and the American regions. In the Southern Hemisphere, the regions with the large UTWV band BT seasonal changes can be found from 5°S to 15°S in Africa, South America and Australia.

(3) In the Northern Hemisphere, the four major regions with the large UTWV band BT seasonal changes, including Africa, India, the SCS and North America are identified. The changes of the UTWV band BT from dry to wet for the four regions all occur in May. The changes in the SCS region start rapidly in the third pentad of May from south to north. The changes in the other three regions, however, are gradually from south to north during May-July. The regions with the significant seasonal changes of the UTWV band BT can reach 30°N in India and North America but only 20°N and 15°N in the SCS and Africa, respectively.

(4) In the interannual time scale, there is a notable relationship between the changes of UTWV band BT in the global monsoon regions and the eastern equatorial Pacific SST anomaly. This relationship shows that the UTWV band BT is above (below) normal in the Indian and South China regions when the eastern equatorial Pacific SST is positive (negative) anomaly. Around the central eastern equatorial Pacific and its surrounding regions, there is a fluctuation pattern in the upper-troposphere water vapor. The pattern may reflect an oscillation

that occurs in the global monsoon–ENSO system.

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