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Changes in Tropical Cyclone Number in the Western North Pacific in a Warming Environment as Implied by Classical Thermodynamics

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Abstract

Observational analyses show that the equatorial trough in the western North Pacific (WNP) is a well-known origin for tropical cyclones (TC) which have tended to weaken in intensity and decrease in number during the last several decades under global warming. A scientific problem then arises as to why higher sea surface temperatures (SSTs), one of the necessary conditions for typhoon genesis, can cause a weakened equatorial trough and a decreased TC number. In this paper, the WNP is taken as an example to illustrate a possible mechanism for the above-mentioned seemingly counterintuitive phenomena and explain the causality between the unusually heterogeneous pattern of SSTs in a warming environment and TC number in the WNP. This mechanism is based substantially on the second law of thermodynamics.

Keywords: Second Law of Thermodynamics, Global Warming, Thermal Wind Relation, Sea Surface Temperature

1. Introduction

A number of papers and the observational data have revealed that a variety of devastating weather/climate events have happened frequently over the world recently. Here we may quote, as examples, the most serious drought since 1940 occurred in the central western part of the United States in 1998 with grain production dropping by 38%, the warmest year 1999 experienced in China in the last hundred years, the extraordinarily powerful and deadly Hurricane Katrina with damages of about $81 billion and fatalities over 1800 in 2005, and so forth [1-5]. However, during this severe period, a counterintuitive phenomenon was seen in that the tropical cyclone (TC) numbers tended to decrease over some oceanic basins while a rise in their sea surface temperatures (SSTs) has been observed [6-8]. As a result, a scientific problem arises as to why, under a background of global warming, higher SSTs, implying more potential energy which is one of the necessary conditions for typhoon genesis, would cause decreased TC numbers?

In the recently published monograph [9] it is stated that most numerical models indicate an overall decrease in the number of storms attributable to greater atmospheric stability and to a decrease in vertical mass flux. However, the analysis in this paper for understanding the observed counterintuitive phenomena is quite different from those described in the previous works. This analysis is based on fundamental dynamics rather than numerical experiments whose results are inevitably affected by the numerical model itself.

In this paper the western North Pacific (WNP) over which the TC numbers tended to decrease with minor fluctuations from late 1960s (**Figure 1**) is taken to illustrate a possible mechanism responsible for the conundrum. This paper is based on the observational results shown in **Figure 1** that are obtained from the *Tropical Cyclone Year Book* or the CMA dataset covering 59 years as indicated in Ref. [10]. And, the relative vorticity (RV) in **Figure 1** is calculated via the definition formula for RV (see Subsection 3.1 below), based on the National Centers for Environmental Prediction/National Center

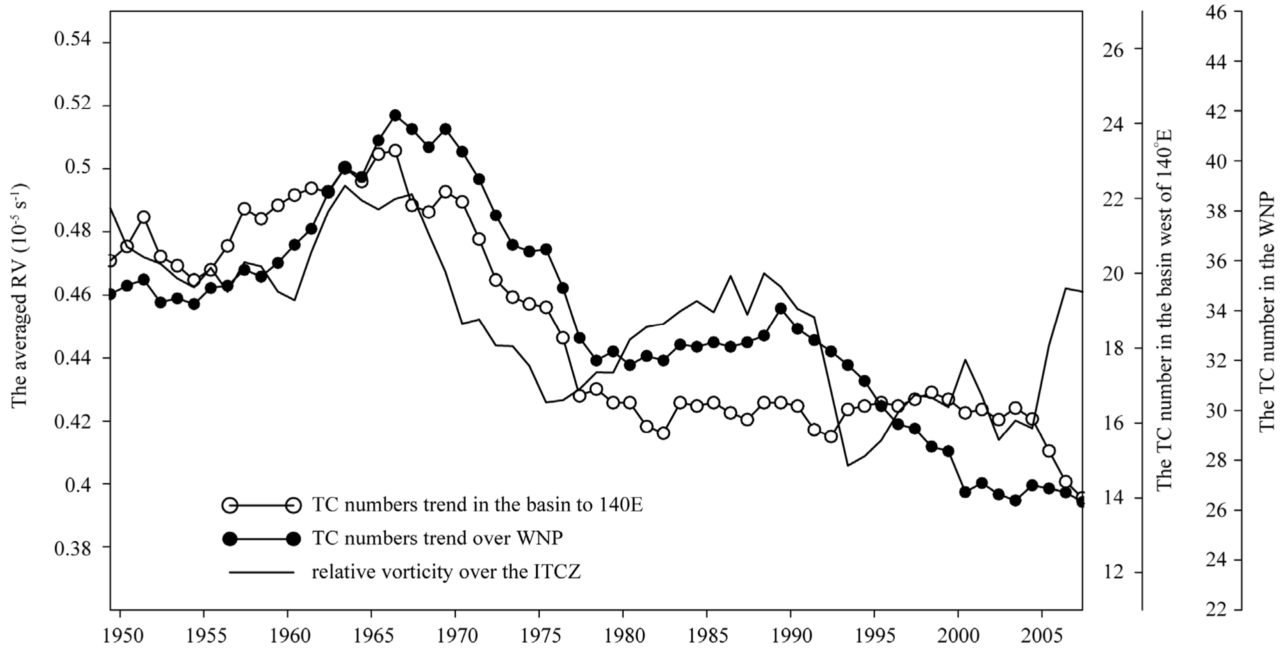


Figure 1. The long term time series for the TC numbers in the WNP and in the basin west of 140˚E as well as the averaged relative vorticity (10^{-5} s^{-1}) in the monsoon trough ITCZ during 1949-2007 (see the text for details).

for Atmospheric Research (NCEP/NCAR) 2.5˚ × 2.5˚ (latitude–longitude grid) reanalysis data.

2. Results and Discussion

2.1. The Main Source of TC Genesis and the ITCZ

According to the previous studies [11-13], 80% - 85% of TCs originate in the ITCZ or just on its poleward side, and the monsoon trough ITCZ located in the basin west of 140˚E is the main origin of TCs over the WNP. Based on the satellite images and the other data analyses, it is noticed that 70% of the TCs originate from the cloud clusters over the ITCZ and the monsoon trough in the WNP [14,15]. The necessary conditions of TC genesis and development include higher SSTs, stronger low level vorticity, weaker vertical wind shear, and a higher latitudinal position of the subtropical anticyclone ridge/ITCZ, though these conditions are not equally important. Among them theoretically low level vorticity should be the fundamental factor for TC genesis since initial disturbances are the embryo of TCs. In addition, the intensity of the ITCZ as a main system generating TCs can be described in terms of the RV e.g. use RV at 850 hPa for defining the ITCZ, as is seen in Ref. [16]. Indeed the TC numbers over the WNP and the basin west of 140˚E have a high correlation with the RV around the ITCZ, as is seen in **Figure 1** where these numbers show almost synchronous changes with those of the RV. The corresponding correlation coefficients for the WNP and the basin west of 140˚E are 0.6552 and 0.6614 at the 0.001 significance level, respectively. It is noticed, in [10], that a 10-year running mean to the annual TC frequency data and NCEP typhoon season mean wind data has been applied to get the long term time series of the averaged TC numbers and RV at 925 hPa in the monsoon trough ITCZ for the period 1949-2007, and, that July-October (JASO hereafter) is defined as the typhoon season since JASO is the most frequent season for TCs over the WNP. It will therefore be a reasonable way to discuss the causality between the TC frequency trend and warming SSTs over the WNP via the ITCZ variability as the medium.

2.2. The ITCZ Variabilities

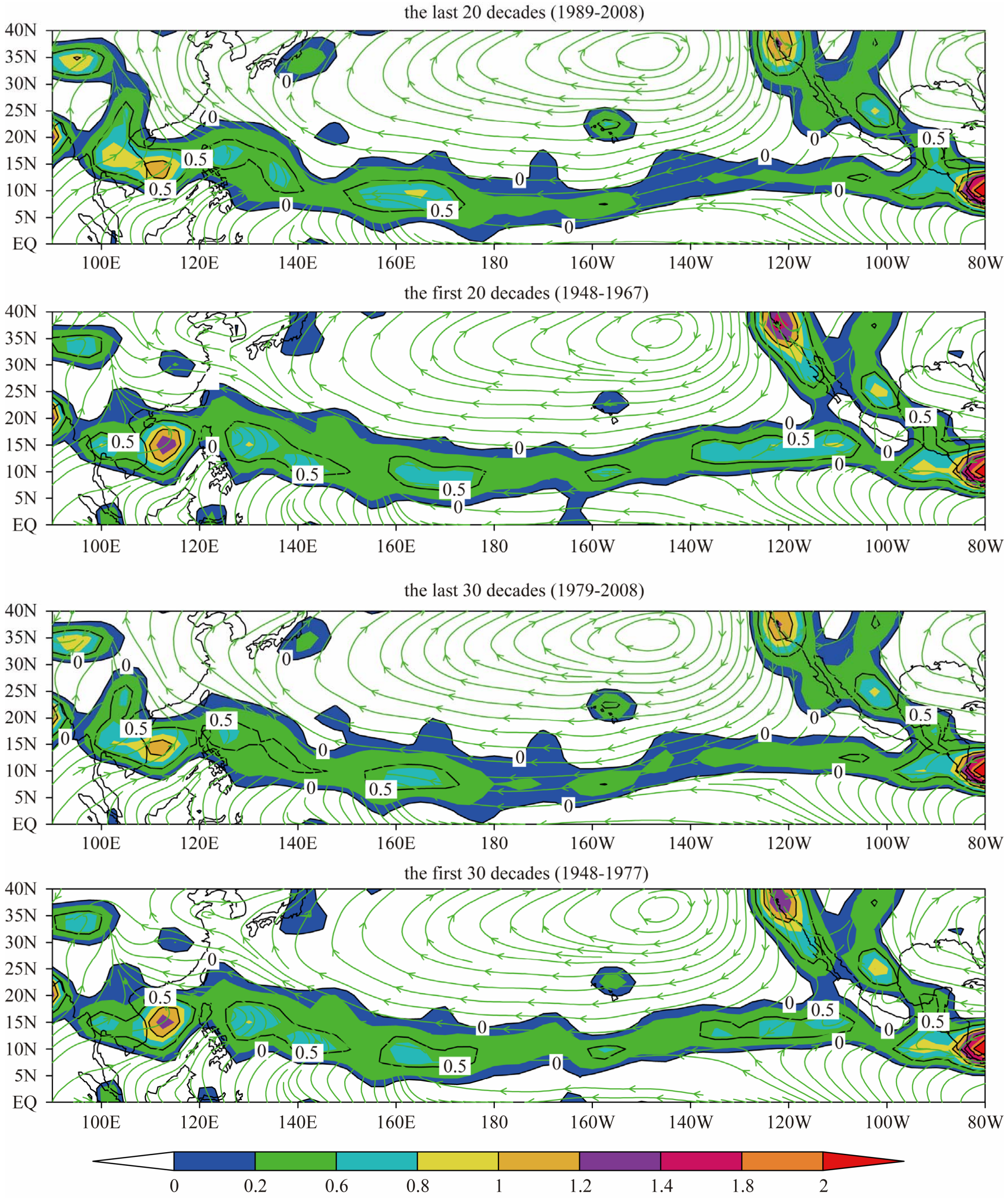
The analyses below are based on the NCEP/NCAR 2.5˚ × 2.5˚ resolution reanalysis data for horizontal winds from which the ITCZ fields in terms of RV are figured out via the definition of RV at constant pressure layer

$$\varsigma_p = \left(\frac{\partial v}{\partial x}\right)_p - \left(\frac{\partial u}{\partial y}\right)_p , \qquad (1)$$

where ς_p, u and v are the RV, the latitudinal and longitudinal velocities at constant pressure, respectively, as well as 2.0˚ × 2.0˚ data for the SST fields [17]. All the means are calculated against the period of JASO as mentioned above.

Figure 2 shows the streamlines fields superimposed on the positive RV at 925 hPa during JASO over the North Pacific. This shows that the zones of positive RV can indicate the general position of the convergence zones in the streamlines fields. These convergence zones should be able to represent the ITCZs since the ITCZ is mainly formed by the trade winds converging [18,19]. As mentioned in Section 2, using RV at 850 hPa for defining the ITCZ has been done [16]. However, the RV in terms of 850 hPa is not continuous in some sections of the ITCZ over the Pacific owing to its weaker intensity (figures not shown here). Therefore the RV at 925 hPa that is more continuous and smoother than that at 850 hPa is chosen instead in this paper.

The variation of the ITCZ over the WNP associated with the reduction in the TC numbers under warming SSTs during the last several decades might be caused by


the last 20 decades (1989-2008)

the first 20 decades (1948-1967)

the last 30 decades (1979-2008)

the first 30 decades (1948-1977)

Figure 2. Comparison of the streamlines fields superimposed on the positive RV at 925 hPa (contours in 10^{-5} s^{-1}) during JASO over the WNP between the first and last 20-year/30-year means (as marked above the respective panels).

the following two factors: 1) the intensity of the monsoon trough ITCZ, the main origin of TCs over the WNP, in terms of RV at 925 hPa was weakened and 2) the position of the ITCZ has shifted further south. The latter can be seen in **Figure 3** in which the central position of the ITCZ is determined by singling out the points with maximum positive relative vorticity values for each 2.5 longitudinal distance within the 100˚E - 140˚E area and then averaging them, both of which would contribute to the decrease in TC numbers over the WNP.

Next we will specifically discuss these two factors.

2.3. The Implication of SSTs Variation

Figure 4 shows consecutive 20-year means of SSTs over the North Pacific for JASO during 1949-2008. It is seen that the SSTs over the North Pacific gradually increase, particularly the 28˚C isotherm, the critical temperature for the warm pool [20], which has extended eastward. This cross-equatorial area of warm water initially limited to the western Pacific has extended into the eastern Pacific. Since there is a close relationship between SSTs and surface wind divergence/convection over the tropical oceans or the ITCZs [21-23] the following questions are then raised: how the SSTs or their gradient influence the intensity of the ITCZ, and why the sea surface warming around the western Pacific is not as dramatic as over the central and eastern Pacific? The latter is relevant to the first of the ITCZ variability factors mentioned above. A potential clue can be found in the theory of modern nonlinear non-equilibrium thermodynamics.

For an isolated thermodynamic system, the state function of the system, entropy s per unit mass, will spontaneously increase with time according to the second law of thermodynamics, which can be expressed by the formula [24,25]

$$\frac{\mathrm{d}s}{\mathrm{d}t} \geq 0 \tag{2}$$

and is usually called the spontaneous entropy increment principle. As a result, an isolated system will spontaneously tend to homogenization. However, for an open system with a diabatic heating rate Q transferred through its boundaries, Equation 2 should be modified to

$$\frac{\mathrm{d}s}{\mathrm{d}t} \geq \frac{Q}{T} \tag{3}$$

where T is the temperature (in ˚K) of the system. The nature of the second law of thermodynamics shows that, if there exists initial differences, heat (particles) will be spontaneously transferred (diffused) from areas with higher T (concentration) to that with lower T (concentration). Any many-body system like the atmosphere or ocean must be controlled by the second law of thermodynamics and, in fact the entropy flow properties of atmospheric systems have been revealed via this law [26-29].

Specifically, if there exist differences in temperature spatially (say, on the sea surface), the original area of warmer sea surface will diffuse its thermal energy (the inner energy, proportional positively to temperature via the formula of $e = C_v T$ where e is the inner energy per unit mass, C_v is the specific heat at constant volume and T is temperature) to its surroundings with lower temperature. As a consequence, compared to the surrounding areas, the original warmer area (e.g., the warm pool) will experience a weaker warming under global warming since it will lose a certain amount of heat via the diffusive process at the same time, and vice versa. **Figure 4** shows the case for the North Pacific as an example in which it is demonstrated that the SSTs around the monsoon trough ITCZ have a smaller increment of temperature while those over the adjacent ITCZ sections near the central and eastern equatorial Pacific have larger increments. Because the ITCZ is mainly caused, at least in the initial stages, by thermodynamic forcings such as the gradient in SST which plays more of a role than the absolute SST value with regard to convection and precipitation [23], the monsoon trough ITCZ should indeed become weaker in response to more uniform SSTs or a weakened SST gradient.

2.4. The Effect of the SST Pattern on the ITCZ Migration

As described above, in the warming environment the higher SST area within the 28˚C isotherm has gradually extended eastward (**Figure 4**) so as to form an apparent zone of higher SSTs with a distinct gradient of nearly north-south direction (y-direction) created on the both northern and southern sides of this zone. Such a SST

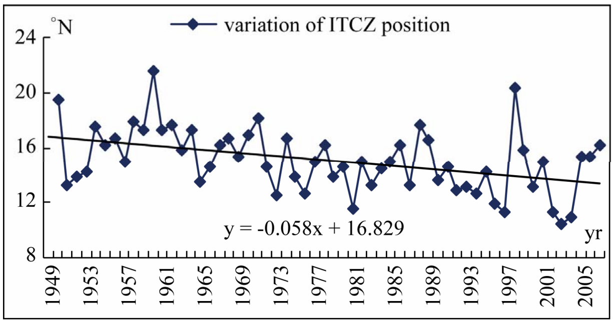


Figure 3. An illustration of changes in the average position of the ITCZ from 1949 to 2007. Here, the central position of the ITCZ is determined from the points with maximum positive RV along the longitudinal direction within 100˚E–140˚E and then averaging their respective latitudinal position.

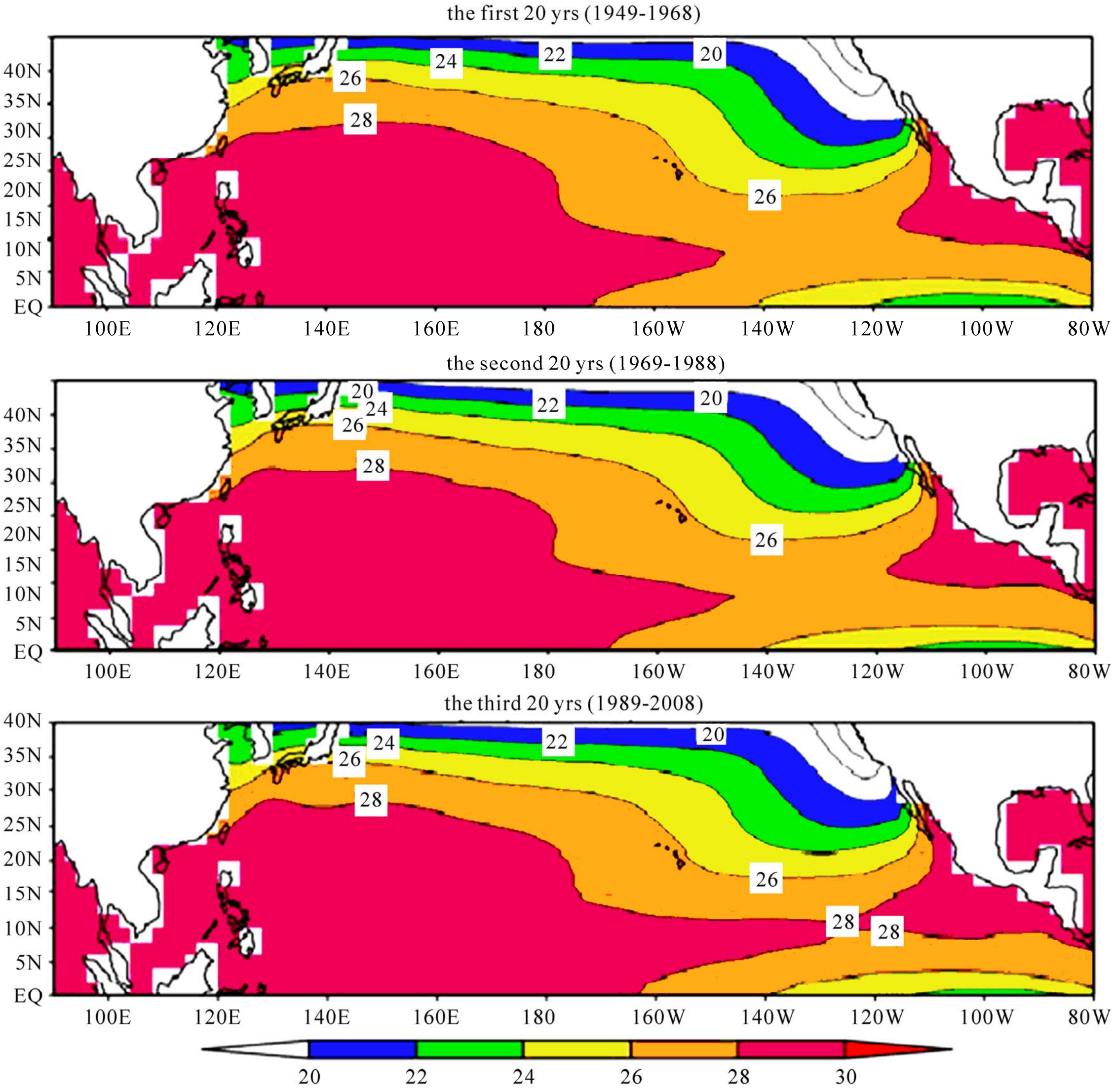


Figure 4. The consecutive 20-year-averaged SST fields (˚C) for the North Pacific south of 40˚N during the period from 1949 to 2008.

pattern will cause changes in the mean temperature T_m of an air layer above the sea surface between p_1 (e.g. 1000 hPa that is near the sea surface) and p_2 (e.g. 925 hPa that is used for defining the ITCZ in terms of RV in this paper). As a result, in some regions to the north of the zone of higher temperature, with the average temperature gradient along the north-south direction $\frac{\partial T_m}{\partial y}$ being smaller than zero, a westerly wind component at higher levels (e.g. at 925 hPa) should be superposed, due to gradient and Coriolis forces.

Similarly, the latitudinal velocity to the south of the zone should be superposed by an easterly component as the gradient in SSTs in the southern regions is the reverse of that in the north. Thus, the RV, as is expressed by $\varsigma_p = \left(\frac{\partial v}{\partial x}\right)_p - \left(\frac{\partial u}{\partial y}\right)_p$, in the regions to the north of the zone of higher temperature will be decreased since the term $-\left(\frac{\partial u}{\partial y}\right)$ becomes smaller while the term $\left(\frac{\partial v}{\partial x}\right)_p$ changes little in this case. At the same time, the RV in the regions to the south of the zone of higher temperature will be increased owing to the reversed gradient in SSTs or T_m there.

Taking the definition of ITCZ in terms of positive RV into account, we might expect that the part of the ITCZ to the north of the zone of high temperature will tend to disappear as a result of a reduction in RV there and, similarly initial ITCZ to the south will be enhanced and even extend south further. This could help to explain why the ITCZ apparently migrates south (**Figures 2**,**3**).

3. Conclusions

As is well-known, the necessary conditions for TC genesis are not equally important and, among them dynamical factors such as low level vorticity and vertical wind shear play a more important role than thermodynamic factors such as SST and moist instability [30-32]. This study shows that, warmer SSTs in the WNP can cause fewer TCs, that is, warmer SSTs are only one of the necessary conditions and so do not definitely lead to an increase in TC numbers. This may be attributed to the heterogeneous effects of complicated patterns of SSTs on RV as implied by the second law of thermodynamics. This paper further also suggests that low level vorticity associated with ITCZ variations should be a fundamental factor for TC genesis. Based on the analyses in this paper, a new way of understanding the mechanism responsible for the causality between SSTs and TC occurrence frequency over the WNP is then suggested. The WNP is only used as an example in this study and the methodology illustrated herein should be universal.

4. Acknowledgements

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