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Impacts of SST and SST Anomalies on Low-Frequency Oscillation in the Tropical Atmosphere

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ABSTRACT

Considering the multiscale character of LFO (low-frequency oscillation) in the tropical atmosphere, the effects of SST on LFO in the tropical atmosphere are discussed by using an absolute ageostrophic, baroclinic model. Here, SST effects include sea surface heating and forcing of SST anomalies (SSTAs). Studies of the influences of sea surface heating on LFO frequency and stability show that sea surface heating can slow the speed of waves and lower their frequency when SST is comparatively low; while higher SST leads to unstable waves and less periods of LFO. Since the impact of a SSTA on ultra-long waves is more evident than that on kilometer-scale waves, long-wave approximation is used when we continue to study the effect of SSTAs. Results indicate that SSTAs can lead to a longer period of LFO, and make waves unstable. In other words, positive (negative) SSTAs can make waves decay (grow).

Key words: Low-Frequency Oscillation (LFO), sea surface heating, sea surface temperature anomaly (SSTA), ultra-long wave, kilometer-scale precipitation

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1. Introduction

Atmospheric intraseasonal oscillation of 30–60 days in the tropics, which Madden and Julian (1971, 1972) first discovered, is one of the basic motions of the tropical atmosphere. It bears a close relation not only with long-range weather change, but also with short-range climate anomalies. Therefore, a series of studies have explored its basic features (He, 1988, 1990; Krishnamurti and Subrahmanyan, 1982; Knutson and Weickmann, 1987; Li and Wu, 1990) .

Based on studies of observational features of Low-Frequency Oscillation (LFO) in the tropical atmosphere, many dynamical and thermal mechanisms (Chao et al., 1996; Krishnamurti et al., 1988; Lau and Chan, 1988; Webster, 1981) have been proposed to explain LFO. In theoretical studies of LFO in the tropical atmosphere, Xu and Gao (2002) summarized a series of factors affecting LFO, among which SST was one of the most important. A series of observational analyses (Li, 1990; Dong et al., 2004) have shown that tropical LFO in the western and eastern Pacific are both very active, while the characteristics of SST in these two regions are obviously very different: SST in the Western Pacific is higher, with little variation; while SST in the Eastern Pacific is lower, but with a greater degree of variation. Therefore, the two effects of SST (heating and anomalies) on tropical LFO are important and require separate study.

Xu et al. (1990) have demonstrated the process of sea surface heating of the atmosphere: convergence (divergence) of a stream field due to higher SST can produce large-scale vertical motion, then the release of latent heat due to condensation warms up air. The effect of this SST anomalies (SSTAs) can be described as the influence on the upper atmosphere circulation

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(including LFO) due to the change of ocean circulation. Gao et al. (1998) point out that low-frequency variation in the atmosphere over the East Pacific is related to SSTAs in this region.

Li and Li (1996) studied CISK containing the effect of SSTAs by using a baroclinic semi-geostrophic model and analyzed the influence of SSTAs on LFO in the tropics. Fu et al. (2000) established a semi-geostrophic model to discuss the influence of SST, including evaporation wind feedback, and pointed out that the forcing of SST on LFO is important. Liu (1990) showed that a semi-geostrophic approximation can only filter the high-frequency Rossby waves that satisfied the condition (wave number is close to 0). Further investigation showed that LFO has a multiscale characteristic in the tropics: that is, the horizontal scale of tropical LFO changes from the planetary scale ($L \sim 10^7$ m) to a smaller scale (e.g. precipitation cloud with a kilometer scale ($L \sim 10^6$ m). Therefore, a semi-geostrophic model has a limitation in describing all scales of LFO motion in the tropics, however it is simple to discuss the equation resolution by using this model. In this paper, an absolute ageostrophic baroclinic model is established to discuss the two effects of SST: sea surface heating and SSTAs. For a detailed discussion of equation resolution, we take appropriate means and approximations according to different scales of tropical LFO.

2. Basic equations and analysis

The linear equations of a baroclinic model on the equator β plane, which utilizes the two effects of SST to describe LFO motion in the tropics, can be written as (not considering the mean flow):

$$\frac{\partial u}{\partial t} - \beta y v = -\frac{\partial \varphi'}{\partial x} , \tag{1}$$

$$\delta \frac{\partial v}{\partial t} + \beta y u = -\frac{\partial \varphi'}{\partial y} \quad (\delta = 0 \text{ or } \delta = 1) , \tag{2}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 , \tag{3}$$

$$\frac{\partial}{\partial t}\left(\frac{\partial \varphi'}{\partial z}\right) + N^2 w = Q + F , \tag{4}$$

where N is the Brunt-Vaisala frequency, $\varphi = p'/\rho_0$ (p' is the pressure perturbation against static pressure, and ρ_0 is the density of static air). In Eq. (4), Q and F show the effect of sea surface heating and the forcing by a SSTA, respectively. $\delta = 1$ represents an ageostrophic model, while $\delta = 0$ is used to describe the terminal adaptation state means zonal momentum equation, which satisfies semi-geotrophic balance.

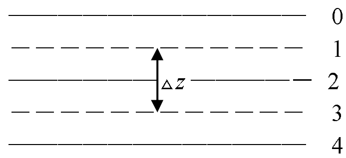

Fig. 1. Schematic diagram of the two-layer model.

Using a two-layer model is one of the easiest methods to show the main characteristics of the baroclinic atmosphere. So, using a simple two-layer model (Fig. 1), we put dynamical equations and a mass continuity equation on the first and third levels. It should be noted that the boundary conditions $W_0 = W_4 = 0$ have been used in the continuity equation. By setting,

$$\begin{cases} \widehat{u} = \dfrac{1}{2}(u_1 - u_3) , \\ \widehat{v} = \dfrac{1}{2}(v_1 - v_3) , \\ \widehat{\varphi} = \dfrac{1}{2}(\varphi_1 - \varphi_3) , \end{cases}$$

Eqs. (1–4) can be rewritten as:

$$\begin{cases} \dfrac{\partial \widehat{u}}{\partial t} - \beta y \widehat{v} = -\dfrac{\partial \widehat{\varphi}}{\partial x} , \\ \delta \dfrac{\partial \widehat{v}}{\partial t} + \beta y \widehat{u} = -\dfrac{\partial \widehat{\varphi}}{\partial y} , \\ w_2 = \Delta z \left(\dfrac{\partial \widehat{u}}{\partial x} + \dfrac{\partial \widehat{v}}{\partial y}\right) . \end{cases}$$

In this simple atmospheric model, there are no oceanic variables and we need to show the effects of SST by parameterization of atmosphere variables.

In the context of this paper, Q is related to convergence or divergence of the stream field, and thus we suppose

$$Q \sim r_T \left(\frac{\partial u_1}{\partial x} + \frac{\partial v_1}{\partial y}\right) \sim -r_T \left(\frac{\partial u_3}{\partial x} + \frac{\partial v_3}{\partial y}\right) ,$$

where r_T is related to SST (the higher the SST, the bigger the values of r_T and Q). Simple parameterization of SST is proposed by

$$Q \sim 2r_T \left(\frac{\partial \widehat{u}}{\partial x} + \frac{\partial \widehat{v}}{\partial y}\right) .$$

Ran et al. (2005) pointed out that the effect of divergent winds excited by external thermal forcing on low-frequency waves is important.

By including the thermodynamic equation on the second layer, and substituting the vertical differential by vertical difference, we have:

$$\frac{2}{\Delta z}\frac{\partial \widehat{\varphi}}{\partial t} + N^2 w_2 = 2r_T\left(\frac{\partial \widehat{u}}{\partial x} + \frac{\partial \widehat{v}}{\partial y}\right) + F_2\,, \tag{5}$$

where the term F_2 represents the height difference between 200 hPa and 850 hPa, as in Li and Li (1996). That is, the influence on atmospheric circulation embodies the change of height difference due to SSTAs and ocean circulation. When the SSTA is positive (negative), the height difference between 200 hPa and 850 hPa increases (decreases). Therefore, the parameterization of the SSTA is proposed as F_2: $-\alpha_s\widehat{\varphi}$. When $\alpha_s > 0$, SSTA is positive; and when $\alpha_s < 0$, SSTA is negative. Equations (1–4) may be further written as:

$$\begin{cases} \dfrac{\partial \widehat{u}}{\partial t} - \beta y \widehat{v} = -\dfrac{\partial \widehat{\varphi}}{\partial x}\,, \\ \delta\dfrac{\partial \widehat{v}}{\partial t} + \beta y \widehat{u} = -\dfrac{\partial \widehat{\varphi}}{\partial y} \qquad (\delta = 0 \text{ or } \delta = 1)\,, \\ w_2 = \Delta z\left(\dfrac{\partial \widehat{u}}{\partial x} + \dfrac{\partial \widehat{v}}{\partial y}\right)\,, \\ \dfrac{1}{\Delta z}\dfrac{\partial \widehat{\varphi}}{\partial t} + \dfrac{N^2 w_2}{2} = -\alpha_s\widehat{\varphi} + r_T\left(\dfrac{\partial \widehat{u}}{\partial x} + \dfrac{\partial \widehat{v}}{\partial y}\right)\,. \end{cases} \tag{6}$$

Considering the multiscale character of tropical LFO, we take the ageostrophic model ($\delta = 1$):

$$\frac{\partial \widehat{u}}{\partial t} - \beta y \widehat{v} = -\frac{\partial \widehat{\varphi}}{\partial x}\,, \tag{7}$$

$$\frac{\partial \widehat{v}}{\partial t} + \beta y \widehat{u} = -\frac{\partial \widehat{\varphi}}{\partial y}\,, \tag{8}$$

$$\frac{\partial \widehat{\varphi}}{\partial t} + C_2^2\left(\frac{\partial \widehat{u}}{\partial x} + \frac{\partial \widehat{v}}{\partial y}\right) = -\alpha_s\Delta z\widehat{\varphi}\,, \tag{9}$$

where

$$C_2^2 = \frac{N^2\Delta z^2}{2} - r_T\Delta z\,.$$

Then, by eliminating $\widehat{u}$ and $\widehat{\varphi}$ from Eqs. (7–9), we have:

$$\left[C_2^2\frac{\partial}{\partial t}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) - \frac{\partial}{\partial t}\left(\frac{\partial^2}{\partial t^2} + \alpha_s\Delta z\frac{\partial}{\partial t} + \beta^2 y^2\right) + C_2^2\beta\frac{\partial}{\partial x} - \beta^2 y^2\alpha_s\Delta z\right]\widehat{v} = 0\,. \tag{10}$$

The boundary condition of Eq. (10) is:

$$\widehat{v}|_{y\to\pm\infty} = 0\,. \tag{11}$$

By invoking $\widehat{v} = V\exp(ikx - i\sigma t)$, where k is the wave number in the x direction, and σ is angular frequency, Eqs. (10) and (11) can be converted into:

$$\begin{cases} \dfrac{d^2V}{dy^2} + \left[-\dfrac{k\beta}{\sigma} + \dfrac{\sigma^2}{C_2^2} - k^2 + \dfrac{i\alpha_s\Delta z\sigma}{C_2^2} \right. \\ \qquad \left. - \left(\dfrac{\beta^2}{C_2^2} + \dfrac{i\alpha_s\Delta z\beta^2}{C_2^2\sigma}\right)y^2\right]V = 0\,, \\ V|_{y\to\pm\infty} = 0\,. \end{cases} \tag{12}$$

This is a Weber-type equation, and its eigenvalues are:

$$\left(-\frac{k\beta}{\sigma} + \frac{\sigma^2}{C_2^2} - k^2 + \frac{i\alpha_s\Delta z\sigma}{C_2^2}\right)\Bigg/\sqrt{\frac{\beta^2}{C_2^2} + \frac{i\alpha_s\Delta z\beta^2}{C_2^2\sigma}} = 2m + 1 \quad (m = 0, 1, 2\ldots)\,. \tag{13}$$

Considering the low-frequency characteristic, we omit $1/\sigma$ and retain σ or σ^2, giving us:

$$\sigma = \frac{k\beta}{k^2 - \dfrac{i(2m+1)^2\alpha_s\Delta z\beta}{2C_2^2 k} + \dfrac{(2m+1)\beta}{C_2^2}\sqrt{C_2^2 - \dfrac{(2m+1)^2\alpha_s^2\Delta z^2}{4k^2} - \dfrac{ik\alpha_s\Delta z C_2^2}{\beta}}}\,, \tag{14}$$

which shows that there is obvious change in the frequency due to the effects of SST heating ($r_T \neq 0$) and SSTA forcing ($\alpha_s \neq 0$). In addition, a low-frequency wave can easily be unstable (the imaginary part of the wave solution is mainly related to α_s). Detailed discussion follows.

First, we take the effect of SST heating when the change in SST is smaller (we suppose $\alpha_s = 0$). Thus, the frequency expression from Eq. (14) can be written as:

$$\sigma = -\frac{k\beta}{k^2 + (2m+1)\dfrac{\beta}{C_2}} \quad (m = 0, 1, 2\ldots)\,. \tag{15}$$

Note that the frequency expression is

$$\sigma = -\frac{k\beta}{(2m+1)\dfrac{\beta}{C_2}}$$

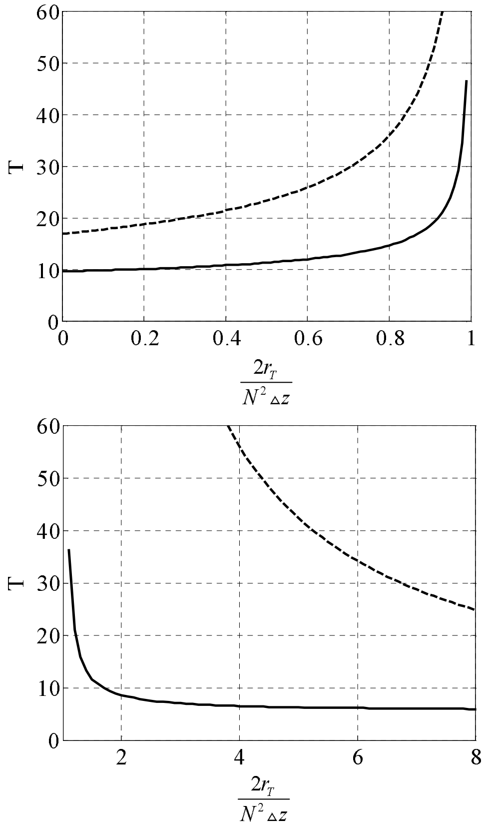

Fig. 2. Variations of period with $2r_T/(N^2\Delta z)$ for ultra-long Rossby waves ($m=1, k=1.5\times10^{-6}$), in weaker convection $[2r_T/(N^2\Delta z)<1]$ and stronger convection $[2r_T/(N^2\Delta z)>1]$ respectively (real line is $k=1.5\times10^{-6}$ m^{-1}; dashed line is $k=4\times10^{-7}$ m^{-1}).

and the frequency becomes larger if we use the semi-geostrophic model, especially for smaller scales (e.g., precipitation cloud with a kilometer horizontal scale, where, $L_s\sim10^6$ m, $k\sim10^{-6}$ m^{-1}, $\beta/C_2\sim10^{-12}, k^2$ cannot be omitted. Or the period of this smaller scale wave will reduce and cannot satisfy the ranges of LFO periods).

We may obtain some results from Eq. (15) as follows:

(1) If

$$r_T<\frac{N^2\Delta z}{2}$$

(low SST), angular frequency is a real number, and the wave is stable. Wave velocity is

$$C_x=\frac{\sigma}{k}=-\frac{\beta}{(2m+1)\beta/C_2+k^2}=$$

$$-\frac{\beta}{(2m+1)\beta/\sqrt{\dfrac{N^2\Delta z^2}{2}-r_T\Delta z}+k^2},$$

that is, low-frequency Rossby waves are westward, and the frequency (σ) and wave velocity (C_x) becomes small because of the existence of r_T.

(2) If

$$r_T>\frac{N^2\Delta z}{2}$$

(higher SST), angular frequency is an imaginary number, and the wave is unstable ($\sigma_i\neq0$).

$$C_2=\pm i\sqrt{r_T\Delta z-\frac{N^2\Delta z}{2}}\ ;$$

$$\sigma=\frac{\beta k\left[-k^2\mp\dfrac{(2m+1)\beta}{\sqrt{r_T\Delta z-\dfrac{N^2\Delta z^2}{2}}}\right]}{\left[\dfrac{(2m+1)\beta_0}{\sqrt{r_T\Delta z-\dfrac{N^2\Delta z^2}{2}}}\right]^2+k^4}=\sigma_{\mathrm{r}}+i\sigma_{\mathrm{i}}\ .$$

And we obtain

$$\sigma_{\mathrm{r}}=\frac{-\beta_0k^3}{\left[\dfrac{(2m+1)\beta_0}{\sqrt{r_T\Delta z-\dfrac{N^2\Delta z^2}{2}}}\right]^2+k^4}\ ;$$

$$\sigma_{\mathrm{i}}=\mp\frac{\beta_0^2k\dfrac{(2m+1)}{\sqrt{r_T\Delta z-\dfrac{N^2\Delta z^2}{2}}}}{\left[\dfrac{(2m+1)\beta_0}{\sqrt{r_T\Delta z-\dfrac{N^2\Delta z^2}{2}}}\right]^2+k^4}\ .$$

That is, when SST is higher, the propogation of Rossby waves is also westward and unsteady (high SST can make waves decay or grow).

For Kelvin waves, setting $\widehat{v}=0$ in Eqs. (7–9), we get $\sigma=C_2k$ by using the same means. The results show that Kelvin waves are eastward when SST is lower $[r_T<(N^2\Delta z)/2]$, while Kelvin waves are unstable (angular frequency is an imaginary number) when SST is higher.

For the tropics, by taking $\beta=2\times10^{-11}$ s^{-1} m^{-1}, $N=1\times10^{-2}$ s^{-1}, and $\Delta z=5$ km in the two-layer model, we draw Fig. 2, from which we can find some differences between the figure with $k=1.5\times10^{-6}$ m^{-1} (smaller scale) and that with $k=4\times10^{-7}$ m^{-1} (ultra scale) under lower (higher) SST.

Figure 2 shows the influences of SST are as follows: when SST is lower $[2r_T/(N^2\Delta z) < 1]$, period becomes longer with an increase in SST; when SST is higher $[2r_T/(N^2\Delta z) > 1])$, period becomes shorter with an increase in SST. Furthermore, periods of ultra-long waves are longer than that of long waves of kilometer-scale size under conditions of the same SST.

Disregarding two important horizontal scales of LFO in the tropics—planetary scale ($L \sim 10^7$) motion and precipitation cloud with a smaller scale ($L \sim 10^6$ m)—we compared the responses of the two scales to SST heating and its anomaly. Using the scale analysis, the results shows the following:

(1) For planetary scale motion in the x direction, which is familiar in the tropics, the characteristic space scales are 10^7 m in the x direction and 10^6 m in the y direction; and the corresponding characteristics of wind velocity in the x and y directions are 10 m s^{-1} and 10^0 m s^{-1} respectively. The characteristic value of divergence is 10^{-6} s^{-1}. We take, $\beta_0 = 10^{-11}$ m^{-1} s^{-1}, $N = 1 \times 10^{-2}$ s^{-1} and $\Delta z = 10^3$ m. By scale analysis, we know that the characteristic value of $\widehat{\varphi}$ and w_2 are 10^2 m^2 s^{-2} and 10^{-3} m s^{-1}. Because the value of $\partial\widehat{\varphi}/\partial t$ is smaller, we take long-wave approximation, i.e. the semi-geostrophic model ($\delta = 0$). In the thermal equation, if the value of $(N^2 w_2)/2$ is equivalent to the value of $\alpha_s\widehat{\varphi}$, the value of parameter α_s, which can show the SSTA, is taken as $\alpha_s \sim 10^{-9}$ m^{-1} s^{-1}; if the value of $(N^2 w_2)/2$ is equivalent to the value of

$$r_T\left(\frac{\partial\widehat{u}}{\partial x}+\frac{\partial\widehat{v}}{\partial y}\right),$$

the value of parameter r_T, which can show SST, is taken as $r_T \sim 10^{-1}$ m^2 s^{-1}.

(2) For large scale motion with $L_x \sim L_y \sim 10^6$, the characteristic wind velocity in the x direction and in the y direction are both 10 m s^{-1}, and the characteristic value of divergence is 10^{-5} s^{-1}. By scale analysis, we can obtain that the characteristic value of $\widehat{\varphi}$ to be 10^1 m^2 s^{-2}, and the characteristic value of w_2 to be 10^{-2} m s^{-1}. Therefore, we must take $\delta = 1$ in Eq. (6). In the thermal equation, if the value of $(N^2 w_2)/2$ is equivalent to the value of $\alpha_s\widehat{\varphi}$, and the value of $(N^2 w_2)/2$ is equivalent to the value of

$$r_T\left(\frac{\partial\widehat{u}}{\partial x}+\frac{\partial\widehat{v}}{\partial y}\right),$$

then the value of α_s is 10^{-7} m^{-1} s^{-1} and the value of r_T is 10^{-1} m^2 s^{-1}.

Based on the above analysis, we know the impacts of SSTAs on ultra-long waves are more evident than on the large scale, while the impacts of sea surface heating on ultra-long waves and large-scale waves are equivalent. In addition, we also realize that the motion of large-scale waves can not be omitted for considering the effects of sea surface heating.

When the effect of the SSTA is evident, we must take $\alpha_s \neq 0$. Based on the results of scale analysis, we know the impacts of the SSTA on ultra waves are more evident than those on a large scale. Therefore, we take long-wave approximation ($\delta = 0$), that is, the term k^2 in Eq. (15) can be omitted, and the planetary scale is emphasized.

The frequency expression in the low-frequency domain can be attained:

$$\sigma=\frac{1}{2}\left[-i\alpha_s\Delta z \pm \sqrt{\frac{4k^2(N^2\Delta z^2/2-r_T\Delta z)}{(1+2m)^2}-\alpha_s^2\Delta z^2}\right]$$
$$=\sigma_{\rm r}+i\sigma_{\rm i}\quad (m=0,1,2\ldots)\,. \tag{16}$$

For Kelvin waves,

$$\sigma=\frac{1}{2}\left[-i\alpha_s\Delta z+\sqrt{4C_2^2k^2-\alpha_s\Delta z^2}\right].$$

Therefore, the propagation of Kelvin waves is eastward due to the effects of SST.

For Rossby waves,

$$\sigma=\frac{1}{2}\left[-i\alpha_s\Delta z-\sqrt{\frac{4k^2C_2^2}{(1+2m)^2}-\alpha_s^2\Delta z^2}\right]$$
$$(m=0,1,2\ldots)\,,$$

and Rossby waves are eastward due to the effects of SST.

From Eq. (16), frequency σ_r is decreasing with the increase of α_s, that is, the periods of LFO in the tropics is becoming larger with the increasing of SSTAs. Furthermore, the impacts of SSTAs ($\alpha_s \neq 0$) can make waves unstable ($\sigma_i \neq 0$). Positive (negative) SSTAs can make waves decay (grow). These results are in agreement with the conclusions of Li and Li (1996), however the results of the present study show the effects of SSTAs on the larger scale is more evident.

3. Discussion and conclusions

SST is an important factor affecting tropical LFO. The influences of SST include not only sea surface heating, but also the forcing of SST anomalies. Tropical LFO ranges from the planetary scale to a kilometer-sized scale. The response to SST anomalies on the planetary scale is much more severe than that on the kilometer-sized scale, while the response to SST heating on the planetary scale is equivalent to that on the kilometer-sized scale. Therefore, LFO on the synoptic scale cannot be neglected when sea surface heating is considered. Using the absolute ageostrophic model, conclusions can be drawn based on the discussion of the frequency equation as follows:

(1) When SST is comparatively low, sea surface heating can slow down the speed of waves and make the frequency low; and when SST is comparatively high, waves become unstable, and periods of LFO become shorter with the increase in SST.

(2) The period of LFO waves augments with the abnormal increasing of SST, and the wave is unsteady under the effect of the SST anomaly. The wave weakens with abnormally high SST, while the wave rises with abnormally low SST.

The influences of sea surface heating and SST anomalies on the frequency and stability of tropical LFO are mainly discussed in this paper. However, we only considered the effects of SST on the atmosphere. In virtue of the complicated interaction between the ocean and atmosphere, this relatively simple model has limitations in that the influences of SST are mainly manifested by parameters of the atmosphere. Therefore, it is necessary to further investigate the impacts of SST on tropical LFO waves, either theoretically or by numerical modeling.

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