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The basic mechanism behind the hurricane-free warm tropical ocean

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Abstract

No hurricane is detected in the tropics off the Brazilian coast due to the lack of initial conditions (e.g., the weak vertical shear of horizontal wind) despite that high sea surface temperature is available. According to previous studies, the initial conditions (as the ingredients of hurricane's embryo) are related so that the thick warm-and-moist layer (due to the updraft vapour) below a cold-and-dry layer frames the convective instability which enhances diabatic processes accompanied by tropical cyclones with the weak vertical shear. So the basic question is how, starting with an internal-disturbance-free balance-situation, external forces create the rapidly-upward acceleration of moist air at the warm sea surface. The answer is revealed by the vertical-momentum equation which shows that boosted by the external-force-induced significant lower-layer equatorial westerly wind (LLEWW), the upward (unit-mass) acceleration could be as significant as the midlatitude Coriolis force. Besides creating cyclonic vortices through the upward acceleration and diabatic processes, the external-force-induced significant-LLEWW could directly create cyclonic wind shears along with easterly jets for the low-level cyclonic vorticity through reducing the peak value of zonally-homogeneous trade easterlies (centered at the Equator between the Northern and Southern Hemisphere subtropical high-belts). We emphasize external forces to avoid the "chicken-and-egg" problem accompanying nonlinear interactions of internal-forcing processes. The external-force-induced significant-LLEWW could result from the deflection of the cross-equatorial flow characterized by the seasonal shift coincident with that of locations of most embryos. This significant cross-equatorial flow is driven by the significant differential heating between the largest continent with the highest plateau and the largest ocean with the warm pool located to the east and on the equatorward side of the continent on the rotating Earth. Unfortunately, in the tropics off the Brazilian coast, the differential heating is weak between the relatively-small ocean and land mostly covered by tropical rainforest. No significant-LLEWW means no hurricane's embryo. A warm spawning ground without the embryo means no hurricane. Our investigation suggests

that the external-force-induced significant-LLEWW embedded in the significant trade easterlies over the warm ocean be necessary and sufficient for making the embryo originate in an internal-disturbance-free balance-situation.

1 Introduction

Although hurricane Catarina observed in March 2004 is documented as the first severe tropical cyclone (STC i.e., hurricane or typhoon) in the South Atlantic region historically, it only affected the latitudes from 25.3° S to 32.3° S during its whole life cycle (McTaggart-Cowan et al., 2006). Therefore, we might say that so far there is no STC detected in the tropics off the Brazilian coast despite that the high sea surface temperature (SST≥26.5 °C) is available (see the figure given by Trenberth, 2007).

According to previous studies, STCs are generated from the initial conditions of humid midtroposphere over a high-SST region, convective instability characterized by a warm-and-moist layer located below a cold-and-dry layer, cyclonic vortices and weak vertical shear of horizontal wind (e.g., Charney and Eliassen, 1964; Ooyama, 1969; Gray, 1979; Anthes, 1982, p. 49). These initial conditions are the ingredients of STC's embryo (borrowed from Emanuel, 1993, 2007; Montgomery et al., 2006; Dunkerton et al., 2009). Among these ingredients of the embryo, the intensity of the embryonic circulation is one of the important factors for the strength of STC (Emanuel, 1999). Dunkerton et al. (2009) not only emphasize the neccesity of embryonic circulation but also raise a profound question: "*yet to be answered, however, is how this 'embryo' and its surrounding circulation are created in the first place*". After carefully examining 55 hurricane cases in 1998–2001, they conclude that an easterly jet with a region of cyclonic vorticity on the equatorward side of the jet is important to the initiation of embryonic circulation (Dunkerton et al., 2009). We follow this line but try to approach the problem from an opposite angle, that is, why the warm tropical ocean off the Brazilian coast is freed of hurricanes.

As pointed out by Anthes (1982, 49–51), the initial conditions are related in such a way that the convective instability depends on the surface-to-midtroposphere moist layer caused by low-level convergence of moist air in convective clouds over high SST regions. This high relative-humidity in convective clouds makes significant contribution to diabatic heating (Anthes, 1982, p. 51) while the diabatic heating in a finite equatorial region can initiate two tropical cyclonic vortices on each side of the Equator (e.g., Gill, 1980; Hartmann and Hendon, 2007). The lower-layer equatorial westerly wind (LLEWW) between these two cyclones creates the weak vertical shear of horizontal wind through reducing the lower-layer trade easterlies beneath the upper-layer westerlies (Fig. 1).

The above studies might lead to a more basic question of how, starting with an internal-disturbance-free balance-situation, external forces create the rapidly-upward acceleration of moist air at the warm sea surface. The reason for emphasizing the role of external forces in creating the disturbance is to avoid being dragged into the "chicken-and-egg" problem caused by the interactions of internal-forcing processes in the nonlinear atmospheric system. In the present study, two kinds of balance situations are considered. One is the idealized-balance situation characterized by the motionless field (e.g., without the presence of trade easterlies). The other is the wave-free trade easterlies between the Northern Hemisphere (NH) and the Southern Hemisphere (SH) subtropical-high belts under the geostrophic balance and hydrostatic balance. The wave-free trade easterlies refer to the zonally-homogeneous trade easterlies without easterly waves and the upstream-and-downstream effects of dispersive waves. The geostrophic balance and hydrostatic balance refer to the absence of horizontal and vertical accelerations and rising motion at the sea surface.

To figure out the answer to the basic question as well as to the basic mechanism behind the hurricane-free warm tropical ocean off the Brazilian coast, we first examine observations (Sect. 3). Then we apply the geophysical-fluid-dynamic equations to explaining physical processes behind observations (Sect. 4). Finally we demonstrate how to extract the leading signal of LLEWW from the observations of the nonlinear atmospheric system under the upstream-and-downstream effects of dispersive waves and the dominant effect of balance flow (Sect. 5). Methods and data used in the present study are described in Sect. 2. Summary and conclusions are in Sect. 6.

2 Methodology and data

In the observational analysis, the daily, long-time mean and anomalous (from the mean) zonal wind, geopotential and SST data on a 1.5°×1.5° latitude-longitude grid are all derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis Archive Interim (ERA-Interim) dataset. Since the daily, long-time mean and anomalous (from the mean) outgoing longwave radiation (OLR) data are not available at the ECMWF, the OLR data with 2.5°×2.5° latitude-longitude resolution are derived from the National Oceanic and Atmospheric Administration (NOAA).

Geophysical-fluid-dynamic conservation laws govern the behaviors of atmospheric motion, so they are applied to the interpretation of observations. The composite technique and empirical orthogonal function (EOF) analysis are then used to extract the leading signal of LLEWW (indicated by the vertical-momentum equation) in the processes before the presence of the embryo for the yearly first STC.

The yearly first STC is determined according to the "best track" data at 00:00, 06:00, 12:00, 18:00 UTC (Klotzbach, 2006) from Joint Typhoon Warning Center (JTWC), National Hurricane Center (NHC) and Japan Meteorological Agency (JMA). We realize that the accuracy of STC records has been improved in recent years due to advanced techniques used in satellites (Chan, 2006; Klotzbach, 2006). Therefore, recent-year records are used in the present study.

3 The inspiration from observations

In order to find the answer to how a rapidly-upward acceleration of moist air starts from the warm sea surface beneath the wave-free trade easterlies under the geostrophic balance and hydrostatic balance in the first place, we first gain the inspiration from observations (Fig. 2). As shown by Fig. 2, although most tropical oceans (including the tropics off the Brazilian coast) experience SST≥26.5 °C, the distribution of the embryo coincides with that of climatological LLEWW better than that of high SST. For example, the seasonal shift of locations of most embryos coincides quite well with that of climatological LLEWW especially in the Western Pacific equatorial region. In March (with very weak westerly wind) and April (with weak westerly wind), the Eastern North Pacific tropical region is freed from embryos although the high SST is available until the westerly wind becomes stronger in May. After May (with the observed stronger westerly wind and the presence of embryo), the region affected by westerly wind enlarges and the number of the embryo increases substantially, leading to the STC-active season in the Eastern North Pacific tropical region. Consistent with Fig. 1, the weak vertical shear appears in the regions to the polarward sides of LLEWW (Fig. 2).

Figure 2 also shows that despite the high SST available throughout the year, the LLEWW, weak vertical shear and the embryo are all absent in the tropics off the Brazilian coast, while Gray (1968) considers the absence of weak vertical shear as a primary reason for the absence of hurricane there. Both previous studies and observations (e.g., the LLEWW embedded in the trade easterlies responsible for the low-level convergence) indicate that there exists a close linkage between the LLEWW and the rapidly-upward acceleration. Excitingly, such a linkage is also revealed by the vertical-momentum equation (Holton, 2004, p. 41) for the geophysical fluid even with the absence of the easterly wind.

4 The linkage between the LLEWW and the upward acceleration

The primitive equation for the vertical momentum of the air motion on the rotating Earth in spherical coordinates (Holton, 2004, p. 41) is:

$$\frac{dw}{dt} = 2\Omega u \cos\phi - \frac{1}{\rho}\frac{\partial p}{\partial z} - g + \frac{u^2+v^2}{a} + F_{rz}. \qquad (1)$$

An internal-disturbance-free balance-situation is at least in the geostrophic balance and hydrostatic balance with:

$$-\frac{1}{\rho}\frac{\partial p}{\partial z} - g = 0. \tag{2}$$

So Eq. (1) becomes:

$$\frac{dw}{dt} = 2\Omega u \cos\phi + \frac{u^2+v^2}{a} + F_{rz}. \tag{3}$$

According to Holton (2004, p. 41), the magnitudes of the last two right-hand side (rhs) terms (respectively associated with the curvature of the Earth and friction) are much smaller than that of the first rhs term. So the last two rhs terms can be eliminated, leading to:

$$\frac{dw}{dt} = 2\Omega u \cos\phi. \tag{4}$$

In Eq. (4), Ω is the angular rotation rate of the Earth while the Earth's rotation is the well-known source of external force acting on the atmosphere. Obviously, if Ω were zero, then hydrostatic balance would lead to:

$$\frac{dw}{dt} = 0. \tag{5}$$

However in reality, the angular rotation rate of the Earth $\Omega = 7.292\times10^{-5}\ \mathrm{s}^{-1}$ is non-zero, so is the external-force-induced LLEWW ($u>0$). Therefore Eq. (4) reveals that even beginning with a zero-relative-wind field, the external-force-induced LLEWW-burst ($u>0$) can boost upward acceleration in the latitudes with $|\phi|<90^\circ$. Keep in mind that $\cos\phi$ reaches its maximum value (i.e., $\cos 0^\circ = 1$) at the Equator and the relative velocities u and w detected on the rotating Earth are in the same equatorial plane with $\boldsymbol{\Omega}$ perpendicular to the vertical coordinate $\boldsymbol{k}_{eq} = \boldsymbol{w}_{eq}/|\boldsymbol{w}_{eq}|$ (Fig. 3). Therefore, $dw/dt = 2\Omega u > 0$

at the Equator created by the external-force-induced evenly-distributed flow (double-line arrows in Fig. 3) could be at least as significant as the middle latitude Coriolis force (Holton, 2004, p. 41). In the following interpretation of physical processes behind Eq. (4), we first consider the situation without the presence of trade easterlies, then that with the presence of trade easterlies.

Figure 3 illustrates how $dw/dt>0$ is created by the external-force-induced LLEWW ($u>0$) alone (referring to the absence of trade easterlies). As shown by Fig. 3, if at $t=0$ the external-force-induced flow is responsible for ($u>0$, $w=0$) at point A, then after the Earth rotates from point A to point B during a short period of time $t=\Delta t$, the external-force-induced flow will account for $w>0$ due to $dw/dt=2\Omega u>0$. Be aware that the above discussion is not suitable for the long-period evolution of a global-scale system which requires the corresponding zonal momentum equation $du/dt=2\Omega w$ (under the geostrophic balance which coexists with the hydrostatic balance (Pedlosky, 1987, p. 50) at the Equator with $uv\tan\phi=0$ and $\cos\phi=1$). A global-scale system is not the focus of the present study.

In the real atmosphere with the presence of traded easterlies, the effect of LLEWW on $w>0$ at the sea surface could be even more robust due to the additional effect of low-level convergence between the LLEWW and the equatorial easterly wind (Anthes, 1982, 49–51). In this situation, the external-force-induced LLEWW working with the trade easterlies (to form the well-known equatorial convergence zone) would be able to create the upward transport of moist air from the warm sea surface to the midtroposphere. This equatorial convergence zone together with $dw/dt=2\Omega u>0$ at the Equator might account for most convective clouds observed around the Equator under the effects of the largest continent with the highest plateau and the largest ocean with the warm pool located to the east and on the equatorward side of the continent on the rotating Earth (Fig. 2).

In the preceding paragraphs, we focus on external forces rather than internal forces because we try to avoid being stuck by the “chicken-and-egg” problem in the nonlinear interactions of internal-forcing processes. In reality, one of external sources of signifi-

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cant LLEWW could be the deflection of the cross-equatorial flow characterized by the seasonal shift coincident with the seasonal shift of locations of most embryos (Fig. 2). The significant cross-equatorial flow can be induced by the significant differential heating between the largest continent with the highest plateau and the largest ocean with the warm pool located to the east and on the equatorward side of the continent on the rotating Earth. We notice that the size of the warm water off the Brazilian coast is relatively small and its neighbouring land is mostly covered by tropical rainforest. So such an external source of significant LLEWW is not available in the warm tropics off the Brazilian coast, which could probably be the basic mechanism behind the hurricane-free warm tropical ocean.

To see this probability, we go back to the original question proposed by Dunkerton et al. (2009) about the initiation of the embryonic circulation. According to previous studies, the favourable processes could be direct and indirect. The direct process is associated with cyclonic wind shear on the equatorward side of a low-level easterly jet demonstrated by Dunkerton et al. (2009), while the external-force-induced significant LLEWW could be a direct contributor (Fig. 4). This direct effect of significant LLEWW on the low-level cyclonic wind shear (Fig. 4b) is accomplished by reducing the peak value of the zonally-homogeneous trade easterlies centered at the Equator between the NH and SH subtropical high belts (Fig. 4a). In view of this process, the embryonic circulation could be created even with the absence of diabatic heating. The indirect process is associated with diabatic processes demonstrated by Charney and Eliassen (1964), Gill (1980) as well as Hartmann and Hendon (2007). After the LLEWW-induced $dw/dt>0$ thickens the warm-and-moist layer underneath a cold-and-dry layer, the convective instability (associated with the potential temperature θ decreasing with height $N^2=g\partial\ln\theta/\partial z<0$) builds up (Anthes, 1982, 49–51) especially in the spring Hemisphere with relatively cold-and-dry troposphere. As a result, the non-hydrostatic buoyancy comes into play, leading to the additional upward acceleration for the air parcel:

$$\frac{Dw}{Dt} = -N^2 \delta z > 0 \tag{6}$$

(Holton, 1979, p. 50, 2004, p. 52) and diabatic processes. According to previous studies (e.g., Charney and Eliassen, 1964; Gill, 1980; Hartmann and Hendon, 2007), the diabatic heating in a finite equatorial region can initiate two tropical cyclonic vortices on each side of the Equator. Since tropical cyclonic vortices are the internal sources of LLEWW, these direct and indirect internal processes are all positive-feedback processes favourable for the $dw/dt>0$ as well as the generation of the embryo in a negative-interference-free situation. In this sense, we might say that the absence of external source of significant LLEWW could lead to the absence of the embryo. A warm spawning ground without the embryo could mean the absence of hurricane.

To justify the linkage between LLEWW and $dw/dt>0$ shown by Eq. (4) with the observational information, we look back to Fig. 2. Through comparing the distribution of the observed OLR≤220 W m^{-2} (representing the strong upward acceleration according to Gunn et al. 1989) and that of climatological LLEWW, we see that the climatological LLEWW centers overlap OLR minimum centers around the Equator. This feature is pronounced especially in the Western Pacific equatorial region under the effects of the largest continent with the highest plateau and the largest ocean with the more significant LLEWW and trade easterlies (for the significant low-level convergence). Notice that in Fig. 2 both OLR minimum centers (≤220 W m^{-2}) and LLEWW are absent in the warm tropics off the Brazilian coast. Although the coincidence of OLR minimum centers with LLEWW centers can also be identified in daily LLEWW and OLR fields in the period prior to the STC-active season (Fig. 5), they might be buried in observations when the STC-active season is approaching. During the STC-active season, both STC-induced LLEWW and upstream-and-downstream effects of dispersive waves (Matsuno, 1966; Gill, 1980; Pedlosky, 1987, p. 679) will mask the leading signal of the external-force-induced LLEWW shown by Eq. (4).

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We realize that in Fig. 2 not all of the embryos are located right in the centers of climatological LLEWW. One of the reasons is that in Fig. 2 the LLEWW is plotted based on the 20-year-mean zonal wind information not single embryo information. Additionally, after the external-force-induced LLEWW boosts the nonlinear process due to the nonlinear term $w\partial w/\partial z$ in $dw/dt(=\partial w/\partial t+\mathbf{V}_2\cdot\nabla w+w\partial w/\partial z)>0$, the upward vapour transport, convective instability and cyclonic-vortex-induced LLEWW will interact with each other nonlinearly in the period before the embryo is detected. Therefore, we would not expect the significant linear relation between the climatological LLEWW and the location of single embryo in Fig. 2. The final reason is that whenever the embryo forms with the feature of cyclonic vortex, westerly winds can only be observed on the equatorward side of the vortex center.

5 Extracting the leading signal of LLEWW from observations

Equation (4) is a nonlinear prognostic equation of w, which states that if $w=0$ at $t=0$, then the external-force-induced LLEWW with $u>0$ will boost the rising motion (i.e., $w>0$) at $t=\Delta t$ (Fig. 4). To extract such a leading signal of LLEWW in the initiation of low-level low-pressure systems, we have to rely on statistical methods such as the EOF analysis due to the unavailable sophisticated-method and highly-accurate w information used in solving the nonlinear w equation numerically. Additionally, as mentioned earlier, this leading signal of LLEWW might be masked by the dominant effect of balance flow, upstream-and-downstream effects of dispersive waves and the STC-induced LLEWW in the nonlinear processes of the real atmosphere (e.g., Matsuno, 1966; Gill, 1980; Pedlosky, 1987, p. 679; Holton, 2004, 186–188). Last but not least, in the STC-active season it is difficult to separate the effect of external-force-induced LLEWW from the effect of STC-induced LLEWW. So we only focus on the embryo of the yearly first STC.

The yearly first STC is determined based on tropical storms' records provided by the JTWC, NHC and JMA. According to Klotzbach (2006) and Chan (2006), the accuracy of the records is improved in recent years due to advanced techniques used in satellites. Thus, the EOF analysis is performed based on 1999–2008 composite records.

The three leading EOF modes of the composite 850 hPa zonal wind, respectively account for 48.1%, 16.5% and 13% of the total variance (Fig. 6). The spatial patterns, respectively associated with these three modes (Fig. 6a, c and e) all show an out-of-phase relationship between the 850 hPa zonal wind to the north and that to the south of the composite center of the embryos which come into being. So the signal for the transition from the equatorial easterly wind to the sustained equatorial westerly wind can be identified clearly by the corresponding three time series of the expansion coefficients. This transition happens 20 days and three days prior to the presence of the composite embryo according to the first mode, second and third modes, respectively (Fig. 6b, d and f).

The three leading EOF modes of the composite 850 hPa geopotential, respectively account for 54.5%, 16.8% and 12.2% of the total variance (Fig. 7). The spatial patterns, respectively associated with these three modes (Fig. 7a, c and e) all show a homogeneous correlation in the geopotential around the composite center of the embryos which come into being. So the signal for the transition from the high to the sustained low can be identified clearly by the corresponding three time series of the expansion coefficients. This transition happens almost 17 days, five days and almost two days prior to the presence of the composite embryo according to the third, second and first modes, respectively (Fig. 7f, d and b).

These results of EOF analysis also show that the earliest signal of sustained LLEWW not only leads the earliest signal of sustained tropical low system by more than three days but also becomes more significant in terms of explaining the total variance. According to the general knowledge, when the external-force-induced LLEWW is the cause, and the low pressure system is the effect, then the extracted signal of the cause not only leads the extracted signal of the effect but also becomes more significant in terms of explaining the total variance. These cause-and-effect characteristics are even more obvious when this cause-and-effect process takes place in the tropics around the Equator where strong winds can be associated with a weak low pressure system (Trenberth et al., 1998). Since a certain period of time is required for the geopotential (the effect) to respond to the evolution of external-force-induced LLEWW (the cause), during this time period, the nonlinear interactions of many processes might weaken the linear relations between the LLEWW EOF modes and the geopotential EOF modes.

For the concern of forecasters, we also investigate several individual cases (Fig. 8). Since recent records show that the yearly first STC is generally detected over the Western North Pacific, yearly first STCs selected for the present case study are all typhoons. Each case in Fig. 8 shows the evolution of the LLEWW in the region on the equatorward side of the embryo which comes into being. Consistent with the preceding results, the LLEWW appears at least two days before the embryo is detected. The leading signal carried by the LLEWW can also be identified in a previous TC activity study (Wu and Chu, 2007). Taking a closer look at Fig. 11 given by Wu and Chu (2007), we might say that the westerly-wind anomaly appears long before the TC genesis in both TC-active and TC-inactive cases in June (i.e., the early stage of the active season for the Eastern-North-Pacific STCs).

6 Summary and conclusions

Dunkerton et al. (2009) recently address a very interesting problem of how the embryonic circulation (as an important ingredient for the hurricane's embryo) is created in the first place through the survey of 55 named tropical storms in 1998–2001. We follow this line but investigate the problem from an opposite angle, that is, why the warm tropical ocean off the Brazilian coast is freed from hurricanes. According to previous studies (e.g., Charney and Eliassen, 1964; Gill, 1980; Anthes, 1982; Hartmann and Hendon, 2007), the initial conditions (as the ingredients of hurricane's embryo) are related in such a way that the thick warm-and-moist layer (due to the updraft vapour) below a cold-and-dry layer frames the convective instability which enhances diabatic processes accompanied by tropical cyclonic vortices with the weak vertical shear (Fig. 1).

So a more basic question is how, beginning with an internal-disturbance-free balance-situation, external forces create the rapidly-upward acceleration of moist air at the warm sea surface. We prefer external forces because we try to avoid the "chicken-and-egg" problem accompanying the interactions of internal-forcing processes in the nonlinear atmospheric system.

Searching for the answer to this basic question and the basic mechanism behind the hurricane-free warm tropical ocean off the Brazilian coast, we first gain the inspiration from observations. According to observations, on one hand, the LLEWW, OLR minimum centers, the weak vertical shear of horizontal wind and the embryo are all absent in the tropics off the Brazilian coast where STC has not yet been detected so far despite the high SST available throughout the year (Fig. 2). On the other hand, the seasonal shift of locations of most embryos coincides quite well with that of climatological LLEWW especially in the Western Pacific equatorial region. Both previous studies and observations (e.g., the LLEWW embedded in trade easterlies responsible for the well-known equatorial convergence zone) indicate that the LLEWW might directly cause the upward acceleration $dw/dt>0$. This direct effect of LLEWW ($u>0$) on $dw/dt>0$ has been described by the vertical momentum equation $dw/dt=2\Omega u$ at the Equator under the hydrostatic balance (Holton, 2004, p. 41) even with the lack of easterly winds (Fig. 3). Despite receiving little attention, $dw/dt=2\Omega u>0$ could be at least as large as the midlatitude Coriolis force due to the significant LLEWW resulting from the deflection of the significant cross-equatorial flow driven by the significant differential heating between the largest continent with the highest plateau and the largest ocean with the warm pool located to the east and on the equatorward side of the continent on the rotating Earth. Unfortunately, such an external source of significant LLEWW is not available in the warm tropics off the Brazilian coast with the relatively-weak differential heating between the relatively small ocean and land mostly covered by tropical rainforest.

As for the contribution of external-force-induced significant LLEWW to the origination of the embryonic circulation (i.e., the tropical cyclonic vortex), there will be a direct

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process besides the indirect process indicated by previous studies. In the indirect process, as the significant-LLEWW-induced upward vapour-transport thickens the near-sea-surface warm-and-moist layer, the convective instability builds up in the spring Hemisphere with relatively cold-and-dry troposphere. Consequently, the nonhydrostatic buoyancy comes into play, leading to a positive feedback process for the stronger upward acceleration (Holton, 1979, p. 50, 2004, p. 52) and diabatic processes accompanied by tropical cyclonic vortices (e.g., Charney and Eliassen, 1964; Gill, 1980) with weak vertical shear (Fig. 1). Different from the indirect process associated with the upward acceleration and diabatic processes, the direct process is associated with the creation of the cyclonic wind shear along with the easterly jet for the low-level cyclonic vorticity emphasized by Dunkerton et al. (2009). This direct effect of significant LLEWW on the low-level cyclonic wind shear (Fig. 4) is accomplished by reducing the peak value of the zonally-homogeneous trade easterlies centered at the Equator between the NH and SH subtropical high belts.

Be aware that the cyclonic-vortex-induced LLEWW will enhance the original effect of external-force-induced LLEWW and trigger another positive feedback process for both the upward acceleration and the initiation of the embryonic circulation. If there is no any negative interruption, then these two positive feedback processes will interact with each other nonlinearly, leading to the much stronger $dw/dt>0$ and the more favourable ingredients in the period before the embryo is detected. Using observational data and EOF analysis, we have demonstrated and justified such a leading role of the LLEWW embedded in the trade easterlies in the processes before (not after) the presence of the embryo for the yearly first STC. This EOF analysis shows that the earliest transition from equatorial easterly to sustained westerly winds can be identified three days before the earliest transition from high to sustained low pressure centers at 850 hPa, while the earliest transition from high to sustained low centers takes place 17 days before the embryo of the yearly first STC is detected.

Different from the studies focusing on the hurricane generation from the given embryo, our investigation focuses on the embryo generation in a balance situation without any net internal forcing and tropical disturbance. We might conclude that the high SST is necessary while the high SST working together with the external-force-induced significant LLEWW would be sufficient for making the embryo originate in the wave-free trade easterlies under the hydrostatic-balance condition. In reality, one of significant-LLEWW external sources could be the deflection of the cross-equatorial flow characterized by the seasonal shift coincident with that of locations of most embryos (Fig. 2). This significant cross-equatorial flow is driven by the significant differential heating between the largest continent with the highest plateau and the largest ocean with the warm pool located to the east and on the equatorward side of the continent on the rotating Earth. So the basic mechanism behind the hurricane-free warm tropical ocean off the Brazilian coast might be the lack of the external-force-induced significant LLEWW (due to the relatively-weak differential heating between the relatively small ocean and land mostly covered by tropical rainforest), leading to the absence of the embryo. A hot spawning ground without the embryo produces no hurricane.

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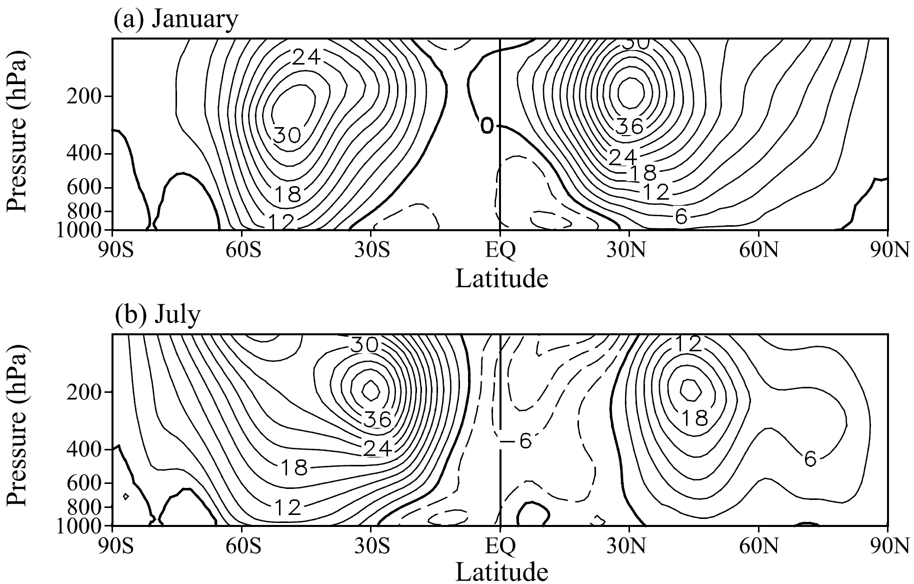

Fig. 1. The vertical-meridional distributions of observed zonal mean easterlies (m s^{-1} dashed) and westerlies (solid) for **(a)** January and **(b)** July based on the time mean (1989–2008) data from the ERA-Interim analysis data. The much-straighter-upward thick solid line in the NH summer indicates the weaker vertical shear due to the presence of LLEWW and the upper-layer equatorial easterlies.

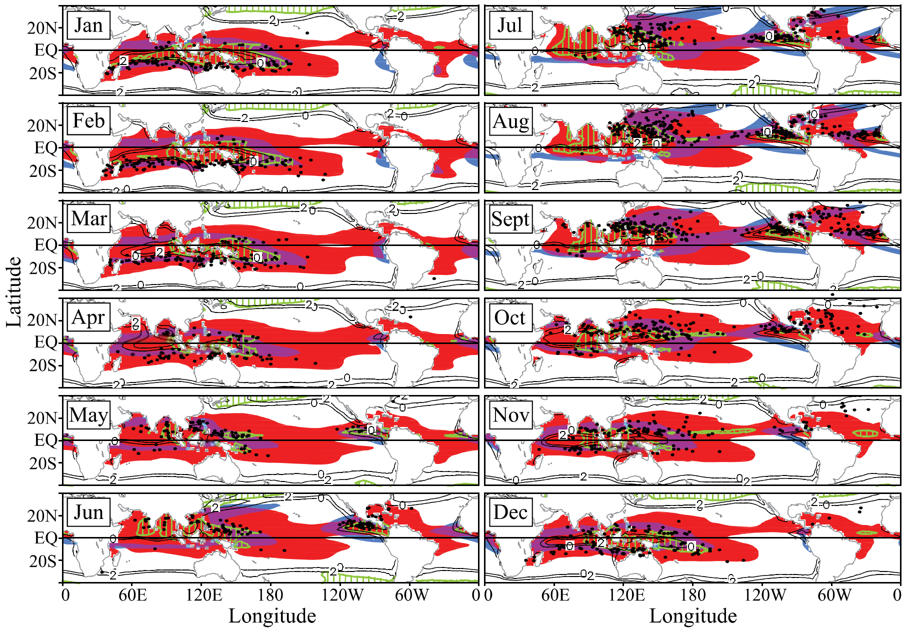

Fig. 2. The distributions of 1989–2008 mean surface westerly winds (thick solid with 0 and $2\,\mathrm{m\,s^{-1}}$ contoured), the vertical shear $|u_{200}-u_{850}|$ ($\leq 5\,\mathrm{m\,s^{-1}}$ blue), SST ($\geq$26.5 °C red) and OLR ($\leq 220\,\mathrm{W\,m^{-2}}$ green stripes). The purple indicates the areas affected by both SST$\geq$26.5 °C and weak vertical shear $|u_{200}-u_{850}|\leq 5\,\mathrm{m\,s^{-1}}$. The dots represent the locations of detected embryos.

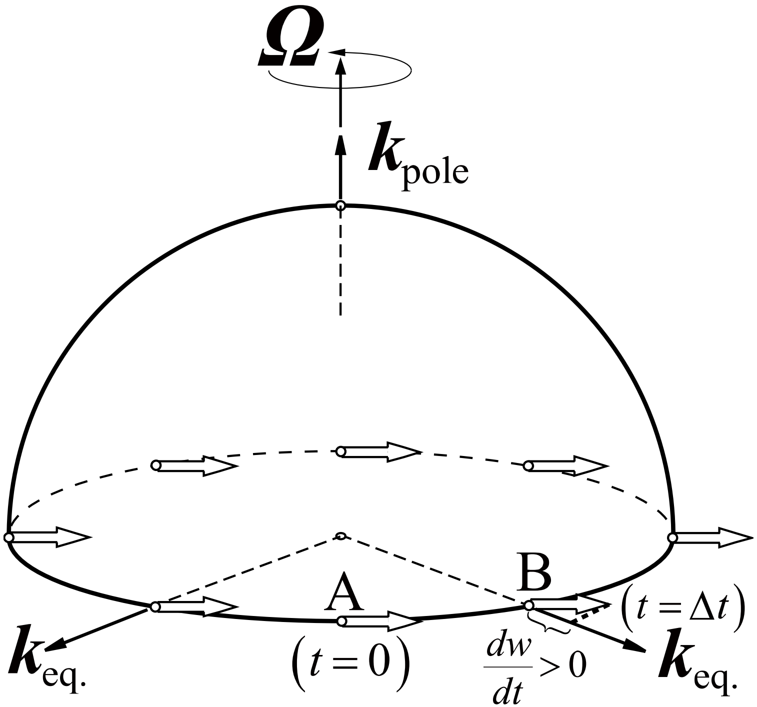

Fig. 3. The schematic illustration for the acceleration of upward motion at the Equator boosted by the external-force-induced LLEWW burst alone. The double-line arrows indicate the fixed and evenly-distributed flow induced by external forces.

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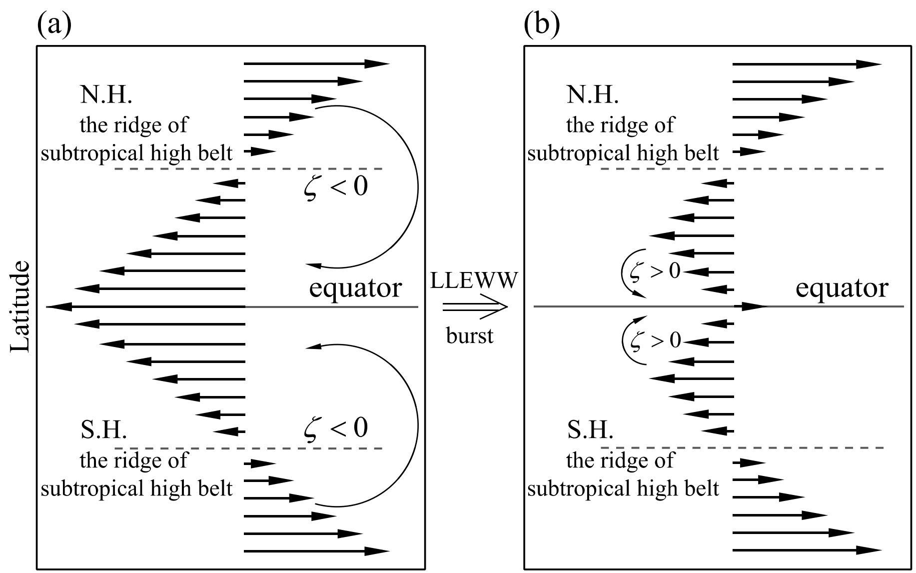

Fig. 4. (a) The zonal flow (thick arrows) distribution with latitude in the balance situation of the zonally-homogeneous trade easterlies between the NH and SH subtropical high belts. **(b)** The one-level cyclonic wind shears on the equatorward side of easterly jets induced by the external-force-induced LLEWW burst. Symbol ζ is the relative vorticity with $\zeta<0$ for anticyclonic vorticity and $\zeta>0$ for cyclonic vorticity.

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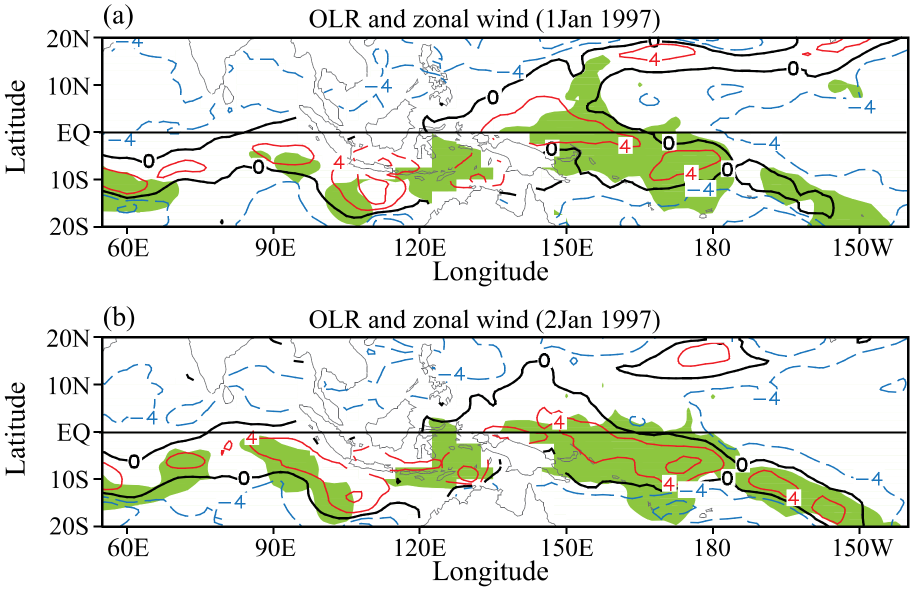

Fig. 5. The distributions of daily surface zonal winds with the interval of $4\,m\,s^{-1}$ (red solid for westerly and blue dashed for easterly) and daily OLR$\leq 220\,W\,m^{-2}$ (green) on **(a)** 1 January 1997 and **(b)** 2 January 1997 over the warm tropical ocean.

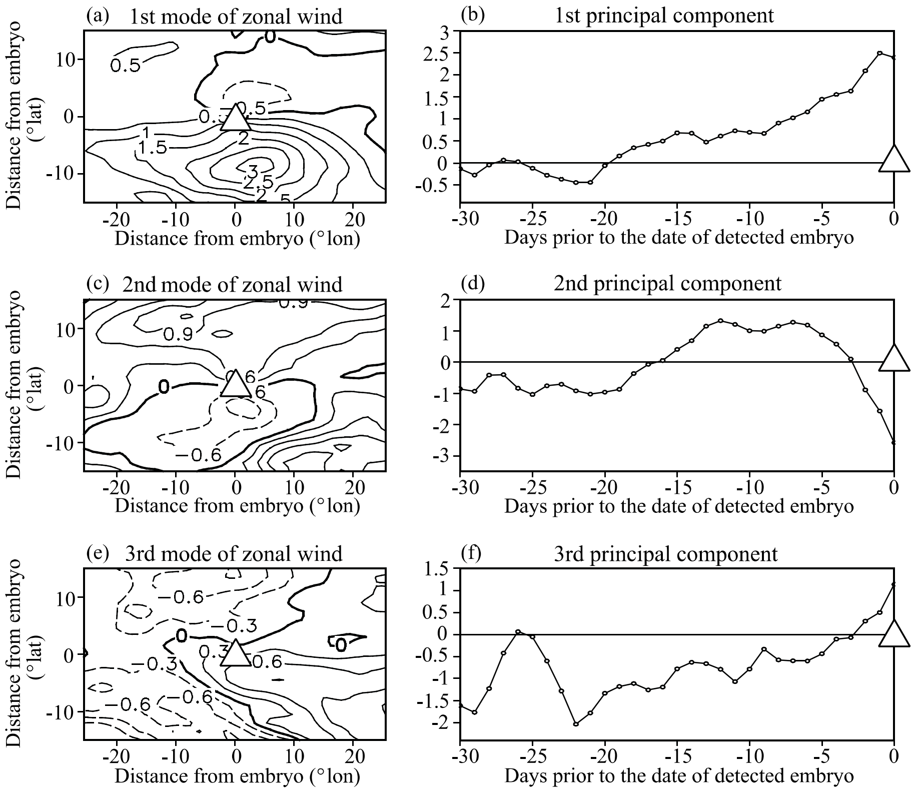

Fig. 6. The EOF-analysis results of 1999–2008 composite 850-hPa zonal wind anomaly departing from the 1989–2008 base period mean based on the ERA-Interim analysis daily data. The composite detected embryo (indicated by the triangle) for the yearly first typhoon is centered at (0, 0). In the left panels, the y-axis (x-axis) is labeled every 10° latitudes (longitudes) away from the center of the detected embryo. In the right panels, the x-axis is labeled every five days prior to the date of detected embryo. The three leading EOF modes explain, respectively 48.1% **(a**, **b)**, 16.5% **(c**, **d)** and 13.0% **(e**, **f)** of the total variance.

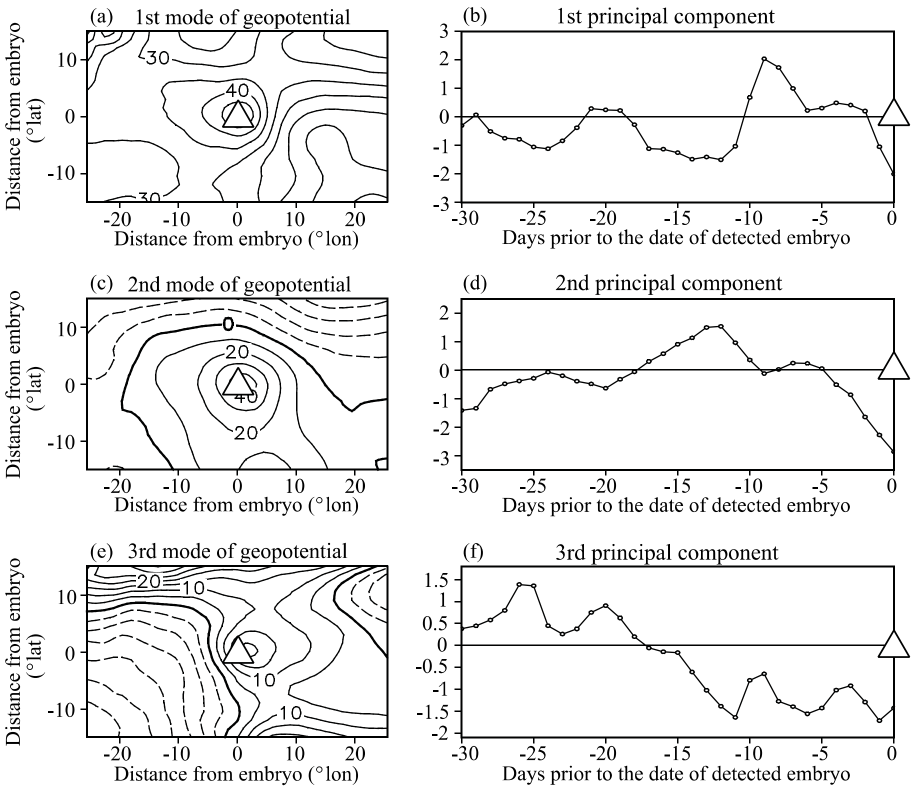

Fig. 7. Same as Fig. 6 except for the geopotential anomaly. The first, second and third EOF modes account for 54.5%, 16.8% and 12.2% of the total variance, respectively.

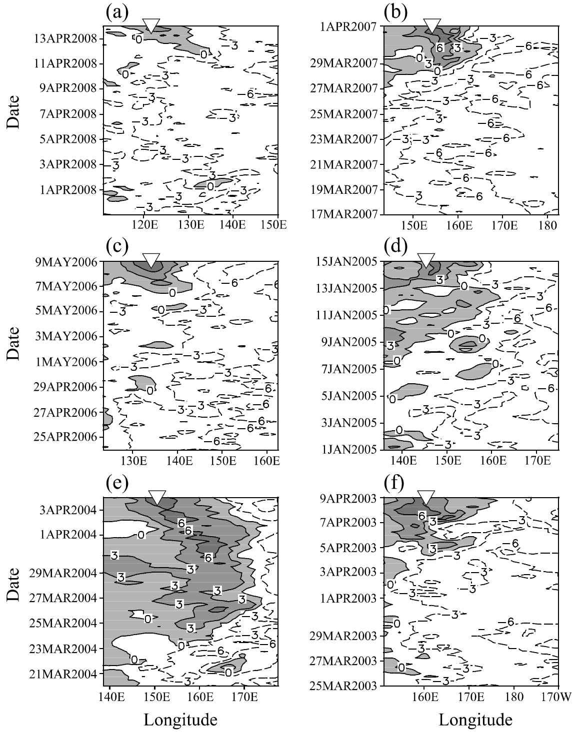

Fig. 8. The time-longitude sections of meridionally-averaged surface zonal wind (westerly shaded with $3\,m\,s^{-1}$ interval) obtained from the ERA-Interim data at fixed four-grid points on the equatorward side of the embryo which comes into being. The triangles indicate when and at which longitude the embryo is detected for the yearly first typhoon. **(a)** The embryo at (9.0° N 120.2° E) for typhoon NEOGURI in 2008. **(b)** The embryo at (8.7° N 153.8° E) for typhoon KONG-REY in 2007. **(c)** The embryo at (8.0° N 133.7° E) for typhoon CHANCHU in 2006. **(d)** The embryo at (6.5° N 147.4° E) for typhoon KULAP in 2005. **(e)** The embryo at (6.9° N 149.5° E) for typhoon SUDAL in 2004. **(f)** The embryo at (4.1° N 160.4° E) for typhoon KUJIRA in 2003.