Zhuojian Yuan
Department of Atmospheric Science
Sun Yat-sen University
Guangzhou, Guangdong 510275
P. R. China
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Dear Reviewer # 1:

Thank you very much for your comments on the manuscript (MS) entitled "*The basic mechanism behind the hurricane-free warm tropical ocean*" (acp-2009-742).

The following are the point-by-point replies to your comments.

Comment 1:"In normal meteorological language, the authors are suggesting that westerly wind bursts create favorable conditions for the formation of tropical cyclones in the equatorial region in both the northern and southern Hemisphere. The cyclonic shear supplied by such events has long been known to provide elevated cyclonic vorticity (above the prevailing planetary vorticity for these latitudes) necessary for the birth of such severe tropical storms in otherwise favorable environmental conditions (low vertical shear, warm SST's moist low- to mid-troposphere, etc.). We needn't look too far for illustrative examples of the importance of westerly wind bursts in tropical cyclone formation in the near equatorial region. This past month or so has provided examples in the south Pacific."

Reply: In the manuscript (ms) we mention that the cyclonic shear could be caused by the external-force-induced westerly wind because we want to support the result from previous studies as well as to emphasize the effect of external-force-induced westerly wind for avoiding the "chicken-and-egg" problem in the nonlinear real atmosphere.

Comment 2:"The authors use the vertical momentum equation in an unorthodox way for a rotating fluid to attempt to provide a

theoretical foundation for their particular argument of embryo formation in the equatorial region. They then examine ERA observations and NOAA OLR data to support their interpretation."

Reply: We just try to understand the unsimplified vertical momentum equation, use it to interpret observations in different atmospheric environments and show people that the effect of $2\Omega u$ at the Equator (the abandoned term by the hydrostatic balance assumption) on destroying the balance condition and creating the vertical acceleration at the sea surface with $w = 0$ from internal-disturbance-free background could exist in the real atmosphere and the magnitude of $2\Omega u$ could be as large as that of the midlatitude Coriolis force. We did not modify and simplify the primitive vertical momentum equation. We do not intend to turn against the traditional perspective valid for the atmosphere satisfying the simplified version of the vertical momentum equation which neglects $2\Omega u \cos\varphi$ even with the presence of horizontal wind. We are aware that the magnitude of $2\Omega u$ at the equator is smaller than that of the gravity. However, $dw/dt > 0$ is required for destroying balance situation and creating upward acceleration of vapour at the sea surface with $w = 0$ in order to initiate severe storms (the focus of our study). So the contribution of $2\Omega u$ to $dw/dt > 0$ could be larger than the net contribution of the gravity and vertical pressure gradient forces especially at the beginning of the convective activity since the gravity g is always balanced more or less by the vertical pressure gradient force $-(\partial p/\partial z)/\rho$.

Comment 3:"Holton 1979, 1992, 2004 (and others) note that some care is required in order to justify the hydrostatic approximation for a moving fluid under rotational influences. Once the background pressure gradient and gravity forces are subtracted from the vertical force balance there remains a perturbation vertical pressure gradient and buoyancy force defined relative to the resting background in hydrostatic balance. It is generally dangerous to invoke cause and effect arguments in a fluid without accounting for the sign and

magnitude of the perturbation pressure and buoyancy forces."

Reply: We agree with you. So when we mentioned the effect of the nonhydrostatic buoyancy on the vertical acceleration on page 9 of the original ms, we emphasized the negative sign of buoyancy frequency and positive sign of dw/dt.

Please see page 10 in the ms for:

"*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, P49-51) especially in the spring Hemisphere with relatively cold-and-dry troposphere. As a result, the nonhydrostatic buoyancy comes into play, leading to the additional upward acceleration for the air parcel:*

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

(Holton, 1979, P50; Holton, 2004, P52) and diabatic processes under the condition that the nonlinear interference is absent or the negative effect of vertical pressure gradient perturbation is small." We also revise the summary to emphasize the sign and magnitude of contributors as: "*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. The significant LLEWW is required to overcome the negative interference involved in the real atmosphere. 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."

The content in green in the revised sentences is added for taking your comments into account.

Comment 4:"In a strictly hydrostatic approximation, in which the perturbation pressure gradient and buoyancy forces are assumed to exactly cancel, THE VERTICAL VELOCITY IS NO LONGER OBTAINED FROM THE VERTICAL MOMENTUM EQUATION. Indeed, the vertical motion is then determined from the mass-continuity equation wherein the horizontal motion field is governed by the horizontal momentum equations. The authors have instead used the RESIDUAL TERMS in the vertical momentum equation to infer conditions favorable for embryo formation without a complete consideration of the horizontal momentum balances. For reasons discussed above, this is inconsistent and generally unwise. All of the subsequent arguments and interpretations in this paper are thus highly suspect."

Reply: Your concern is also our concern. So in the original ms, we did mention the conditions for the unavailability of vertical momentum equation. However, we didn't emphasize the conditions enough.

Following your advice, we review the textbook written by White (2002, p23, please see the attached copy of this page) who has mentioned that the term associated with $2\Omega u$ together with other smaller terms is neglected in the comparison with the gravity. However, so long as the horizontal wind comes into play, the contribution of $2\Omega u$ to $dw/dt \neq 0$ (for destroying the balance and initiating severe storms from an internal-disturbance-free situation at the Equator, which is the focus of our study) could be more important than the net contribution of the gravity and the vertical pressure gradient forces since the gravity is always almost (if not exactly) cancelled by vertical pressure gradient force. Adopting White's perspective and taking your comments into account, we revise the paragraphs associated with hydrostatic balance as following:

"*Focusing on the mechanisms for destroying the balance situation and creating upward acceleration (* $dw/dt > 0$ *) of vapour at the sea surface under the zero vertical velocity (* $w = 0$ *) and internal-disturbance-free conditions, we turn to the external contributor of* $dw/dt > 0$. *The creation of vertical acceleration at the sea surface is described clearly by the primitive vertical momentum equation on the rotating Earth in spherical coordinates (Holton, 2004, P41):*

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

1 2 3 4 5

The contributors of $dw/dt \neq 0$ *include the Coriolis effect on the relative zonal velocity (term 1), the vertical pressure gradient force (term 2), the gravity (term 3), the Earth's curvature effect (term 4) and the friction force (term 5). An internal-disturbance-free balance-situation considered in the present study is at least in the geostrophic balance and hydrostatic balance with:*

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

As a result, the contribution to $dw/dt > 0$ *comes from the following three right-hand side (rhs) terms:*

$$\frac{dw}{dt} = 2\Omega u \cos\varphi + \frac{u^2 + v^2}{a} + F_{rz} \qquad (3)$$

for destroying the balance situation and creating upward acceleration of vapour at the sea surface in an internal-disturbance-free environment. According to Holton (2004, P41), the magnitudes of the last two rhs terms of (3) are much smaller than that of the first rhs term. So the last two rhs terms can be eliminated, leading to:

$$\frac{dw}{dt} = 2\Omega u \cos\varphi. \qquad (4)$$

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. Be aware that only if* Ω *were zero or horizontal velocity were absent (White 2002, p23) together with zero horizontal convergence i.e.,* $\nabla_2 \cdot \mathbf{V} = 0$*, then hydrostatic balance would lead to the zero vertical acceleration:*

$$\frac{dw}{dt} = 0. \qquad (5)$$

Without the vertical acceleration and without the horizontal convergence, the moist air at the sea surface with $w = 0$ *could not be transported to the middle troposphere.* *However in reality, the angular rotation rate of the Earth* $\Omega = 7.292 \times 10^{-5}\ s^{-1}$ *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 (*$u = v = w = 0$*), the external-force-induced LLEWW-burst (*$u > 0$*) can boost upward acceleration in the latitudes with* $|\varphi| < 90^{\circ}$. *Keep in mind that* $\cos\varphi$ *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* $\mathbf{\Omega}$ *perpendicular to the vertical coordinate* $\mathbf{k}_{eq} = \mathbf{w}_{eq} / |\mathbf{w}_{eq}|$ *(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, P41). Although the magnitude of* $2\Omega u$ *is smaller than that of the gravity, the gravity is always balanced more or less by the vertical pressure gradient force. So long as the horizontal wind comes into play, the contribution of* $2\Omega u$ *(despite being abandoned as a residual term) to* $dw/dt > 0$ *(commonly observed at the equator) might be greater than the net contribution of the gravity and vertical pressure gradient forces especially at the beginning of the convective activity. 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."*

The effect of horizontal motion field together with mass-continuity and horizontal-momentum equations are involved in the ms implicitly. Taking your comments into account, we revised the sentence to make this effect explicitly:

"*In the real atmosphere with the presence of traded easterlies, the contribution of horizontal wind to the upward vapour transport could also attributed to the physical processes in the horizontal momentum equations through the linkage between the horizontal convergence* $\nabla_2 \cdot \mathbf{V} < 0$ *and the rising motion determined by the mass-continuity equation. Therefore, the effect of LLEWW embedded in trade easterlies on* $w > 0$ *at the sea surface could be even more robust due to the additional effect of low-level convergence (Anthes, 1982, P49-51). This well-known equatorial convergence zone would be able to create the upward transport of moist air from the warm sea surface to the midtroposphere under the condition that the negative effect of other internal disturbances is small as compare with the effect of the equatorial convergence zone. 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).*"

Comment 5:"For example, the term embryo is never defined in this paper. Does embryo refer to the pouch as defined in Dunkerton et. al. 2009, or does it refer to a tropical depression as declared by NHC, JTWE or JMA forecaster? If the former is the intended meaning, how do the authors identify the 'embryo' from the best track data for named systems?"

Reply: We are sorry that although we have defined 'embryo' at the beginning of the second paragraph of introduction as: "*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, P49).*

These initial conditions are the ingredients of STC's embryo (borrowed from Emanuel, 1993; Montgomery et al., 2006; Emanuel, 2007; Dunkerton et al., 2009)", we did not make the definition stand out. So in section 2 of the revised ms, we not only change the title of section 2 but also make a clear definition of hurricane's embryo as: "***2 Methodology, data and the definition of hurricane's embryo***

…

The location of the embryo for the yearly first STC is determined according to the "best track" data at 0000, 0600, 1200, 1800 UTC (Klotzbach, 2006) from Joint Typhoon Warning Center (JTWC), National Hurricane Center (NHC) and Japan Meteorological Agency (JMA). The embryo defined in the present study is the disturbance (according to the first record reported by JTWC or NHC) owning the cyclonic vorticity and some other initial conditions for the formation of hurricane. 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."

Sincerely,

Zhuojian Yuan

Professor

it is neutrally stable. Large positive values of $\partial\theta/\partial z$ tend to inhibit vertical motion.

In the Earth's atmosphere, well away from the surface, the vertical gradient of potential temperature is generally much greater numerically than the horizontal gradient; the atmosphere is said to be *stratified.* (Horizontal gradients are not, of course, negligible; the difference of potential temperature between different horizontal locations is a key driving agency of the circulation, as Jeffreys' theorem suggests.) Well away from the Earth's surface, values of $\partial\theta/\partial z$ are typically $4 \times 10^{-3}\mathrm{Km}^{-1}$ in the troposphere, and about a factor of 4 greater in the stratosphere; see the schematic climatological section shown in Figure 4(b). Considerable spatial and temporal variations occur, however, especially in the troposphere. The transition region between the troposphere and the stratosphere – the tropopause – across which $\partial\theta/\partial z$ and potential vorticity both change markedly (see Thuburn and Craig (2000)) tends to act as a quasi-horizontal lid to motions beneath. Locally, the tropopause exhibits major variations in height associated with the passage of weather systems (see Keyser and Shapiro (1986) and Browning and Reynolds (1994)) and a general decrease with latitude is evident in Figure 4(b), but a typical value is 10km.

The physical significance of the quantity $\partial\theta/\partial z$ is further illuminated by considering the vertical displacement of a parcel of air in dynamic terms (Figure 5). Upon neglecting the (small) metric and Coriolis terms in (4.6) (terms which vanish if the motion is purely vertical), and assuming again that the displaced parcel experiences the pressure field $\overline{p}(z)$ of its surroundings, we find

$$\frac{Dw}{Dt} + g + \frac{1}{\rho}\frac{d\overline{p}}{dz} = 0. \tag{5.10}$$

Since $d\overline{p}/dz = -\overline{\rho}g$, the second and third terms in (5.10) combine to give $(\rho - \overline{\rho})g/\rho$. Given $p = \overline{p}(z)$ and small displacements δz, we have (from (3.16) and (3.17)):

$$\left(\frac{\rho-\overline{\rho}}{\rho}\right) = \left(\frac{\overline{T}-T}{\overline{T}}\right) = \left(\frac{\overline{\theta}-\theta}{\overline{\theta}}\right) \approx \frac{1}{\overline{\theta}}\frac{d\overline{\theta}}{dz}\delta z. \tag{5.11}$$

But $w = D/Dt(\delta z)$, so (5.10) becomes

$$\frac{D^2}{Dt^2}\delta z + N^2\delta z = 0, \tag{5.12}$$

where $N^2 = (g/\overline{\theta})\,d\overline{\theta}/dz$ is the *buoyancy frequency* (also known as the Brunt–Väisälla frequency). The period of small vertical oscillations in a stable atmosphere is thus $2\pi/N$. If $N^2 < 0$, small vertical displacements amplify with time as $\exp(Nt)$; this is consistent with our earlier identification of $\partial\theta/\partial z < 0$ as the condition for instability to vertical displacements.

volume of the atmosphere:

$$\frac{\partial}{\partial t}\int_{\substack{\text{whole}\\ \text{atmosphere}}} \rho\, d\tau = -\int_{\text{boundaries}} \rho\,\mathbf{u}.\,\mathbf{dS} = 0. \tag{4.1}$$

The second equality assumes there is no net mass transfer into or out of the atmosphere.

4.2 Total energy conservation

By taking the scalar product of $\mathbf{u}$ with (3.13), and using (3.14), one readily obtains a Lagrangian conservation law for the total energy E per unit mass ($E = \frac{1}{2}\mathbf{u}^2 + \Phi + c_v T$ is the sum of the specific kinetic, potential and internal energy):

$$\rho\frac{DE}{Dt} = -\operatorname{div}(p\mathbf{u}) + \rho(Q + \mathbf{u}.\,\mathbf{F}). \tag{4.2}$$

Hence

$$\frac{\partial}{\partial t}(\rho E) = -\operatorname{div}[(\rho E + p)\mathbf{u}] + \rho(Q + \mathbf{u}.\,\mathbf{F}), \tag{4.3}$$

which is the Eulerian version of (4.2). Since it acts at right angles to $\mathbf{u}$, the Coriolis force in (3.13) does not figure directly in the energetics. Equation (4.3) may be regarded as a statement of the conservation of energy; for the case $\mathbf{F} = 0$, Holton (1992) derives (3.6) from (4.3).

Atmospheric energetics is a large subject; White (1978a) gives an elementary account. An important issue is the extent to which potential and internal energy may be converted into flow kinetic energy ($\frac{1}{2}\mathbf{u}^2$ per unit mass). Availability in this sense is the subject of continuing study – see Shepherd (1993), Marquet (1993), Kucharski (1997) and references in these papers.

4.3 Axial angular momentum conservation

The components of (3.13) in the zonal, meridional and vertical directions may be derived by considering the rates of change of unit vectors over the sphere. One finds (see Phillips (1973))

$$\frac{Du}{Dt} = 2\Omega v\sin\phi - 2\Omega w\cos\phi + \frac{uv\tan\phi}{r} - \frac{uw}{r} - \frac{1}{\rho r\cos\phi}\frac{\partial p}{\partial\lambda} + F_\lambda \tag{4.4}$$

$$\frac{Dv}{Dt} = -2\Omega u\sin\phi - \frac{u^2\tan\phi}{r} - \frac{vw}{r} - \frac{1}{\rho r}\frac{\partial p}{\partial\phi} + F_\phi \tag{4.5}$$

$$\frac{Dw}{Dt} = +2\Omega u\cos\phi + \frac{(u^2+v^2)}{r} - \frac{1}{\rho}\frac{\partial p}{\partial r} + F_r - g. \tag{4.6}$$