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The role of boundary layer momentum advection in the mean location of the ITCZ

Vishal Dixit[1,2,3,*] and J Srinivasan[1,2]

[1] *Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bengaluru 560 012, India.*
[2] *Divecha Centre for Climate Change, Indian Institute of Science, Bengaluru 560 012, India.*
[3] *Present address: Climate Change Research Centre, University of New South Wales, Sydney, NSW 2052, Australia.*
**Corresponding author. e-mail: v2dixit@gmail.com*

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The inter-tropical convergence zones (ITCZ) form closer to the equator during equinoxes while they form well away from the equator during the boreal summer. A simple three-way balance between the pressure gradients, Coriolis force and effective Rayleigh friction has been classically used to diagnose the location of maximum boundary layer convergence in the near equatorial ITCZ. If such a balance can capture the dynamics of off-equatorial convergence was not known. We used idealized aqua planet simulations with fixed, zonally symmetric sea surface temperature boundary conditions to simulate the near equatorial and off-equatorial ITCZ. As opposed to the convergence of inter-hemispheric flows in the near equatorial convergence, the off-equatorial convergence forms due to the deceleration of cross-equatorial meridional flow. The detailed momentum budget of the off-equatorial convergence zone reveals that the simple balance is not sufficient to capture the relevant dynamics. The deceleration of the meridional flow is strongly modulated by the inertial effects due to the meridional advection of zonal momentum in addition to the terms in the simple balance. The simple balance predicts a spurious near equatorial convergence and a consistent off-equatorial convergence of the meridional flow. The spurious convergence disappears when inertial effects are included in the balance. As cross equatorial meridional flow decelerates to form convergence, the inertial effects cancel the pressure gradient effects near the equator while they add away from the equator. The contribution to the off-equatorial convergence induced by the pressure gradients is significantly larger than the contribution due to the inertial effects and hence pressure gradients appear to be the primary factor in anchoring the strength and location of the off-equatorial convergence.

Keywords. ITCZ; momentum budget; off-equatorial convergence.

1. Introduction

The inter-tropical convergence zones (ITCZ) are the east–west oriented cloud bands which are associated with the most intense rainfall in tropics (Schneider *et al.* 2014). These are the most prominent features of the tropical climate when viewed from the space. They transport mass, momentum

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and energy and play important role in driving the circulation in the tropics. Predicting the accurate location and intensity of the ITCZ is one of the fundamental puzzles of climate science (Bony *et al.* 2015).

Charney (1971) coined the term ITCZ to highlight that near the equator a low pressure belt exists where the boundary layer flow from the two hemispheres converges to form zones where moist air rises to form deep clouds. In this sense, the ITCZ were identified with the location of maximum boundary layer convergence or where the meridional winds changed direction or where the surface pressure was the lowest. With the advent of satellites, researchers noticed a marked seasonal cycle in the latitude of deep clouds associated with the ITCZ (Waliser and Somerville 1994; Sikka and Gadgil 1980). Also see the reviews by Waliser (2002) and Schneider *et al.* (2014). The seasonal cycle is most pronounced in the Indian Ocean and west Pacific Ocean. The ITCZ moves as far north as 15°–20°N in boreal summer, while it moves to the south of the equator during winter in these oceans (Gadgil 2003). A relatively moderate seasonal cycle is observed in the location of ITCZ in east Pacific and Atlantic oceans. A double ITCZ straddling the equator is found in the month of March–April over east Pacific Ocean, while a single ITCZ as north as 10°–12°N can be found in boreal summer (Hu *et al.* 2007; Schneider *et al.* 2014). This seasonal cycle is observed in associated precipitation (Gu *et al.* 2005), boundary layer winds (Berry and Reeder 2014) and multi-level flows associated with it (Zhang *et al.* 2008; Dixit and Srinivasan 2016). The seasonal movement of the ITCZ away from the equator is known to be associated with the monsoons and the strong and weak phases of the monsoons are strongly modulated by the ITCZ location (Gadgil 2003). This underlines the importance of understanding the factors responsible in controlling the location of the ITCZ.

Many of the previous investigators have used aqua planet simulations to simulate and isolate the processes controlling the location of the ITCZ (Numaguti and Hayashi 1991; Hess *et al.* 1993; Numaguti 1993; Neale and Hoskins 2000; Chao and Chen 2001). In this, the steady state of the ITCZ is simulated by prescribing the zonally symmetric meridional distribution of the SST (Williamson 2008; Möbis and Stevens 2012; Oueslati and Bellon 2013; Williamson *et al.* 2013). These studies simulated the ITCZ either at the equator or a 'double-ITCZ' was formed around the equator in these simulations. While a lot of emphasis has been given on mechanisms and processes controlling the near equatorial ITCZ, there have been only few studies simulating the off-equatorial ITCZ (Numaguti 1993; Vidyunmala *et al.* 2007; Dixit and Srinivasan 2016). It is not clear if the same boundary layer dynamics control the location of the ITCZ when in its seasonal cycle it forms well away from the equator such as during the south Asian monsoon or during autumn over the east Pacific Ocean.

To highlight the dominant forces in the steady state boundary layer, a linear bulk model has been classically used to describe the boundary layer dynamics in the tropics (Lindzen and Nigam 1987; Deser 1993; Stevens *et al.* 2002). In this, a three-way balance between the Coriolis force, the pressure gradient force and friction are considered. The friction is assumed to absorb all the non-linear effects of advection. This model has been used successfully to explain the near equatorial ITCZ location by various researchers (Lindzen and Nigam 1987; Li and Wang 1994; Waliser and Somerville 1994; Sobel and Neelin 2006). If the same model can be applied successfully to explain the location of the off-equatorial ITCZ is not clear. Moreover, Tomas and Webster (1997) and Schneider and Bordoni (2008) have used simple and dry GCM model respectively to propose that the boundary layer dynamics is different when the precipitation zones are located away from the equator. In monsoon literature, Mahrt and Young (1972) and Krishnamurti and Wong (1979) have noted that the boundary layer is advective during the onset of the Somali jet which is the key element of south Asian monsoon. The study of momentum budget in monsoon months by Yang *et al.* (2013) also points to a different boundary layer dynamics during boreal monsoons in south Asia. In this study, we explore the role of momentum advection in deciding the location of off-equatorial boundary layer convergence using moist aqua planet simulations.

We briefly discuss the simple bulk models that are generally used to predict the location of convergence in section 2. The GCM model used in the present study is explained and the details of simulation are presented in section 3. The results are described in section 4. A discussion about the relevance of the results is made in section 5.

2. Simple models of the location of ITCZ

Classically, the ITCZ was viewed as an equatorial trough of surface pressure girdling the equator throughout the globe. The hydrostatic model is the simplest one to predict the minimum in surface pressure. According to hydrostatic approximation, the surface pressure is approximately equal to the net weight of atmospheric column per unit area Ambaum (2008), it can be expressed as a layer-by-layer integration of the air masses in the column,

$$Ps = \int_{\text{surface}}^{\text{Ztop}} \rho g dz. \quad (1)$$

Using the ideal gas law, the density can be uniquely expressed as a function of pressure and temperature,

$$Ps = \int_{\text{surface}}^{\text{Ztop}} \left(\frac{P}{R * T_v} g dz \right). \quad (2)$$

According to classical view, the ITCZ forms where the surface pressure is lowest. This implies that,

$$\text{Min}(Ps) = \text{Min} \left(\int_{\text{surface}}^{\text{Ztop}} \left(\frac{P}{R * T_v} g dz \right) \right). \quad (3)$$

In an isothermal atmosphere (and when moisture effects are neglected), the location of surface pressure is governed solely by the distribution of pressure. This is not a good approximation since the temperature changes significantly vertically in troposphere. If we assume that the density is solely a function of temperature, then this implies that the minimum in surface pressure is governed by maximum in column mean temperature,

$$\text{Min}(Ps) = \text{Min} \left(\int_{\text{surface}}^{\text{Ztop}} \left(\frac{P}{R * T_v} g dz \right) \right) = f(\max(\text{Tvmean})) \quad (4)$$

where Tvmean is tropospheric mean virtual temperature and Ztop is the height at the top of the atmosphere. The later assumption (ρ is function of temperature alone) is made in many of the simple models (Lindzen and Nigam 1987). It is not obvious from this analysis if that is a good approximation to make. The above explanation relies on an assumption that ITCZ is formed over lowest surface pressure. Gu *et al.* (2005) as well as Tomas and Webster (1997) have reported cases in which the ITCZ was not found on the location of lowest surface pressure in the east Pacific Ocean. The differences between location of ITCZ, minimum surface pressure and maximum surface temperature become more evident when ITCZ is away from the equator.

2.1 *Linear bulk models*

Among the dynamical models explaining the relationship between surface pressure and boundary layer winds and convergence, the most popular simple models consider that convergence in ITCZ can be understood by writing a linear bulk model for the boundary layer (Lindzen and Nigam 1987; Deser 1993; Li and Wang 1994). These models were named as anisotropic Rayleigh friction models by Stevens *et al.* (2002). These models are motivated by the fact that the precipitation in the ITCZ is approximately balanced by the moisture convergence in the column. Since the scale height of the water vapour is approximately equal to boundary layer height, most of the moisture convergence is controlled by the dynamic convergence in the BL. These models assume that the geopotential gradients in the boundary layer are well represented by surface pressure gradients, hence the BL winds are represented by the three-way balance between Coriolis force, surface pressure gradients and friction. A simple representation of this model is given below, a detailed advancement of these models and involved dynamics is discussed in Stevens *et al.* (2002) and Sobel and Neelin (2006). The meridional winds can be diagnosed from these as (see equation 3 in Stevens *et al.* 2002),

$$v = \frac{f \frac{1}{\rho_0} \frac{\partial P_s}{\partial x} - \varepsilon_x \frac{1}{\rho_0} \frac{\partial P_s}{\partial y}}{\varepsilon_x \varepsilon_y + f^2}. \quad (5)$$

Since ITCZ is generally east–west oriented, neglecting zonal geopotential gradients,

$$v = \frac{-\varepsilon_x \frac{1}{\rho_0} \frac{\partial P_s}{\partial y}}{\varepsilon_x \varepsilon_y + f^2}. \quad (6)$$

These models assume that the non-linear advection effects as well as the effect of turbulent eddies can be represented by Rayleigh friction coefficients in zonal and meridional directions. Typically, friction coefficient in zonal direction is shown to be two to three times smaller than meridional friction coefficient (Deser 1993). We investigate if this framework is sufficient or if not then can it be extended to capture the boundary layer dynamics of the simulated off-equatorial convergence zone.

3. Aqua planet model

We have used a community atmosphere model (CAM 3.0) developed by National Center for Atmospheric Research (USA) to perform aqua planet simulations. The model uses a Eulerian dynamical core with triangular truncation of 42 waves (T42). This amounts to approximate resolution of 2.8 degree in horizontal. The model has 26 vertical levels and uses hybrid coordinate system. The deep convection is treated using Zhang and McFarlane (1995) convection scheme while the shallow convection is treated using Hack (1994) scheme. The other important model details can be found in Collins *et al.* (2004). This model configuration has been tested for its grid sensitivity and numerical convergence by Williamson (2008).

We performed three aqua planet simulations following the protocol suggested by Neale and Hoskins (2000). The Sun was held fix in all the simulations. The model was run for 3 years in each simulation and the averages for the last 6 months are shown here. The initial conditions files were obtained from the CAM 3.0 distribution server and were identical to the ones described in the control simulation described in Collins *et al.* (2004). The model was forced with zonally symmetric SST distributions with varying SST maximum. The ITCZ forms near the equator during equinoxes when the zonal mean SST conditions are approximately symmetric about the equator. The ITCZ gradually starts forming northwards in response to the warmer SST conditions in the northern hemisphere during the boreal summer. To mimic this effect we have shifted the SST maximum polewards gradually. The control SST distribution (ϕ_0 = SSTmax = 0) is similar to the one recommended by Neale and Hoskins (2000) with the SST maximum at the equator. In other experiments, the SST maximum (ϕ_0) was displaced to 10°N (SSTmax = 10) and 20°N (SSTmax = 20), respectively. It is deliberately varied such that the southward SST gradient from SST maxima is weaker than the northward SST gradient. This was done to study the effect of SST gradient on the ITCZ location. The meridional variation of SST can be written as:

$$T_s = \begin{cases} 0 & \phi > \frac{\pi}{3} \\ 27\left(1-\sin^2\left(\frac{\pi}{2}\frac{\phi-\phi_0}{\frac{\pi}{3}-\phi_0}\right)\right) & \frac{\pi}{3} \geq \phi \geq \phi_0 \\ 27\left(1-\sin^2\left(\frac{\pi}{2}\frac{\phi-\phi_0}{\frac{\pi}{3}+\phi_0}\right)\right) & \phi_0 > \phi \geq -\frac{\pi}{3} \\ 0 & -\frac{\pi}{3} > \phi \end{cases}.$$

Note that the observed SST and SST gradients are different in different ocean basins and may have discontinuities. To avoid the spurious instabilities associated with the discontinuous SST profiles (e.g., Hess *et al.* 1993) we chose the idealized continuous meridional distributions of SST which simulates near and off-equatorial ITCZ.

4. Results

We first discuss the simulated mean state of the ITCZ location in response to the shift in SST maximum in these simulations. A double ITCZ is simulated when the SST maximum is at equator (SSTmax = 0, figure 1). Two peaks in precipitation of around 10 mm/day magnitude are found at 7°S and 7°N. It is interesting to note that, as the SST maxima is shifted to 10°N (SSTmax = 10, figure 1), the double ITCZ about the latitude of SST maximum persists. The magnitude of precipitation is comparable to control simulation.

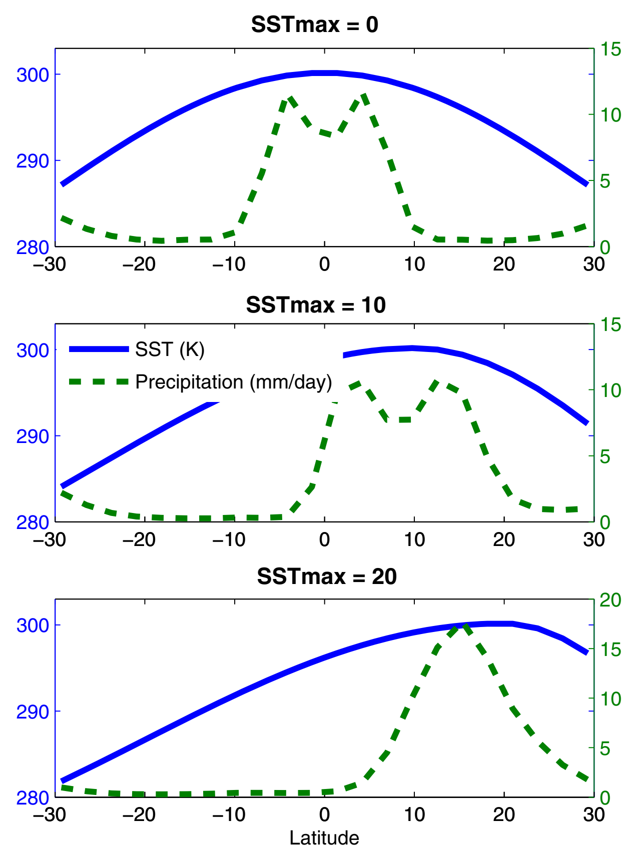

Figure 1. The time invarient, zonally symmetric distributions of sea surface temperature for SSTmax = 0 (top), SSTmax = 10 (middle), SSTmax = 20 (bottom) simulations are shown in blue. The time-zonal mean precipitation response for these simulations is shown in green.

When SST maximum is shifted to 20°N (SSTmax = 20, figure 1), a single ITCZ at 15°N is simulated. The location of ITCZ is to the south of SST maximum where the SST gradients are lower than to the north. The strength of ITCZ in this simulation is 17.5 mm/day which is (75%) more than control case. This is in disagreement with the axisymmetric theory presented by Lindzen and Hou (1988) who showed that the dry axisymmetric Hadley circulation is very sensitive to small (as small as 2°) off-equatorial shift of heat source. In the present case, the off-equatorial ITCZ and associated Hadley circulation intensifies only when the SSTmax was placed as north as 20°N. This suggests that the moist dynamics of the ITCZ shows differences from dry axisymmetric theory.

The mean state of zonally averaged meridional winds in these simulations can be seen in figure 2 (top row). The multilevel flows are observed in all the simulations. The strength of the shallow return flow is increased as the ITCZ moves at 15°N. This is consistent with the results of Dixit and Srinivasan (2016). A marked difference in the flows to the north and south of SST maximum can be found when ITCZ is at the off-equatorial location (SSTmax = 20). Consistent with the observations, the off-equatorial ITCZ is formed as a result of deceleration of the southerly flow in the boundary layer to the south of the SST maximum. The southerly winds change sign at the location of SST maximum (20°N).

Figure 2 (bottom row) shows the mean state of zonally averaged zonal winds. There is a marked difference between control and SSTmax = 20 simulation. The subtropical jets in the upper troposphere (150 mb) are found symmetric to the equator at 30°S–30°N in control case. As the maximum SST moves northwards (SSTmax = 10), the subtropical jet in the northern hemisphere is pushed northward. A weak easterly jet is formed at 5°N in the upper troposphere (150 mb). The lower tropospheric westerlies are found between 5° and 10°N in association with the northward movement of ITCZ. When SST maximum is at 20°N (SSTmax = 20), the upper tropospheric easterly jet strengthens to magnitudes as high as 20°m/s. A westerly jet of magnitude 10 m/s is formed at lower level (900 mb). These features in flow structure of zonal winds resembles the flow structure found in south Asian monsoon region during boreal summer.

Figure 3 shows the important terms of time mean, zonally averaged zonal momentum budget for SSTmax = 0 and SSTmax = 20 simulation. Especially in the boundary layer, as the ITCZ shifts to off-equatorial location in SSTmax = 20 simulation, the meridional advection becomes more important. The meridional advection of zonal momentum is the most important between the equator and 15°N. It changes sign around the location of ITCZ at 15°N. The Coriolis force is important between the equator and 20°N. The

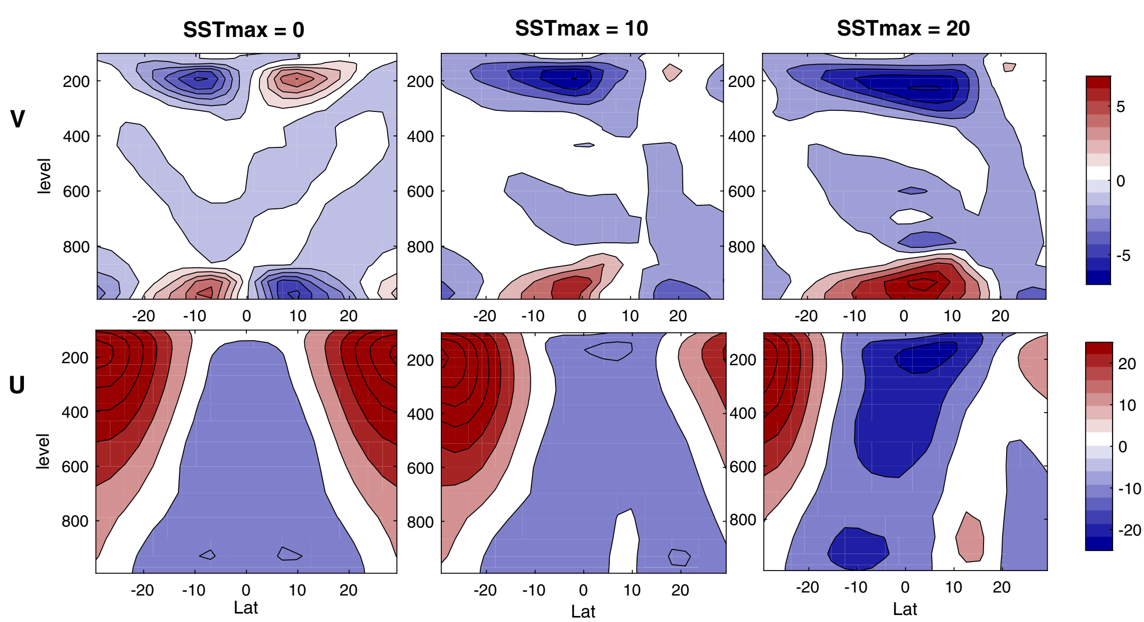

Figure 2. The zonal-time mean vertical structure of meridional winds (m/s, top row) and zonal winds (m/s, bottom row) for the three simulations.

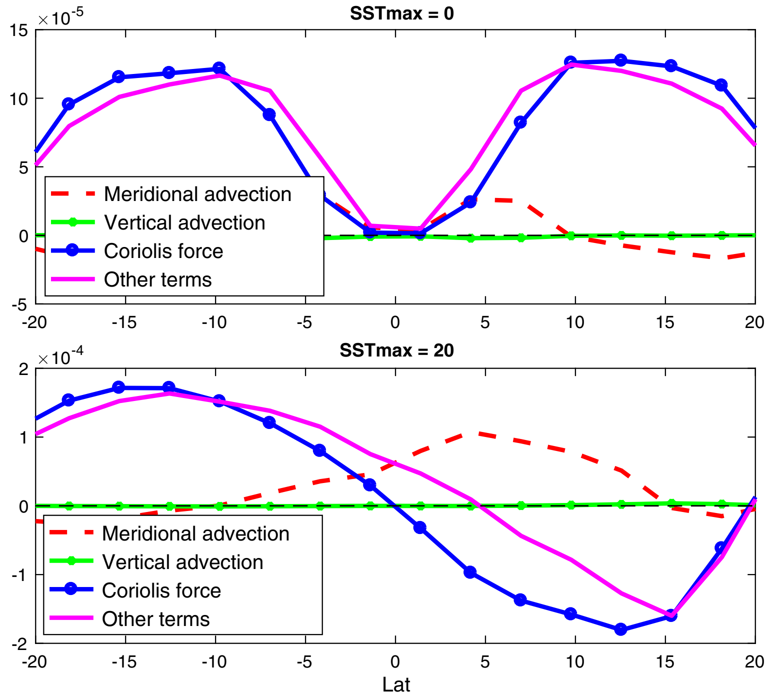

Figure 3. The meridional distribution of important terms from time mean, zonally averaged zonal momentum budget evaluated at 970 hPa for two contrasting simulations. All the values are in m/s^2. The top panel shows balance for SSTmax = 0 simulation while the bottom panel shows balance for SSTmax = 20 simulation.

vertical advection term and zonal geopotential gradient terms are negligible as compared to the dominant terms in zonal momentum balance. The meridional momentum balance shows the dominant balance between Coriolis force, friction and pressure gradients as assumed in the linear bulk models (not shown). It is important to compare this result with results of Richter *et al.* (2014) who found that both meridional and vertical advection were important in their analysis. They argued that they neglected Coriolis force assuming it to be small near equator while doing momentum budget analysis. From our analysis, we find that Coriolis force is one of the dominant force in both equatorial and off-equatorial ITCZ and cannot be neglected.

Evidently, these balances are different from previously discussed linear bulk model since the meridional advection term is found to be dominant and cannot be absorbed in the effective friction coefficient. For the zonal mean state of the ITCZ, the modified bulk model can be written as:

$$v\frac{\partial u}{\partial y} - fv = -\varepsilon_x u, \tag{7}$$

$$fu = -\frac{1}{\rho_0}\frac{\partial P_s}{\partial y} - \varepsilon_y v. \tag{8}$$

This system can be solved to obtain diagnostic estimate of meridional wind,

$$v = \frac{fv\frac{\partial u}{\partial y} - \varepsilon_x \frac{1}{\rho_0}\frac{\partial P_s}{\partial y}}{\varepsilon_x\varepsilon_y + f^2}. \tag{9}$$

In this, the advection of the meridional wind is written on right hand side explicitly so that the effect of advection and effect of geopotential gradients can be separated. If the advection is due to mean flow, then the advection can be coupled with the Coriolis force to modify the diagnostic equation as:

$$v = \frac{-\varepsilon_x \frac{1}{\rho_0}\frac{\partial P_s}{\partial y}}{\varepsilon_x\varepsilon_y + f(f+\zeta)}, \tag{10}$$

where $\zeta = -(\partial u/\partial y)$ is zonally averaged relative vorticity. This formulation was previously used by Schneider and Bordoni (2008) to explain the dynamics of convergence zones in their dry simulations of ITCZ and associated Hadley circulation. In the present formulation (equation 9), it can be noted that zonal geopotential gradients and meridional advection play similar role in the diagnostic formula for meridional wind (see equation 5). We call the present formulation as 'non-linear model' to highlight the inclusion of advection term. If we neglect the advection, then this model reduces to linear bulk model. We have used the standard values of Rayleigh friction coefficients ($\varepsilon_x = 10^{-5}$ s^{-1}, $\varepsilon_y = 3 \times 10^{-5}$ s^{-1}, Bellon and Srinivasan 2006).

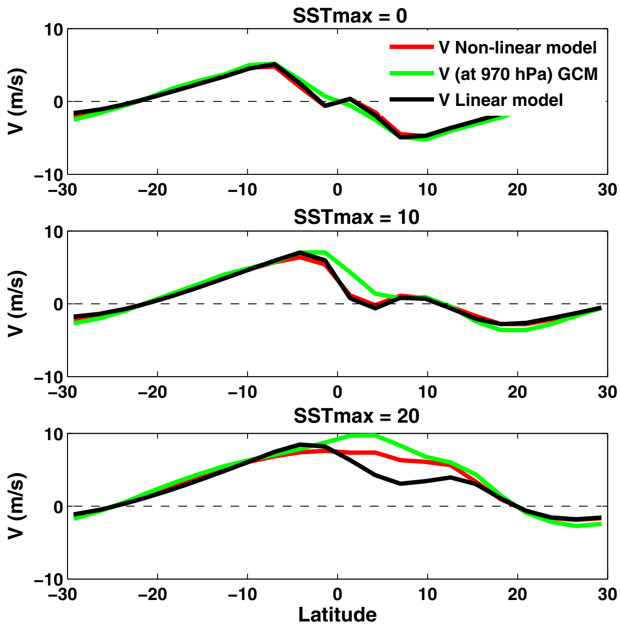

Figure 4. The comparison between the 970 hPa meridional winds predicted by linear and non-linear model for different simulations (as indicated in the figure). All values are in m/s and are zonally and time averaged. The contributions from pressure gradinet term (black) and non-linear advection term (blue) are shown separately. The decomposition follows as in equation (9).

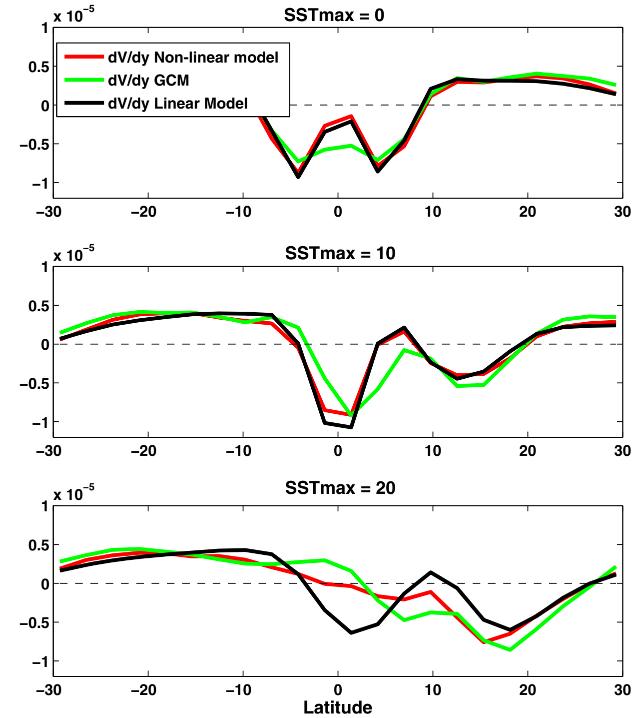

Figure 5. The comparison between the 970 hPa meridional convergence predicted by linear and non-linear model and GCM simulated convergence for different simulations (as indicated in figure). All values are in /s and are zonal-time mean. The terms emerging from non-linear advection of zonal momentum are clubed together. See text for more details.

Figure 4 shows the comparison between meridional winds at 970 hPa as observed in GCM, linear bulk model (equation 9 without the advection term) and non-linear model for all the three simulations. We have used surface pressure (Ps) as representative of boundary layer geopotential gradient calculations similar to Back and Bretherton (2009). When SST maximum is at the equator (SSTmax = 0), the meridional winds change sign at the equator (figure 5). They are maximum in magnitude at around 9°S and 9°N. The linear bulk model (black curve) predicts the winds correctly. There is no significant difference between the prediction of linear (black) and non-linear model (red) indicating that the non-linear advection terms are negligible when ITCZ is at equator. In contrast, when ITCZ is at 15°N in SSTmax = 20 simulation, the southerly flow is maximum near equator and changes its sign at 20°N (green curve). The simple linear model (black curve) predicts the winds correctly to the south of 5°S and north of 15°N. The linear model fails to predict near equatorial maximum. A large difference between GCM simulation and simple linear model prediction is seen between equator and 15°N. A non-linear model improves this and predicts the near equatorial maximum in meridional winds correctly. The discrepancy still exists near equator which can probably be attributed to the vanishing Coriolis parameter near the equator and simple nature of model presented here. This is seen more explicitly when individual contributions of linear term and non-linear term are shown (supplementary figure S1). This highlights that as the ITCZ moves away from equator, the non-linear advection term starts playing important role in determining the magnitude and direction of the southerly flow.

A model for predicting meridional convergence can be obtained by differentiating equation (10) with respect to latitude.

$$\frac{\partial v}{\partial y} = v\frac{\partial u}{\partial y}\frac{\partial}{\partial y}\left(\frac{f}{\varepsilon_x\varepsilon_y + f^2}\right) + \frac{f}{\varepsilon_x\varepsilon_y + f^2}\frac{\partial}{\partial y}\left(v\frac{\partial u}{\partial y}\right) - \frac{\varepsilon_x}{\varepsilon_x\varepsilon_y + f^2}\frac{\partial^2 \phi}{\partial y^2} - \frac{\partial \phi}{\partial y}\frac{\partial}{\partial y}\left(\frac{\varepsilon_x}{\varepsilon_x\varepsilon_y + f^2}\right). \quad (11)$$

The first two terms arise due to inclusion of advection term in the linear bulk model while the last two terms are prediction from linear bulk model similar to Lindzen and Nigam (1987). The first term and fourth term arise due to latitudinal variation of Coriolis parameter. The fourth was named as 'Beta convergence' by Lindzen and Nigam (1987). We call the first as 'Advection-Beta' term. We call the second term as 'advection term' and the third as 'Psyy' term since it is due to Laplacian of surface pressure. To simplify the explanation, we name the first two as 'non-linear advection terms' and the last two as 'pressure gradient term' respectively.

Figure 5 shows the comparison between the meridional convergence simulated by linear bulk model and non-linear model for equatorial (SSTmax = 0) and off-equatorial ITCZ (SSTmax = 20). The convergence predicted by linear bulk model and non-linear model almost coincide showing that the advection terms are negligible. When the ITCZ shift northwards (SSTmax = 10) though the double ITCZ feature with equal precipitation peaks is still observed, corresponding boundary layer convergence shows higher convergence near equator than in the peak away from the equator. Both linear as well as non-linear model captures this peak. This shows that though the SST forcing and ITCZ is shifted to the northward location, the double ITCZ behaviour is still present and advection effects are small. This suggests that there can be an association between the formation of double ITCZ in this GCM and role of advection which needs further investigation. When ITCZ is simulated at off-equatorial location farther north at 15°N (SSTmax = 20) there are large differences between the prediction of linear model and non-linear model. Non-linear model predicts a single peak in convergence similar to the GCM output. The linear model predicts two convergence peaks of comparable magnitude one near equator and another near 17°N.

A further decomposition of meridional convergence due to non-linear advection and pressure gradient is carried out to understand the contributions of individual terms. This can help us understand why the linear bulk model failed to predict the correct location of convergence in SSTmax = 20 simulation.

Figure 6 shows that the contribution of advection terms is negligible as compared pressure gradient term in both SSTmax = 0 and SSTmax = 10 simulation. When ITCZ is formed well away from north, the contribution from advection (divergence induced) is almost equal and opposite to the contribution of pressure gradients near equator to cancel the convergence induced by pressure

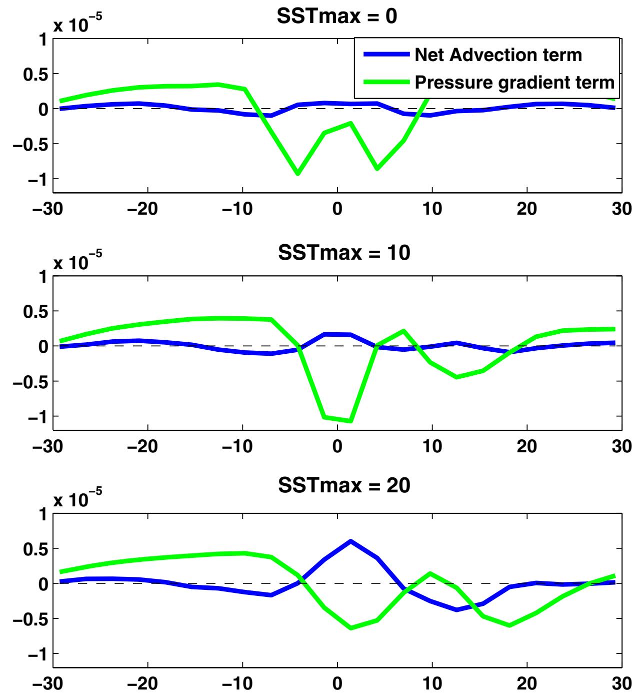

Figure 6. The decomposition of 970 hPa convergence predicted by non-linear model. It is decomposted into the effect of advection (blue) and pressure gradient term (green, essentially the linear model). All values are in /s and are zonal-time mean.

gradients. The advection term induces convergence to the north of this divergence but the magnitude of convergence induced by advection is small as compared to the convergence induced by pressure gradient term. This is similar to the formation of convergence–divergence doublet suggested by Tomas and Webster (1997). They argued that the convergence induced to the north as a response of inertial instability may serve as an anchor for the formation of ITCZ. In present simulations, the convergence induced by advection term is approximately half of the convergence induced by pressure gradients. Moreover, the location of maximum convergence induced by advection is to the south of convergence seen in GCM (near 17°N). To investigate the role of inertial instability in the present simulations we plotted the time and zonal mean absolute vorticity in these simulations.

Figure 7 shows the meridional cross section for absolute vorticity. As noted by Tomas and Webster (1997) when the zero absolute vorticity contours cross the equator, the flow is expected to be inertially unstable. We notice that when ITCZ is close to equator (SSTmax = 0), the absolute vorticity contours aline along the equator but as the ITCZ moves away from the equator in

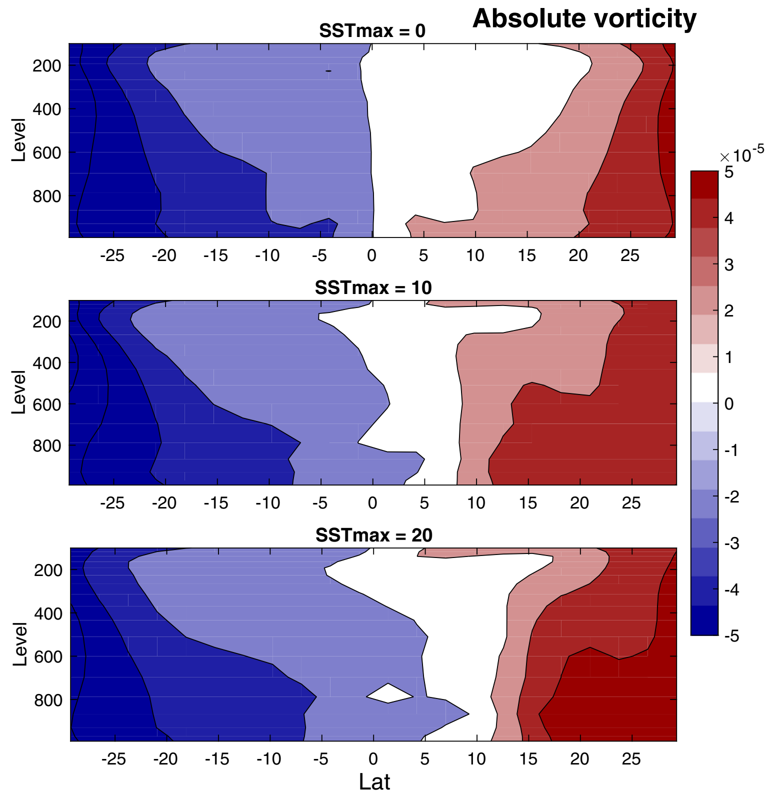

Figure 7. The vertical distribution of zonal-time mean absolute vorticity for three different simulations. The values are in /s.

SSTmax = 10 and SSTmax = 20 simulations, the zero contours of absolute vorticity crosses equator. It is important to notice that though the condition for inertial instability is met in SSTmax = 10 simulation, a pronounced convergence–divergence doublet is not formed. This suggests that probably the convergence–divergence doublet is associated with off-equatorial ITCZ placed well off the equator. The zero absolute vorticity contours in boundary layer are placed at around 5°N in SSTmax = 20 simulation. The convergence–divergence doublet is found to be centered around 5N suggesting that the present results are in agreement with results of simple model used by Tomas and Webster (1997) as far as the generation of doublet is concerned. This can be further confirmed by investigating the surface pressure gradients simulated in these three simulations. Supplementary figure S2 shows the surface pressure associated with the different simulations. When ITCZ is close to equator in SSTmax = 0 and SSTmax = 10 simulations, the pressure gradients are weak between equator and location of ITCZ. As the ITCZ shifts further north in SSTmax = 20 simulation, large cross equatorial pressure gradients are developed. Why do pressure gradients increase rapidly only when ITCZ crosses a certain latitudinal band is not clear. The pressure gradients are in agreement with the drastic increase in the amount of convergence observed associated with off-equatorial ITCZ (see figure 1).

As noted in equation (8), it is useful to diagnose the relative contribution of advection, pressure gradients and effect of rotation. Each of the advection term and pressure gradient term was further decomposed into effects due to rotation and effect due to either advection or due to pressure gradient. Figure 8 shows the contribution from Beta-advection and advection term (red) as well as contribution from Beta convergence and Psyy term. We can notice that the advection effects are weakest when ITCZ is close to equator. As ITCZ moves farthest from the equator in SSTmax = 20 simulation, Beta convergence and Psyy term contribute to the convergence to the north of equator at two locations, one near the equator and another at around 15°N. But the convergence induced near equator is cancelled by advection-Beta term which arises since it is amplified by the rate with which Coriolis parameter decreases near equator.

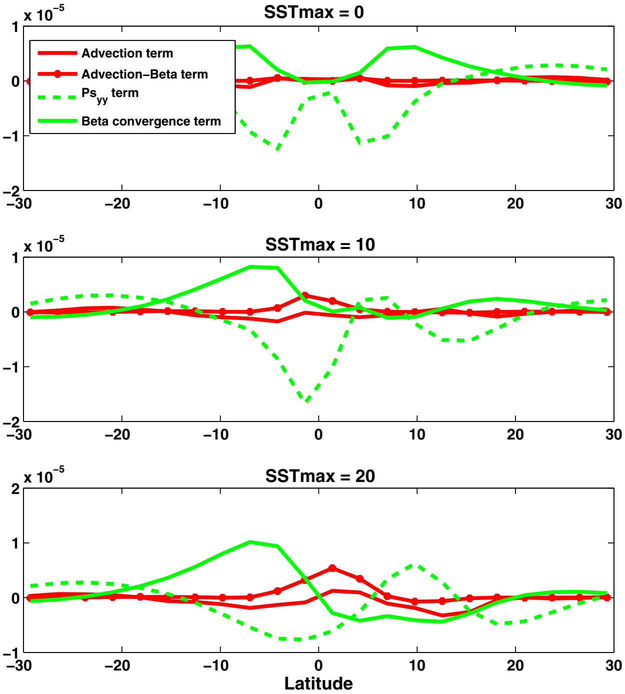

Figure 8. The decomposition of the non-linear model for meridional convergence into contributions due to advection term (solid red), advection-beta term (solid+circles, red), Psyy term (dotted, green) and Beta convergence term (solid, green). All values are zonal-time mean and are in m/s.

5. Discussion

Generally linear bulk models are used to describe the boundary layer dynamics in the ITCZ. The linear bulk models assume a three-way balance between pressure gradient force, Coriolis force and surface friction. The present analysis investigated if such a balance is sufficient to capture the dynamics of the boundary layer convergence in the ITCZ. When the ITCZ was placed at equator (with a double maximum in precipitation in SSTmax = 0 simulation) or close to the equator (in SSTmax = 10 simulation), the linear three-way balance was found to be sufficient to capture the dynamics of the maximum boundary layer convergence. Though, the criteria for inertial instability was met in SSTmax = 10 simulation, a strong cross equatorial pressure gradient was not developed. The ITCZ strength also did not increase drastically. A double ITCZ was observed similar to the SSTmax = 0 simulation. When the ITCZ was located farther north at 15°N in SSTmax = 20 simulation, the convergence increased drastically. The associated surface pressure gradients were stronger. The linear bulk model failed to capture the single ITCZ location at 15°N. It simulated two convergence zones, one near equator and another near the actual location of the ITCZ. Only when the non-linear advection effects of zonal momentum were included in the model, a correct prediction of the boundary layer convergence could be obtained. This suggests that, when the ITCZ forms well away from the equator, the nature of the boundary layer is advective. The acceleration of the meridional flow provided by the pressure gradients supports two convergence zones, one near the equator and another away from it. The near equatorial convergence is compensated by the divergence induced by the inertial effects of the zonal flow. In simple terms, the meridional flow generated due to pressure gradients carries zonal momentum polewards. In doing so, it cancels the convergence due to the decelerating meridional flow induced by the pressure gradients. This view of the boundary layer dynamics of the off-equatorial ITCZ has to be adapted to understand the off-equatorial formation of the ITCZ in south Asian monsoon as well as the off-equatorial east Pacific ITCZ during boreal autumn.

It is important to highlight that the present work mainly highlighted the limitations of the established bulk linear models that do not explicitly consider non-linear terms in the boundary layer momentum budget of the steady state of the ITCZ. A further decomposition of these non-linear terms in the rotational and divergent parts may highlight more refined features of the ITCZ dynamics and associated mass and pressure adjustment. The time dependent adjustment of the boundary layer flows is complex and need further investigation. Moreover, we have discussed about the boundary layer dynamics while other potentially important thermodynamic mechanisms (such as fluxes, energy budget) may also put constraint on the location of the ITCZ. The dynamics and thermodynamic controls on the near equatorial and off-equatorial ITCZ will be assessed using reanalysis data in future.

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