1. Introduction

The tropical easterly jet (TEJ), discovered by Koteswaram (1958), is an important feature of the Indian summer monsoon (ISM). The TEJ is unfailingly observed during the June-July-August (JJA) south-west monsoon season.

In general, it is believed that the TEJ exists because of the presence of the Tibetan Plateau. This belief owes its origins to researchers like Flohn (1965, 1968) and Krishnamurti (1971) who related the summertime upper tropospheric anticyclone above the Tibetan Plateau to sensible heating over the Tibetan Plateau as well as monsoonal latent heating over the central, eastern, and southern Himalayas. Laboratory experiments by Ye (1981) also strengthened this supposition.

However, Rao and Srinivasan (2016) showed the primacy of latent heat in determining the location, structure, and strength of the TEJ. Using reanalysis data and an atmospheric general circulation model (AGCM), they showed that the shifts in the TEJ could be explained by shifts in the precipitation patterns. In particular, they showed that the zonal location of the TEJ in 1988 and 2002 differed by ~20°. This was due to similar zonal shifts in precipitation patterns in these two years. This, along with the AGCM simulations, found that orography may not be critical for the location, structure, and strength of the TEJ. The TEJ is a result of the thermal wind equation; therefore, the location of maximum meridional geopotential gradients determines the location of the TEJ.

Such ideas were also indirectly proposed by other researchers. According to Hoskins and Rodwell (1995) and Liu et al. (2007), the position of the summertime upper tropospheric anticyclone is primarily influenced by heating. Boos and Kuang
showed that presence or absence of the Tibetan Plateau did not affect the large-scale south Asian summer monsoon circulation.

Because orography has been shown to be of secondary importance in determining the location, strength, and structure of the TEJ (Rao and Srinivasan 2016), the next step is to study the effect of only latent heating on the TEJ. This can be done using an aqua-planet model of an AGCM. In aqua-planet simulations, there is no land; thus, it is possible to more closely understand the impact of latent heating on the TEJ. Therefore, a series of aqua-planet experiments have been conducted to determine the factors influencing the location, structure, and strength of the TEJ. The goal was to study whether it is possible, in an aqua-planet configuration, to simulate a jet that is similar to the TEJ simulated in the control (Ctrl) experiment (Rao and Srinivasan, 2016). This Ctrl simulation included all orography and land-sea contrast. If such an exercise is successful, then it can be inferred that the TEJ is primarily influenced by latent heating.

The paper is organized as follows: in Section 2, the AGCM and numerical experiments are explained; in Section 3, the impact of orography on the TEJ is discussed; in Section 4, the ability of aqua-planet simulations in simulating the location, strength and structure of the TEJ is presented. Finally, in Section 5, the major inferences from the aqua-planet simulations are elucidated.

2. Model and simulation details

2.1 Description of CAM-3.1

The AGCM that has been used for the present work is the Community Atmosphere Model, version 3.1 (CAM-3.1). The finite-volume dynamical core has been used with the default horizontal grid resolution of $2\degree \times 2.5\degree$ and 26 vertical levels. The time-step has the default value of 30 min. Deep and shallow convective schemes are the Zhang and McFarlane (1995) scheme and the Hack (1994) scheme, respectively. Stratiform precipitation scheme is the Rasch and Kristjánsson (1998) scheme updated by Zhang et al. (2003). A generalization of the scheme introduced by Slingo (1989) is used to calculate the cloud fraction. The longwave and shortwave radiation schemes are from Ramanathan and Downey (1986) and Briegleb (1992), respectively. Monin–Obukhov similarity theory is used to calculate land surface fluxes of momentum, sensible heat, and latent heat. Climatological sea surface temperatures, which are a composite of the annual cycle for the period 1981–2001, have been used (Collins et al. 2004).

2.2 CAM-3.1 simulation details

The model simulations are divided into two parts. The first set shows that orography is not important in determining the location, strength, and structure of the simulated TEJ. The second and larger set comprising of aqua-planet simulations shows that it is sufficient to prescribe heat sources alone to study the TEJ. The first part has been included because it is necessary to compare these simulations with aqua-planet experiments.

For the first set, CAM-3.1 was run in its default configuration to simulate a five year period. This simulation is known as the Ctrl simulation. The effect of orography on the TEJ was studied by conducting a simulation for the same five years with same boundary conditions but with orography removed all over the globe. This simulation is known as the noGlOrog simulation. Both simulations used the default initial condition of 1st September 1991. As in Rao and Srinivasan (2016), the month of July has been studied because this is when the ISM is the strongest.

a) Aqua-planet simulations

The aqua-planet configuration of CAM-3.1 was used for the second set. The aqua-planet configuration represents a major simplification because land, sea-ice, and seasonal cycles are totally removed, while all the important physics that the AGCM offers are still retained. Sea surface temperature (SST) is prescribed as a boundary condition. The solar insolation is perpetually fixed at 21st March, which is March Equinox.

The simulations are divided into single and multiple heat source simulations. The background temperatures are kept uniform, similar to Chakraborty et al. (2009). The heat sources are indirectly specified by setting SST perturbations on this uniform SST background. Precipitation induced on account of these SST perturbations are representative of atmospheric heating. The implicit assumption is that latent heating is the dominant effect in the region of precipitation. The names of these simulations start with “AP”. Tables 2–4 and Fig. 3 can be used to supplement the description below.

The single heat source simulations had a uniform background SST of either 20°C or 25°C. Heat sources were prescribed by elevating SSTs in circular and oval shaped regions centered at (i) 90°E, 10°N or (ii) 90°E, 20°N. The choice of different shapes was used
to understand the effect of the shape of heating on the TEJ. The circular shaped regions have a diameter of 20°. The oval shaped regions have a minor axis of 15° aligned meridionally. The major axis was either 50°, 90°, 120°, or 180°. The name “extended oval” refers to the simulations with 90°, 120°, and 180° major axis. The peak SSTs for the 20°C uniform-background cases were 23°C, 27°C, 29°C, 32°C, 35°C, and 37°C; for the 25°C uniform background cases, they were 27°C, 28°C, 29°C, 32°C, 35°C, and 37°C. However, the SSTs for the extended oval simulations had only 25°C uniform-background SSTs and peak SSTs were limited to 35°C. These peak SST values were linearly or nonlinearly brought down to the background temperatures. In Fig. 3, S denotes the heat source at 90°E, 20°N. The heat source at 90°E, 10°N can be visualized to be directly below S.

The multiple heat source simulations had a uniform background SST of 22°C. Precipitation in regions shown in Fig. 3 (except in region S) has been induced by elevating SSTs there. In these regions, the goal is to induce precipitation magnitudes comparable to Ctrl simulation and also to keep the peak SSTs realistic. A peak SST of 29°C or lesser was enough for this purpose. In other words, the SST peaks were chosen on a trial-and-error basis to get the desired precipitation levels, and these SST peaks do not exceed 29°C. In all cases, SSTs linearly increase to the peak value. In each subtype, there are a few simulations with SST maxima at the same location but of slightly differing peaks (for example AP_N1 and AP_N2). The differences in the subtypes help to understand the relative impact of the strength of the heat sources on the TEJ. Although only a few simulations of each subtype are listed to check the robustness of the assertions, many such simulations were conducted with different SST peaks in the same locations. Table 3 lists the SST peaks of the different heat sources used in the simulations discussed here.

The aqua-planet simulations used initial conditions that were output from Ctrl simulation. They were run for one year and the mean of the last six months has been used for analysis. Additional details are given in Section 4.

3. Location and structure of the TEJ in Ctrl and noGlOrog simulations

The data presented here are five-year averages of maximum zonal wind (henceforth $U_{\text{max}}$), and precipitation for the month of July. Unless otherwise mentioned all figures for the zonal wind are shown at the location of $U_{\text{max}}$. The horizontal sections of the TEJ in Ctrl and noGlOrog simulations are shown in Figs. 1a, b. The horizontal section also shows the precipitation. The zonal and meridional sections are shown in Figs. 1d, 1f and 1c, 1e respectively. Table 1 lists the location and magnitude of $U_{\text{max}}$. The location of the peak zonal wind is virtually the same for Ctrl and noGlOrog simulations, whereas the jet is relatively weaker in the latter. Rao and Srinivasan (2016) showed that although the vertical structure was simulated well, the simulated TEJ was significantly westward shifted compared to reanalysis data. The meridional sections show the jet peak lying between 0–20°N. A vertical equator to pole tilt is seen in the jet. At higher latitudes, the mean height of maximum easterly zonal winds moves to lower pressure levels. The vertical extent of the zonal wind contours, henceforth, defined as the depth of the TEJ, is more on the poleward side. Although not shown, the TEJ and the low-level Somali Jet are the strongest at approximately the same longitudes.

The similarities in the TEJ in these simulations are due to similar precipitation patterns in both Ctrl and noGlOrog simulations. As in Rao and Srinivasan (2016), the centroid of the precipitation, henceforth, $P_c$, is computed using the following equation:

$$x_c = \frac{\sum_i P_i x_i}{\sum_i P_i}, \quad y_c = \frac{\sum_i P_i y_i}{\sum_i P_i},$$

where $x_c$ and $y_c$ are the zonal and meridional coordinates of $P_c$. $P_i$ is the precipitation at each grid point, $x_i$ and $y_i$ are the zonal and meridional distances from a fixed coordinate system. In each case, the grid point where the peak precipitation occurs is chosen as the origin of the coordinate system.

The $P_c$ has been computed for a region that is spatially quite significant and covers the monsoon region. The region chosen for averaging the precipitation is 40–110°E, 16°S–36°N. The values of precipitation equal to and exceeding 5 mm day$^{-1}$ are considered. The reason for choosing this threshold is because the goal is to identify the impact of only significant precipitation zones on the TEJ. Including low amounts of precipitation that occur in a significant part of the region under consideration will obscure the effect of precipitation hotspots. This threshold will be useful in comparing Ctrl simulation with aqua-planet simulations.

Table 1 and Figs. 1a, b show that because the precipitation patterns and centroid is similar in Ctrl
and noGlOrog simulations, the location of $U_{\text{max}}$ is also almost the same. The reduction in the magnitude of $U_{\text{max}}$ is related to the reduction in the magnitude of precipitation. The meridional geopotential gradients, shown in Fig. 2, have the same patterns in both simulations. The zonal location of the geopotential maxima is different for both simulations. This shows that rather than the location of the geopotential maxima, it is the spatial distribution of the geopotential gradients that determine the location of the TEJ. These simulations show that in CAM-3.1, orography is not important in determining the location and spatial structure of the jet.

4. Aqua-planet simulations

Because orography hardly impacted the TEJ in the previous simulations, it is instructive to study the atmospheric response only due to heating. The multiplicity of heat sources in the simulations previously discussed preclude any easy interpretation of the influence that each heat source has on the TEJ. A major simplification is conceivable if one uses the aqua-planet configuration of CAM-3.1. In the aqua-planet simulations of CAM-3.1, the role of different heat sources on the location, structure, and strength of the TEJ has been studied by specifying combinations of heat sources. The aqua-planet TEJ is henceforth referred to as “AqTEJ”, while in Ctrl, the name “TEJ” is retained.

Before proceeding further, the rationale for imposing heat sources on a uniform SST background in contrast to a zonally symmetric and meridionally varying SST profile is explained. Equatorial easterlies are simulated even if a zonally symmetric but meridionally varying SST profile that is symmetric about the equator is used. The existence of an equatorial jet also depends on the presence of twin or single Inter-Tropical Convergence Zone (Rajendran et al. 2013; Neale and Hoskins 2000); Using a meridionally varying SST profile makes it difficult to determine the role played by weak heat sources in the formation of an AqTEJ in aqua-planet simulations. Thus, a uniform background SST was the simplest conceivable case to ascertain the role of additional heat sources on the AqTEJ and thus the Ctrl TEJ. In doing so, the assumption is that these uniform SSTs, which exist beyond 60°N and 60°S, do not critically influence the dynamics governing the model TEJ. This was also suggested by Hoskins and Rodwell (1995) where they conducted a series of experiments to understand the Asian summer monsoon. The simulations of Matei et al. (2008) showed that it was primarily through oceanic mechanisms that the subtropics affected the equatorial surface climate. According to Lau and Nath (1996), the atmospheric response associated with midlatitude SST anomalies was less compared to the impact of tropical SSTs. A significant amount of inter- and intra-annual variability was due to the internal dynamics of the system. In their review article, Liu and Alexander (2007) noted that the atmosphere responded more to tropical SSTs than to middle- and high-latitude temperature anomalies. The forcing due to the equatorward atmospheric bridge was random unlike the oceanic forcing, which was more deterministic. Thus, the extratropical impact on the dynamics of the TEJ is reduced since the direct oceanic impact is absent in the aqua-planet mode of CAM-3.1.

Using only uniform background SSTs of 20°C and 25°C, a weak equatorial easterly, symmetric about the equator, was in fact developed. The zonal mean of the easterly winds had magnitudes of 10–15 m s$^{-1}$ located at a pressure level of 200–225 hPa. The reason for the existence of these easterlies is because these simulations had a band of weak precipitation near the equator. This would naturally imply that moist parcels rise aloft, implying the presence of a weak Hadley cell. According to Lee (1999), in the deep tropics, the horizontal transient eddy momentum flux accelerates the zonal-mean zonal wind. Transient eddies of intra- and inter-annual timescales were important determining factors. Hadley cell dynamics was also important.

The details of all the aqua-planet simulations are in Section 2.2 and Tables 2–4. Figure 3 shows the

| Case       | Zonal wind | Precipitation |
|------------|------------|---------------|
|            | Peak       | Lon | Lat | Press | Mean  | Lon | Lat |
| Ctrl       | 47.19      | 42.5°E| 8.8°N| 125   | 10.16 | 76.9°E| 9.8°N|
| noGlOrog   | 43.45      | 43.5°E| 7.6°N| 125   | 9.55  | 77.4°E| 7.0°N|

Ctrl: default orography; noGlOrog: no orography
Fig. 1. July Ctrl and noGlOrog simulations. (a), (b) Precipitation (mm day$^{-1}$, shaded), and horizontal zonal wind contours at pressure level where $U_{max}$ is attained, ‘cross-diamond’ (red) is location of peak zonal wind, ‘star’ (blue) is location of $P_c$; (c), (e) meridional, and (d), (f) zonal cross-section of zonal wind at location where $U_{max}$ is attained. Details are in Table 1.
different locations where SSTs are imposed. The magnitudes of peak zonal wind and mean precipitation are in Table 4. The centroid is calculated using Eq. (1) and the methodology explained in Section 3. The zonal wind for each month has not been separately computed and then averaged, rather the zonal winds for the six month period were added and then averaged. Therefore, the locations of $U_{max}$ correspond to grid point values of the model. This method is acceptable because the heat source is stationary, and over a six month time scale the response too averages out. The model resolution implies that minor fluctuations in location will hardly distort the main observations and inferences. In the figures that follow, the zonal winds are at cross-sections that pass through the location of $U_{max}$. Figure 4 shows the zonal and meridional separation between the location of $U_{max}$ and $P_c$. The simulations that clearly exhibit the impact of different heat sources are discussed. It must also be mentioned that the precipitation patterns will not
be identical in shape to the SST profiles nor can it be assured that the precipitation peak is directly over the SST peaks.

4.1 Single heat source simulations

The SST profiles imposed have circular and oval shapes all centered at 90°E, 20°N that mimic the off-equatorial monsoonal heat source in the northern Bay of Bengal. The heat source at 90°E, 10°N is to study the impact of lower latitudinal tropical heating on $U_{\text{max}}$. Figure 5 shows that heat sources closer to the equator generate slower zonal winds. There is also a difference in the variation of $U_{\text{max}}$ with increase in precipitation, which in turn is a consequence of increase in SST. As before, the mean precipitation is calculated by choosing a region surrounding the precipitation maxima such that all values $\geq 5$ mm day$^{-1}$ are captured. The $U_{\text{max}}$ trends are not as robust in the 10°N case in comparison with the 20°N case. Although there is a small increase in $U_{\text{max}}$ with SST, the increase is not monotonic for the 10°N heat source, whereas there is a steady increase and more than doubling for the 20°N simulations. This shows that heating in the lower latitudes in the tropics does not increase the magnitude of $U_{\text{max}}$ compared to heating in the higher tropical latitudes. The number of extended oval simulations for the 10°N case is much lesser than that of the 20°N case because all simulations showed that the former simulation sets exhibited no trend in $U_{\text{max}}$ with increasing precipitation.

The reduction in the strength of the AqTEJ by heat sources at lower latitudes is also predicted by the Gill (1980) model. In this model, if the length scale is reduced, then the location of the heat source is in the lower latitudes and the strength of the zonal easterlies also reduces. However, the Gill model is linear and is seldom used to explain upper tropospheric winds. The zonal winds in the upper and lower halves of the atmosphere have the same magnitude but are of opposite sign. Thus, it does not capture the significant differences between the wind structure in the lower and upper troposphere.

Because the heat sources at 90°E, 10°N do not generate adequate zonal wind velocities, only the cases with heat sources at 90°E, 20°N will now be discussed; these are the AP_S1–AP_S6 simulations. The shapes of the SST profiles are listed in Table 2. The simulations with oval-shaped SSTs serve to demonstrate the effect of the shape of the heating region on the jet. The peak SSTs go linearly down to the background temperature. However, the profile with major axes of 90° (AP_S5 and AP_S6) has a nonlinear SST profile that was used to make the profile more realistic. The background temperature is 25°C. The first simulation in each set has 29°C peak SST, while the second has 32°C peak SST. For example, AP_S3 has 29°C and AP_S4 has 32°C SST peak.

| Region | Shape of SST profile | Location of SST peak |
|--------|----------------------|----------------------|
| S      | Circle (C) 20° diameter | 90°E, 20°N          |
|        | Oval (Oa) 50° major axis 16° minor axis |                   |
|        | Oval (Ob) 90° major axis 16° minor axis |                   |
| E      | Circle 20° diameter 10° slope | 60°E, 4°N          |
|        | Rectangle | 62°E, 4°S to 94°E, 2°S |
| B      | Circle 20° diameter | 50°E, 20°N          |
| C      | 70°E, 14°N | 50°E, 20°N          |
| D      | 85°E, 10°N | 50°E, 20°N          |
| P      | Oval As in (Ob) above | 120°E, 20°N        |
|        | 150°E, 10°N | 120°E, 20°N        |
|        | 130°E, 2°S | 120°E, 20°N        |
The meridional and zonal cross-sections (Figs. 6a, b) are shown for the AP_S6 simulation. The jet is not meridionally symmetric. The major difference with Ctrl simulation lies in the vertical extent of the AqTEJ. With a single off-equatorial heat source, the jet depth is more on the equatorward side in contrast to Ctrl TEJ (Fig. 1c) where the depth is more on the poleward side. For lower magnitudes of heating, the easterlies were the dominant atmospheric flows in the tropics. Below 500 hPa and between 60°–90°E, there was a weak low-level jet, which is the aqua-planet counterpart of the Somali jet (not shown). This shows that for low heating rates, the easterlies developed do not significantly change the equatorial pattern of zonal easterly flows. As aforementioned, zonal easterlies were developed with uniform SSTs and with no additional heat sources. However, for higher magnitudes of heating, the low-level jet was stronger and had greater zonal extent. However, even then, the low-level jet peaks at approximately 5° to the west of \( P_c \), which is not the case in Ctrl and noGlOrog.

To the east of the jet, there is an upper-level westerly intrusion (Fig. 6b). A hint of this westerly is also observed in the Ctrl and noGlOrog simulations (Figs. 1d, f). In Fig. 6d, the precipitation region is demarcated by the 5 mm day\(^{-1}\) and above shaded contours. The precipitation (also refer Table 4 for mean precipitation) for the AP_S6 case is quite high, which is unrealistic. This high precipitation causes high values of \( U_{max} \), and yet, this AqTEJ does not have vertical structures that have any resemblance with the Ctrl TEJ. Consequently, one cannot understand the structure of the TEJ using a single heat source.

From Table 4, it can be seen that as the zonal extent of the SST profile increases, the zonal location of \( U_{max} \) also moves westwards. In comparison, the \( P_c \) varies by less than ~5°. This demonstrates that more zonally constricted heating reduces the zonal separation between \( P_c \) and \( U_{max} \). This is shown in Fig. 4 where points A and B are for the AP_S2 and AP_S6 simulations.

A simulation with the same SST peak and uniform background temperature as AP_S6 but with a linear profile was also conducted. This simulation was used to study if the SST gradient has any qualitative change on the jet. It was found that the amount of precipitation was marginally lower and correlated with \( U_{max} \) being lower by ~5 m s\(^{-1}\). There was a minimal effect on the zonal location of \( U_{max} \) and \( P_c \), which were very close to the AP_S6 simulation.

4.2 Simulations with multiple heat sources resembling Ctrl simulation

The major finding of the previous section is that a single off-equatorial heat source is inadequate in explaining Ctrl TEJ. Therefore, it is necessary to study the impact of combinations of heat sources. Fig. 1a shows the regions where precipitation exists in Ctrl simulation. The Ctrl simulation was chosen because it has orography as well as many precipi-
tating regions in the region of interest. The goal is to simulate an AqTEJ that has features similar to the Ctrl TEJ in location, shape, and magnitude. If this exercise is successful, then this will show that the TEJ is significantly influenced by the location and magnitude of heating.

The names AP_N1 to AP_M6 are for these cases. The locations and peak SSTs are given in in Tables 2–4 and Fig. 3. In regions of overlap, the maximum SSTs are chosen, which removes any kinks in the profiles. The uniform background temperature is 22°C. Although it would have been more realistic to incorporate a 25°C background temperature, it was thought that 22°C would help in clearly identifying the role the different zones play as elsewhere precipitation would be less, while simultaneously, a 22°C background temperature would allow for minimal convection to occur.

**Simulations without near-equatorial heating**

These are the AP_N1 and AP_N2 simulations that have heating in regions B, C, and D, as shown in Fig. 3. This set has no equatorial heating (region E). Because the heating is mostly off-equatorial, the meridional and zonal structures are similar to those with a single heat source at 90°E, 20°N (Figs. 6a, b) and thus are not shown. The interesting point to note from Table 4 and Fig. 7 is the 20° westward shift of \( U_{\text{max}} \) in AP_N1 (Fig. 7a) in comparison to AP_N2 (Fig. 7b), while \( P_c \) shifts by only ~5°. The zonal separation between \( P_c \) and \( U_{\text{max}} \) (points D and E in Fig. 4) shows this difference clearly. The precipitation in

| Case   | SST region | Zonal wind | Precipitation |
|--------|------------|------------|---------------|
|        |            | Peak       | Lon | Lat | Press | Mean | Lon | Lat |
| AP_N1  | B, C, D    | 33.08      | 37.5°E | 10°N | 150   | 9.02 | 67.5°E | 16.7°N |
| AP_N2  | B, C, D    | 30.41      | 57.5°E | 6°N  | 175   | 9.27 | 72.3°E | 16.2°N |
| AP_E1  | E          | 15.54      | 52.5°E | 2°N  | 225   | 11.52 | 74.2°E | 3.6°S  |
| AP_E2  | E          | 17.58      | 37.5°E | 6°N  | 225   | 11.35 | 72.1°E | 2.0°S  |
| AP_NE1 | B, E       | 26.73      | 37.5°E | 8°N  | 175   | 10.56 | 67.7°E | 2.7°N  |
| AP_NE2 | B, E       | 23.8       | 42.5°E | 14°N | 150   | 7.51  | 67.3°E | 3.1°N  |
| AP_M1  | C, D, E    | 30.89      | 55.0°E | 6°N  | 125   | 11.4  | 70.8°E | 5.4°N  |
| AP_M2  | C, D, E    | 24.91      | 52.5°E | 4°N  | 150   | 11.77 | 71.7°E | 2.6°N  |
| AP_M3  | B, C, D, E | 24.31      | 40.0°E | 10°N | 150   | 10.52 | 71.9°E | 2.3°N  |
| AP_M4  | B, C, D, E | 36.02      | 35.0°E | 8°N  | 150   | 9.2   | 69.7°E | 5.3°N  |
| AP_M5  | B, C, D, E | 34.43      | 32.5°E | 6°N  | 150   | 11.05 | 70.0°E | 4.8°N  |
| AP_M6  | B, C, D, E, P | 35.7 | 32.5°E | 8°N  | 150   | 10.22 | 68.8°E | 3.1°N  |

Uniform background SST: 22°C  Peak SSTs: ≤ 29°C
these two simulations shows that the precipitation in region B is relatively less in AP_N2 in comparison to AP_N1. This shows the importance of the heating that is closest to the peak zonal wind location. When the westernmost heating is below a certain threshold, the jet is influenced by the next closest heating, and in this case, it is the heating in region C. Although not shown, aqua-planet simulations with heating only in regions C and D have been conducted. In these cases, the zonal separation between P_c and U_{max} is approximately 15° less compared to AP_N1 and AP_N2. In other words, additional heating at location B increases this separation. This could be one of the reasons why Ctrl and noGlOrog simulations show a westward shift in the TEJ. In these cases, there is significant precipitation in the Saudi Arabian region.

b. Importance of near-equatorial heating

Referring to Fig. 1a, it can be seen that in the Ctrl simulation during July, there is a broad precipitation zone just to the south of the Equator between 50°–100°E, and also at ~60°E just to the north of this broad zone. Two simulations, AP_E1 and AP_E2, were conducted to understand the impact of this precipitation on the location and structure of the TEJ. Heating is present only in region E in Fig. 3.

From Table 4, it is seen that the zonal wind speeds barely qualify as a jet. The speeds are hardly more than one-and-a-half times the easterlies that are obtained for a uniform background simulation with no additional SST peaks. The location of peak zonal wind is also at a lower height (below 200 Pa). The most important observation is the stark contrast in the meridional structure compared to off-equatorial heating. The meridional section (Fig. 8a) shows that the maximum depth of the easterly is now on the poleward side. A low-level westerly of comparable strength extending beyond 500 hPa was observed. The upper part of this westerly is seen in Fig. 8a. As with Ctrl and noGlOrog, this westerly and upper-level AqTEJ were the strongest at approximately the same longitudes. Thus, with just equatorial heating the vertical structure has a realistic baroclinic structure.

However, the horizontal structure (Fig. 8b) immediately shows that the zonal wind structure is actually nowhere near the Ctrl TEJ. The peak zonal was observed to be to the west of 90°W, thus very far from the precipitation centroid. This far-off value has not been tabulated because the region chosen for locating the peak zonal wind is 0–90°E. Inspite of the maximum heating being in the south of the equator, the easterly is in the northern hemisphere. Compared to Ctrl (Fig. 1a), there is a significant westerly to the east of the upper-level easterly. This signifies the reduced zonal extent of the easterly flows. Table 4 shows that for this simulation set, the location of U_{max}.
(a) No increase in zonal wind speed; SST peak centered at 90°E, 10°N

(b) Rapid increase in zonal wind speed; SST peak centered at 90°E, 20°N

Fig. 5. Aqua-planet simulations. Mean precipitation (mm day$^{-1}$) versus $U_{\text{max}}$ magnitude (m s$^{-1}$). Aqua-planet simulations with single SST peak at (a) 90°E, 10°N and (b) 90°E, 20°N. The names indicate the SST profiles and numbers indicate the uniform background temperatures. Additional details are in Section 2.2.
varies significantly in comparison to $P_c$.

All these show that near-equatorial heating is necessary for imparting a baroclinic structure that resembles reality; however, stand-alone near-equatorial heating is by itself insufficient to generate a jet that resembles the TEJ.

c. Interplay between heating in near-equator and Saudi Arabian regions

It is interesting to study the effect of heating in region B in addition to region E discussed above; these are the AP_NE1 and AP_NE2 simulations. From Tables 1 and 4, it is seen that for these simulations the location of $U_{max}$ is closer to Ctrl simulation.

The meridional structure for AP_NE1 (Fig. 9a) is similar to the equatorial heating case. There is also the equator to pole tilt that is observed in Ctrl simulation. The meridional structure does not exhibit any increase in the equatorward jet depth till the precipitation in region B increases beyond a threshold compared to precipitation in region E. The precipitation is less in region E of AP_NE2 (Fig. 9d) in comparison to AP_NE1 (Fig. 9b). The increase in equatorward jet depth can be seen in Fig. 9c. However, in spite of the increase in equatorward jet depth, this depth is moderated by the equatorial heating effects.

Fig. 6. AP_S6 simulation (aqua-planet with single heat source in region S shown in Fig. 3.) (a) Meridional and (b) zonal cross-section at $U_{max}$ longitude and latitude location; (d) precipitation (mm day$^{-1}$, shaded), and zonal wind contours (m s$^{-1}$) at pressure level where $U_{max}$ is attained, ‘cross-diamond’ is location of $U_{max}$, ‘star’ is location of $P_c$; (c) negative of meridional gradient of geopotential ($\Phi$) divided by Coriolis parameter [-1/(\$\partial\Phi/$\partial y\$), m s$^{-1}$] (shaded), and $\Phi$ contour (continuous (blue) line), ‘star’ (blue) is location of peak $\Phi$ ($\Phi_{max}$). $\Phi$ contour is $138.9 \times 10^3$ m$^2$ s$^{-2}$ which is 99.5% of $\Phi_{max}$, ‘cross-diamond’ (red) is the location of $U_{max}$. Additional details are in Tables 2–4.
d. Effect of all heat sources except Pacific Ocean warm pool region

The discussion on the influence of near-equatorial and off-equatorial heating on the AqTEJ can now be used to combine all of them and study how close the net effect is compared to Ctrl simulation. These are the AP_M1 to AP_M5 simulations (refer Table 4). In this effort, once again, the focus is on the role of the westernmost heating on the jet structure and location. Therefore, the only difference between AP_M1–AP_M2 and AP_M3–AP_M5 simulations is the presence of heating in region B in the latter set. From the discussion in section a, it can be inferred that heating in region D is expected to have minimal role to play as it is the easternmost source.

The first and foremost difference, as observed from Table 4, is in the zonal location of $U_{max}$. Precipitation contours (mm day$^{-1}$) are shaded, ‘cross-diamond’ indicates location of $U_{max}$, ‘star’ is location of $P_c$. Aqua-planet with multiple off-equatorial heat sources in regions B, C, and D shown in Fig. 3. Additional details are in Tables 2–4.
where points G and H are for the AP_M1 and AP_M5 simulations. The zonal separation without heating in region B in the former causes the location of $U_{\text{max}}$ to be much closer to $P_c$. Compared to just equatorial heating, the AqTEJ zonal velocities are generally greater, and this is because of heating in regions B, C, and D (in Sections 4.1 and b, it was shown that heating in the lower latitudes does not contribute significantly to the magnitude of tropical easterlies, whereas heating in the higher tropical latitudes significantly contributes to the strength of these easterlies).

The zonal wind structures are similar in all cases (except for the difference in location of $U_{\text{max}}$ when heating in region B is present); hence in Fig. 10, only the AP_M5 simulation has been shown. The upper-level meridional structure of the jet (Fig. 10a) resembles Ctrl and noGlOrog simulations (Figs. 1c, e) with greatest jet depth always on the poleward side. This demonstrates that in aqua-planet configuration, precipitation patterns similar to Ctrl simulation result in similar meridional shapes. The horizontal and zonal sections (Figs. 10d, b) show that the AqTEJ zonally does not have eastward extent compared to Ctrl and noGlOrog cases (Figs. 1a, b, d, f). The discrepancy in the reduced eastward extent will be addressed in section e below. From the horizontal section (Fig. 10d), it can be seen that except for the westerly to the east of 90°E, the overall AqTEJ simulated in this multiple heat source aqua-planet configuration manages to have a satisfactory TEJ structure.

Fig. 9. (a), (c) meridional sections are at the longitude where $U_{\text{max}}$ is attained; (b), (d) horizontal cross-section at pressure level where $U_{\text{max}}$ is attained, ‘cross-diamond’ is location of $U_{\text{max}}$, ‘star’ is location of $P_c$; precipitation contours (mm day$^{-1}$) are shaded. Aqua-planet with multiple heat sources in regions B and E shown in Fig. 3. Additional details are in Tables 2–4.
The relatively weaker and more eastward location of peak zonal wind speed in the AP_M3 simulation compared to the AP_M5 simulation is because the precipitation in region B in AP_M3 was much lower in comparison to AP_M5. This once again underscores the influence of Saudi Arabian heating in distorting the location of the jet in the Ctrl simulation. However, even with lower heating in region B in the AP_M3 simulation, the meridional structure has greater poleward depth (not shown).

The location of the geopotential high (Fig. 10c) bears resemblance to Ctrl simulation (Fig. 2a). Although this peak in AP_M5 is shifted more westwards in comparison, it can be seen from Tables 1 and 4 that the location of \( U_{\text{max}} \) and \( P_c \) is also westwards compared to Ctrl. More specifically, the location of \( P_c \) and \( U_{\text{max}} \) for AP_M5 are shifted westwards by \( \sim 7^\circ \) and \( \sim 10^\circ \), respectively, in comparison to Ctrl. However, it can also be seen from Fig. 4 that the separation between \( P_c \) and \( U_{\text{max}} \) for Ctrl and AP_M5 are quite similar. Thus, in the AP_M5 simulation, if the SST profiles were to be shifted eastwards by \( \sim 7^\circ \), then the precipitation would have had the same features as before except for an eastward shift by the same amount. This would have also made the zonal wind and geopotential shift eastwards by \( \sim 10^\circ \). Then there would have even more similarity with Ctrl simulation.

It is also interesting to observe from Table 4 that
addition of a heat source in region B may or may not increase jet velocities. Comparing AP_M1 and AP_M2 against AP_M3 to AP_M5 it is seen that the greatest increase is between AP_M2 and AP_M4, while AP_M2 and AP_M3 are almost the same. This clearly shows the impact of heating in region B which is heat source located in the highest tropical latitude, as seen in Fig. 3. In the single heat source simulations (Section 4.1), it was shown that the jet velocities increased when the intensity of heating increased both spatially and magnitude wise, provided the heat source is in the higher tropical latitudes. If the source is strong, then the velocities increase significantly as is seen in AP_M4 and AP_M5. If this heat source is weaker, then $U_{max}$ may not increase significantly. This is the reason why AP_M3 simulation has about the same magnitude of $U_{max}$ as AP_M2. Heating in region B in AP_M3 was quite less than that in AP_M4 and AP_M5. This was also seen in section a., where relatively less heating in region B also causes a reduction in the magnitude of $U_{max}$. Inspite of this, in AP_M3 the zonal location of $U_{max}$ is westwards by more than 10° compared to AP_M1 and AP_M2. At the same time, the zonal location of $P_c$ in AP_M1, AP_M2 and AP_M3 are very similar to each other. This suggests that when multiple, well-distributed heat sources are present, the strength and location of the TEJ depends both on the intensity of heating as well as the number of heating zones.

e. Importance of heating in the Pacific Ocean warm pool

In all the above multiple heat source simulations, an important mismatch in zonal wind structure with the Ctrl and noGlOrog simulations is the westerly that was always present to the east of 90°E. This westerly was prominently reflected in all the zonal cross-sections. From Figs. 1a, b, it can be observed that there is significant precipitation occurring to the east of 100°E. This significant precipitation in the Pacific warm pool was not incorporated in the previous aqua-planet simulations. Hence an additional experiment, named AP_M6, was conducted incorporating additional heating in region P as shown in Fig. 3. The ratio of mean precipitation between 110°E–180° and 20°S–30°N for AP_M6 and Ctrl is ~0.95. Everywhere else, the SST profiles and maxima were same as AP_M5. The results are shown in Fig. 11. The horizontal section (Fig. 11b) now shows the extension of the easterly beyond 90°E and this is also reflected in the zonal section (Fig. 11a). The meridional section is not too different from Fig. 10a and hence is not shown.

The location and magnitudes of peak zonal wind in AP_M5 and AP_M6 are almost the same. This is to be expected since precipitation located significantly eastwards does not impact the location of $U_{max}$. Thus heating in the Pacific warm pool is necessary for the eastward extent of the TEJ.

5. Conclusions

The July climatological structure of the Tropical Easterly Jet in Ctrl and noGlOrog simulations is compared with aqua-planet simulations. In the absence of orography, the spatial location and structure of the TEJ is practically unchanged. This suggests that the simulated TEJ is not directly influenced by orography. This then leads to the concept that certain aspects of the TEJ can be understood from the viewpoint of latent heating alone, if assumed that land-sea contrast is of secondary importance. Hence, aqua-planet experiments with different heat sources were conducted. These aqua-planet simulations have given the following insights about the location, strength, and structure of simulated TEJ:

1. The simulation of the TEJ in an aqua-planet configuration of CAM-3.1 shows that orography and land-sea interactions are not as important as latent heat release.
2. A heat source at 20°N is more to be robust in generating zonal wind speeds comparable to that of the TEJ. Similar magnitude of heating in the lower latitudes in the tropics does not generate high-speed zonal easterlies.
3. Equatorial heating alone does not generate zonal winds that are strong enough.
4. Equatorial heating is necessary to generate a strong low-level westerly which imparts a realistic vertical baroclinic structure in the tropical longitudes where the TEJ is located. However it is insufficient in generating a true TEJ horizontal structure.
5. Equatorial heating is essential to create meridional structures of the TEJ seen Ctrl and noGlOrog simulations. Greater poleward depth of the TEJ is possible only if adequate equatorial heating is present.
6. The longitudinal location of peak zonal wind is influenced by higher latitudinal tropical heating that is closest to it. If this heat source is strong it tends to shift the TEJ peak westwards. It is thus likely that the significant westward shift of the TEJ in Ctrl simulation in comparison to reanalysis, documented in Rao and Srinivasan (2016), is due to rainfall in Saudi Arabian region.
Heating in the Pacific warm pool is necessary to cause greater eastward extent of the TEJ.

When all the important heat sources are incorporated in the aqua-planet configuration, many observed features of the Ctrl TEJ are correctly simulated. These results along with those in Rao and Srinivasan (2016) show that, for the TEJ, sensible heating due to the presence of Tibetan Plateau is less important when dominated by latent heat release due to convective processes. Even though there are similarities in the magnitudes of mean precipitation of the different cases of multiple heat sources, individually each heat source may have quite different effects on the location, shape and strength of the TEJ. Thus aqua-planet simulations play an important role in understanding the role of heat sources in the absence of any influence of land and orography.

Fig. 11. AP_M6 simulation (aqua-planet with multiple heat sources in all regions, except S, shown in Fig. 3). (a) zonal wind at the latitude where \( U_{\text{max}} \) is attained, (b) horizontal cross-section at pressure level where \( U_{\text{max}} \) is attained, ‘cross-diamond’ is location of \( U_{\text{max}} \), ‘star’ is location of \( P_c \), precipitation contours (mm day\(^{-1}\)) are shaded. Additional details are in Tables 2–4.
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