OTREC2019: Convection Over the East Pacific and Southwest Caribbean

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Abstract We present preliminary results from the field program Organization of Tropical East Pacific Convection (OTREC), with measurements during August and September of 2019 using the NSF/NCAR Gulfstream V over the tropical East Pacific and Southwest Caribbean. We found that active convection in this region has predominantly bottom-heavy vertical mass fluxes, while decaying systems exhibit top-heavy fluxes characteristic of stratiform rain regions. As in other regions that have been studied, a strong anti-correlation exists between the low to mid-level moist convective instability and the column relative humidity or saturation fraction. Finally, the characteristics of convection as a function of latitude differ greatly between the Southwest Caribbean and Colombian Pacific coast on one hand, and the intertropical convergence zone to the west. In particular, the strongest convection in the former is to the south, while it is to the north in the latter, in spite of similar latitudinal sea surface temperature distributions.

Plain Language Summary Understanding and modeling the physics of tropical atmospheric convection still poses a big challenge. Things are complicated over the tropical oceans because there is no easy way to gather data. Field projects such as the one presented in this paper, Organization of Tropical East Pacific Convection (OTREC2019) are of great importance to our scientific community for this reason. During OTREC, 22 research flights were performed over East Pacific and Southwest Caribbean gathering data from 13 km to surface. This paper presents early results that will help us understand the physics of convection and improve our weather and climate models.

1. Introduction

Understanding and describing the nature of convection in the East Pacific intertropical convergence zone (ITCZ) remains a challenge. Riehl et al. (1951), Lindzen and Nigam (1987), Battisti et al. (1999), Tomas et al. (1999), Stevens et al. (2002), Back and Bretherton (2009) suggest that Ekman balance theory plus downward momentum transfer from above the boundary layer are responsible for the ITCZ. Alternatively, Raymond (2017) proposed that thermodynamic factors mainly in the free troposphere are sufficient to explain the latitudinal distribution of convection across the ITCZ in the tropical East Pacific. This paper presents early results from the Organization of Tropical East Pacific Convection (OTREC2019) field program that cast light on this issue.

Previous to OTREC2019, the most recent field project to study East Pacific convection was East Pacific Investigation of Climate (EPIC2001), which took place from 1 September to 10 October 2001. One of the goals was to determine variability, strength and location of deep convection, and the structure of the boundary layer. The program had a large oceanic component as well. (For more details on EPIC, see Raymond et al. (2004).) During EPIC, two aircraft, NCAR C-130 and NOAA P-3, were deployed from Huatulco, Mexico. The P-3 was used to map the ITCZ by flying a grid pattern at 1,900 m. C-130 flew along 95 W to the equator at low altitude, but in its return leg dropped dropsondes from 6,300 m height. It also flew missions targeted at individual convective clusters.

Raymond (2017) studied the Eastern Pacific ITCZ based on EPIC2001 C-130 data by looking at thermodynamic parameters such as deep convective inhibition (DCIN), saturation fraction and instability index as a function of latitude. However, EPIC C-130 data were limited to the lower troposphere at a single longitude, which introduced significant limitations.

Deep convective inhibition is defined as
where \( s_{th}^* \) is threshold entropy, defined as the average of the saturated moist entropy in the 1.5–2 km layer, minus the boundary layer moist entropy \( s_{bl} \) averaged over the 0–1 km layer. If the boundary layer convergence is driven by sea surface temperature (SST), we will expect to observe decrease in convective inhibition on the average in East Pacific near 7 to 8 N (Raymond, 2017).

The saturation fraction is defined as precipitable water over the saturated precipitable water

\[
SF = \frac{\int r dp}{\int r_s dp}
\]

where \( r \) is the mixing ratio, \( r_s \) is the saturation mixing ratio, and \( p \) is the pressure. It is a measure of the amount of moisture in the atmospheric column and is a good proxy for precipitation. (Bretherton et al., 2004). Singh et al. (2019) developed a simple theoretical model for the environmental control of convection that explained the sharp dependence of rainfall on the saturation fraction. It also showed that decreasing the instability is associated with increasing relative humidity and therefore increasing precipitation.

Instability index is defined as

\[
\text{II} = s_{low} - s_{high}
\]

where \( s_{low} \) and \( s_{high} \) are respectively the saturated moist entropy averaged over the altitude ranges of 1–3 km and 5–7 km. It is a measure of low to mid-tropospheric moist convective instability. Lower, but still positive, values are associated with more rainfall, (Raymond et al., 2014; Singh et al., 2019). This result is reflected in observations (Gjorgievska & Raymond, 2014; Raymond et al., 2014; Raymond et al., 2015) and in cloud resolving models (Raymond & Flores, 2016; Raymond & Kilroy, 2019). This suggests that thermodynamic parameters saturation fraction and instability index are likely predictors of the local properties of the environment and that the interaction of ensembles of convection with the environment depends only on the local properties of the environment. Raymond et al. (2014) called this relation moisture quasi-equilibrium (MQE).

Based on the T-PARC/TCS08 (THORPEX Asian Regional Campaign/Tropical Cyclone Structure experiment) and PREDICT (PREDepression Investigation of Cloud systems in the Tropics), Raymond et al. (2014) also find that decrease in instability index is associated with bottom-heavy vertical mass flux profiles. The vertical mass flux profile is defined as

\[
M(z) = \rho w
\]

where \( \rho \) is the density and \( w \) is the vertical component of velocity.

The tropical East Pacific ITCZ is unique due to the existence of a strong meridional SST gradient with lowest SSTs occurring on the equator. Both the form and the forcing of deep convection there are still not understood well. In contrast, the Southwest Caribbean exhibits much more uniform ocean temperatures. The two regions together provide a broad range of atmospheric and sea surface conditions and a great deal of diversity in convective behavior. This served as the motivation for OTREC2019.

Flight operations for OTREC took place from 5 August to 3 October 2019. Twenty-two research flights (127 research flight hours) over the East Pacific and Southwest Caribbean were performed out of Liberia, Costa Rica, using the NSF/NCAR Gulfstream V aircraft. Six hundred and forty-eight dropsondes were deployed in a grid and the Hiaper Cloud Radar calculated data on cloudiness and precipitation below the aircraft. Radiosondes were launched from Santa Cruz and Limón (Costa Rica) and Nuquí (Colombia) during the time period of OTREC. Intensified radiosonde launches were also executed at the standard radiosonde sites across Colombia. Additional weather and global positioning system column water vapor stations were established in Costa Rica and Colombia. Rainfall samples were collected in Costa Rica and Colombia.
In this paper we present preliminary results from OTREC. Section 2 presents the data and methods used. Overall results are shown in section 3, as well as summaries of the characteristics of convective systems in the ITCZ, off the Pacific coast of Colombia, and in the Southwest Caribbean. Conclusions are presented in section 4.

2. Data and Methods

The research flights took place in B1 and B2 boxes mostly on consecutive days to capture the passage of easterly waves. Figure 1 shows examples of research flights (RF) executed in B1 (left) and B2 (right). Box B1a off the coast of Colombia was chosen to study Chocó jet, which impinges on the coast of Colombia and produces massive rainfall there (Poveda & Mesa, 2000), and possible initiation of easterly waves in that area (Kerns et al., 2008; Rydbeck & Maloney, 2015). Box B1b in Southwest Caribbean was chosen due to the uniform SST in the Caribbean and to study passage of easterly waves across Central America. Box B2 facilitated the study of Eastern Pacific ITCZ and convection in the area of strong meridional SST gradient as well as the passage of easterly waves from Southwest Caribbean and from the coast of Central America and Colombia.

The B1 pattern in Figure 1 shows RF04 performed on 16 August 2019 (blue line) superimposed over a GOES-16 satellite longwave-infrared image. Circles show the targeted dropsonde location used by our three-dimensional variational analysis (3DVAR) from which regular grids of data are derived (Elsberry & Harr, 2008; Gjorgjievska & Raymond, 2014; Juračić & Raymond, 2016; Lopez Carrillo & Raymond, 2011; Montgomery et al., 2012; Lopez Carrillo & Raymond, 2011; Raymond et al., 2011). Grid cell dimensions are 0.25 degree horizontally and 200 m vertically up to 16 km. No background analysis data were used in this scheme to avoid contamination by potentially spurious analysis results. For the thermodynamic data, the 3DVAR cost function included forcing agreement with the dropsonde data with sufficient horizontal smoothing to fill in the gaps between the dropsondes. Only a small amount of vertical smoothing was
used. For the winds, enforcing mass continuity was imposed in order to derive the vertical wind \( w \), which was set to zero at the surface and 16 km. The corresponding B2 pattern shows RF01 performed on 7 August 2019. The data set for dropsondes used in this paper is NCAR/EOL AVAPS Dropsonde Quality Controlled Data Version 1.0, Voemel, H. (2019).

Nine flights were performed in the Eastern Pacific off the coast of Colombia (box B1a) and in Southwest Caribbean (box B1b), while 12 flights were performed in the flight pattern B2 in the Eastern Pacific area. An additional flight was performed in collaboration with the National Oceanic Administration Hurricane Research Division P-3 while studying early stages of developing tropical storm Ivo. The main goal was to sample convection at all stages including the initial stage. The flight days were picked randomly in order to avoid selection bias. The B2 pattern was mainly flown a day after the B1 pattern to capture the passage of easterly waves.

3. Results

3.1. Results Overview for all Research Missions During OTREC

Figure 2 summarizes results from the 3DVAR analysis of dropsondes for the entire project, that is, all 22 flights. For clarity, results from every tenth 0.25 by 0.25 degree column are plotted. Colombian (B1a) and
Caribbean boxes (B1b) are plotted in red dots and Eastern Pacific ITCZ box (B2) in blue dots. The red line at the bottom of each latitude plot indicates the land mass over Panama that was crossed while performing the B1 pattern. Note that it is easy to distinguish box B1a from B1b based on latitude.

Plots (a) and (b) in Figure 2 show vertical mass flux averaged over 3–5 km (mfluxlo) and 7–9 (mfluxhi) altitude respectively as a function of latitude. Mfluxlo in Eastern Pacific (blue dots) shows no strong tendency with respect to latitude except for a number of negative fluxes between 7 and 11 N (associated with stratiform rain regions which exhibit mesoscale downdrafts in the lower troposphere) and high positive mfluxlo associated with rare and intense convection from RF20 that took place on 30 September 2019 south of 4.5 N. The B1b Caribbean box mfluxlo shows rather weak vertical mass fluxes. In contrast, the B1a Colombian box (south of 7 N) shows large positive values of mfluxlo. Plot (b) shows that for B2 box, with the exception of the RF20, large values of positive mfluxhi increase north of 7 N with a maximum near 11 N. In contrast, in the Colombian box the large values of mfluxhi are observed south of 7 N.

Figure 2c shows the difference, mfluxdif, between mfluxhi and mfluxlo which is a measure of top-heaviness of convection. The B1 box shows no strong tendency in mfluxdif with respect to latitude, while the B2 eastern Pacific box south of 7 N shows predominantly negative values of mfluxdif, indicating bottom-heavy vertical mass flux profiles. In the North of 7 N, there are many cases of bottom-heavy fluxes in B2, though some top-heavy ones (representing decaying stratiform rain areas) occur as well.

Table 1
Summary of Location, Time and Nature of the Convective Events that Occurred During the OTREC Flights

| Research flight | Date      | Location   | Description                  | Vertical mass flux profile |
|-----------------|-----------|------------|------------------------------|----------------------------|
| B1a Colombian box: Convective events |           |            |                              |                            |
| 02              | 08/11/2019 | −81 to −78 W 5.5 to 7 N | Developing                   | Top                        |
| 04              | 08/16/2019 | −81 to −78 W 5.5 to 8 N | Decaying; off the coast      | Bottom                     |
| 13              | 09/17/2019 | −81 to −78 W 4 to 7 N  | Shallow convection           | Bottom                     |
| 15              | 09/22/2019 | −81 to −78 W 5.5 to 7 N | Developing                   | Bottom                     |
| 17              | 09/25/2019 | −81 to −78 W 3.5 to 8 N | Developing                   | Bottom                     |
| B1b Caribbean box: Convective events |           |            |                              |                            |
| 04              | 08/16/2019 | −83 to −81 W 9 to 11 N | Developing                   | Top                        |
| 07              | 08/22/2019 | −83 to −79.5 W 9.5 to 11.5 N | Developing                  | Bottom                     |
| 10              | 09/03/2019 | −83 to −79.5 W 9 to 11 N | Developing                   | Bottom                     |
| B2 Eastern Pacific box: Convective events |           |            |                              |                            |
| 01              | 08/07/2019 | −89 to −86 W 6 to 11 N | Developing                   | Top                        |
| 03              | 08/12/2019 | −89 to −86 W 8 to 11 N | Decaying at the flight time, later became tropical storm Henriette | Top                        |
| 14              | 09/21/2019 | −89 to −86 W 7 to 9.5 N | Developing                   | Bottom                     |
| 14s             | 09/21/2019 | −89 to −86 W 10 to 12 N | Decaying                     | Top                        |
| 18              | 09/27/2019 | −89 to −86 W 10 to 11 N | Developing                   | Bottom                     |
| 19              | 09/28/2019 | −89 to −86 W 6 to 10 N | Decaying                     | Top                        |
| 20              | 09/30/2019 | −89 to −86 W 3 to 6 N  | Developing                   | Bottom                     |
| 21              | 10/01/2019 | −89 to −86 W 7 to 10 N | Developing                   | Bottom                     |
Plot (d) of Figure 2 shows a scatter diagram of DCIN as a function of latitude. Most values of DCIN at all latitudes and for all flight regions are between $\approx 10 \text{JK}^{-1}\text{kg}^{-1}$ and $10\text{JK}^{-1}\text{kg}^{-1}$ with a scattering of higher values. These higher values are absent from the pronounced minimum in DCIN at 7–8 N in the Eastern Pacific B2 box as well as in B1 region.

Plot (e) of Figure 2 shows a scatter plot of instability index as a function of latitude, while plot (f) shows a scatter plot of saturation fraction versus latitude. Instability index shows a strong dependence on latitude with lower values to the south of B1 and B2 regions. Saturation fraction shows a broad maximum in the range 7–9 N for the Eastern Pacific box. The very low values of saturation fraction north of 7 N are associated with the aforementioned September 30 case. The highest values of saturation fraction are at 6 N in the Colombian B1a box, significantly lower in the Caribbean box B1b.

A major conclusion from Figure 2 is that the convection in the Caribbean and off the Colombian coast differs greatly from that observed in the East Pacific ITCZ. In particular, the convection south of 7 N near Colombia is much stronger on average than typically occurs in corresponding latitudes in the ITCZ. This is accompanied by unusually high values of saturation fraction and instability index. In contrast, ITCZ convection north of this latitude is on the average stronger than that in the Southwest Caribbean. These differences occur in spite of similar latitudinal distributions of SST in the two regions and will be the subject of future research.

### 3.2. Convective Cases During OTREC

Out of nine flights performed in the B1 pattern, five convective cases were observed in B1a box and three in B1b box. Out of 12 flights performed in the B2 pattern, 8 convective cases were observed. The convective cases were defined subjectively by looking at GOES-16 satellite loops and images with the help of the log that we kept during the flight missions. Table 1 shows the summary of location, time, and nature of the convective events that occurred during the OTREC flights. The goal is to look at the correlation between the instability index and the saturation fraction as well as vertical mass flux profiles to see if they are related to thermodynamic variables for those convective events.

Figure 3 shows the scatter plot between saturation fraction and the instability index for all convective cases in B1a, B1b, and B2 boxes. Each dot represents measurements from one dropsonde deployed within or around the convective event (similar plot can be obtained using the 3DVAR; the authors chose to show dropsondes to remain as close to observations as possible). Note that the area of the convective cases is significantly smaller than the flight region resulting in fewer dropsonde points in Figure 3. Dropsonde data for B1a (the Colombian box) are given by red dots, for B1b (the Caribbean box) by blue dots and for B2 (the East Pacific box) by black dots. We can see that there is an inverse correlation between the saturation fraction and instability index (correlation coefficient of 0.607 at the 99% level) as one would expect from MQE.

The slope of the anti-correlation between the saturation fraction and instability index, as seen subjectively from Figure 3, is different between the Colombian box and the other boxes. This may be due to the proximity of land and is a subject of further research. As saturation fraction is a good proxy for precipitation (Bretherton et al., 2004, Singh et al., 2019), and instability index is anti-correlated with saturation fraction, low instability index might be a good environmental indicator for convection and precipitation.

The 3DVAR analysis is used to calculate the average mass flux profile only for the area with the convective events defined in Table 1. Each convective event’s vertical mass flux profile is given in a different color with a legend referring to the research flight during which the event had occurred. Every RF shown in Figure 4 had one convective event except RF14, which had two. (See summary in Table 1.) Bottom-heavy vertical mass flux profiles are shown by solid lines, while top-heavy are represented by dashed lines.

**FIGURE 3.** Scatter plot between the saturation fraction and instability index for soundings in and near deep convection. Data for B1a Colombian box are given in red, for B1b Caribbean box in blue, and for B2 East Pacific box in black.
As with defining the convective systems, we subjectively separated growing from decaying convective systems using GOES-16 satellite loops and mission reports and logs. Out of eight convective cases in the Eastern Pacific box B2, we identify five cases that had developing convection and three cases that had decaying convection. Out of five convective cases in the Colombian box B1a, three cases had developing convection, one (RF04) had very pronounced shallow convection, and one case (RF02) had mixed convection (decaying off the coast, otherwise developing). Out of three convective cases in the Caribbean box B1b, all had developing convection. Regardless of location, every developing case had a bottom-heavy or neutral vertical mass flux profile, while every decaying case had top-heavy mass flux profile characteristic of a stratiform rain region. RF02 that exhibited signs of mixed convection was dominated by a top-heavy vertical mass flux profile.

4. Conclusions

The NSF/NCAR Gulfstream V aircraft was used to study convection over the tropical East Pacific and the Southwest Caribbean during the OTREC project (5 August to 3 October 2019). 648 dropsondes were deployed from near 13 km in predefined Cartesian grids over 22 flights. Figure 1 shows the three study regions. (One flight was made over a pattern further west in a special tropical cyclogenesis study in cooperation with a NOAA HRD P-3 aircraft.)

The thermodynamic characteristics of the atmosphere in and near convection were studied using individual dropsondes for 16 convective cases. In addition, a 3DVAR was made over the dropsonde grid for each flight in order to compute convective mass fluxes and other profiles. This analysis does not incorporate background fields from models.

A composite study of all flights shows distinctly different patterns in the ITCZ region of the tropical East Pacific compared with the Pacific adjacent to the Colombian coast and the Southwest Caribbean. In
particular, bottom-heavy vertical mass flux patterns are found at all latitudes of the ITCZ region, with increasing convective depth with higher latitude. In contrast, the Colombian coastal region shows more deep convection with mixed vertical mass flux patterns, even though the SSTs are no higher than those at corresponding latitudes in the ITCZ region. Thermodynamic parameters are very different in the Colombian from those at corresponding latitudes in the ITCZ region. Convection further north in the Caribbean can be deep, but is generally weaker.

An examination of individual convective events observed during the project supports the above conclusions. In the ITCZ region, bottom-heavy convective mass flux profiles dominate except in cases of decaying convection, where top-heavy stratiform rain profiles are observed. Off the Colombian coast and in the Caribbean, the form of the mass flux profiles is more mixed. Individual soundings in convective regions also support the validity of the MQE hypothesis.

The differences between thermodynamic profiles and convective characteristics in the ITCZ region and in the Pacific near Colombia as well as in the Caribbean remain to be explained and will be the subject of future research.

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