4C.6.   CARIBBEAN WAVES AS PRECURSOR SYSTEMS OF LATE HURRICANE SEASON FORMATION.

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1. INTRODUCTION

Easterly Waves are prominent synoptic-scale features of the summer climate in the tropical atmosphere. Over the Atlantic, African Easterly Waves (AEWs) frequently serve as seeds for tropical cyclones and their characteristics have been extensively documented (e.g. Reed et al, 1977, Simpson et al. 1968, Kiladis et al. 2006 and refs therein). Traditionally it has been thought that AEW move across the Atlantic Ocean reaching continental America even though early observations suggested that some disturbances formed within the Caribbean and eventually become tropical cyclones there (Frank 1972). The concept of the Caribbean Wave lost favor in the literature to the more widely studied AEWs, and consequently the amount of research focusing on waves in the Caribbean and their origin has been limited. We argue that there remains uncertainty with respect to the origin of some Caribbean waves and that is the focus of this study.

Previous research on Easterly Waves in the Caribbean has mostly considered seasonal composites (June to September) in order to identify their typical structure and related dynamics (e.g. Serra et al. 2010). However the region of the Caribbean and/or Intra-Americas Sea is characterized by a unique environment with a remarkable range of meteorological phenomena (such as waves, hurricanes, temporales, Mid-Summer drought, cold fronts, trade surges) and climatic features such as a low level jet. Therefore, composite studies encompassing such a wide range environments through time averaging over intraseasonal variations hinders identification of the possible mechanisms that lead to the origin to Easterly Waves over this region.

The purpose of this research is to identify the origin of Easterly Waves over the Caribbean and their relationship with cyclogenesis. Regression analysis show that there are two distinctive easterly waves regimes, the first one comprises of those waves crossing the Atlantic from Africa in the months of June, July and August (AEWs) and the second one comprises of those waves generated in situ in the month of September. To illustrate their relation to cyclogenesis, the 2013 Atlantic hurricane season is considered, in this, the Tropical Storm Fernand (August 25-26) and hurricane Ingrid (12-17 September) will be explored as examples of Easterly Waves that had their origin from an AEW and those generated over the Western Caribbean.

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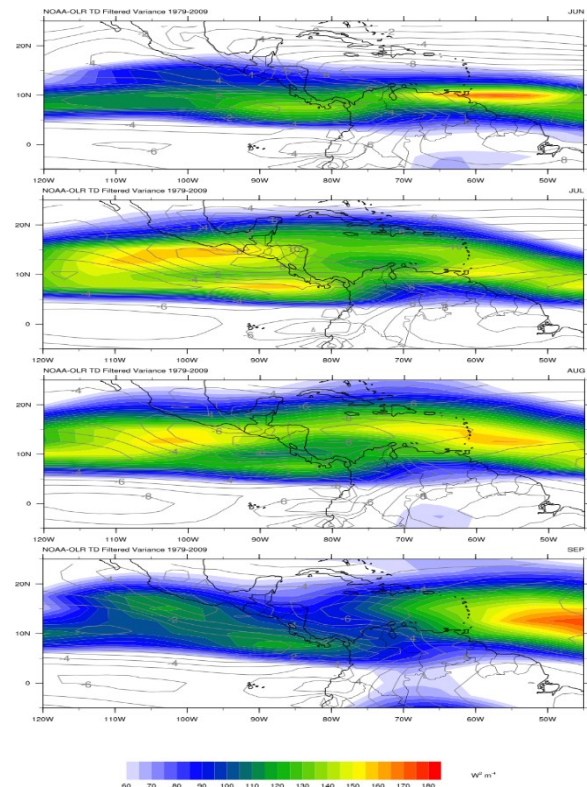
Figure 1. Geographical distribution of the variance of TD wave-filtered OLR (shading) and zonal wind (contours) for the months of June, July, August and September.

2. DATA AND METHODOLOGY

To produce monthly composite structures and highlight the typical evolution of Easterly Waves over the Caribbean, lagged regressions of dynamical fields associated with the OLR variations of the Easterly Waves were employed similar to those of Wheeler et al. (2000). To do this, we start by taking a time series of the space-time filtered OLR dataset at a single grid point, which is chosen to be where the variance of the filtered OLR in the Tropical Depression (TD) band is at its maximum over the Caribbean. This forms the reference time series against which all of the dynamical variables, as well as the total OLR itself, are regressed. The method for wave filtering is the one used by Roundy and Frank (2004) by filtering OLR in wavenumber-frequency (zonal westward 6 to 20; 2-10 days).
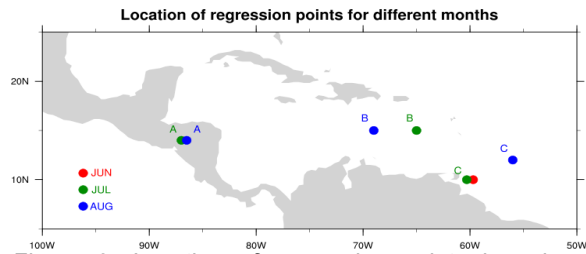
Figure 2. Location of regression points based on monthly peak variances from figure 1.

To maximize the signal-to-noise ratio, however, we computed the linear regression only for those intervals in which a discrete signal in the filtered OLR is determined to be present. This deviation in OLR is chosen to be -2 standard deviations of the windowed and filtered OLR, yielding magnitudes that are typical of individual wave events based on case studies (Wheeler and Kiladis, 1999). Statistical significance of the local linear relationship in wind was retrieved using a bootstrap-t test (Efron and Gong 1983).

Following previous studies on Convectively Coupled Equatorial Waves, the proxy used for deep tropical clouds or convection is the twice daily record of satellite-observed outgoing longwave radiation for the period 1979-2009. For the dynamical fields, ERA-Interim products for the period 1989-2010 were used.

3. RESULTS
3.1 TD variance

Figure 1 presents the geographical distribution of the TD wave-filtered OLR variance over the months of June, July and August and September. As can be observed, peak variance occurs at different locations depending on the month of the year. In July the TD storm track appears continuous between the tropical Atlantic and the Caribbean suggesting a link to AEWs. In September this link is more tenuous, suggesting a weaker impact of AEWs in the Caribbean region during this month.

Locations where the variance is greatest to study the evolution of Easterly Waves are shown in figure 2. The point of the month of August over Central America is selected to study the possible link to AEWs and the impact on cyclogenesis following the methodology previously described.

3.2 Lagged Regressions

The 700-hPa stream function and wind structure of the composite TD wave for the month of August at 14ºN, 87ºW is shown in figure 3 for the lags -4 to 4. Four days before the peak in convection at this point, an elongated trough near 62°W,15°N tilted to the northwest with a positive OLR anomalies ahead and negative OLR anomalies to the southeast; at this lag, the convective signal is centered about 57°W,10°N. A wave train from Africa is present at this time.
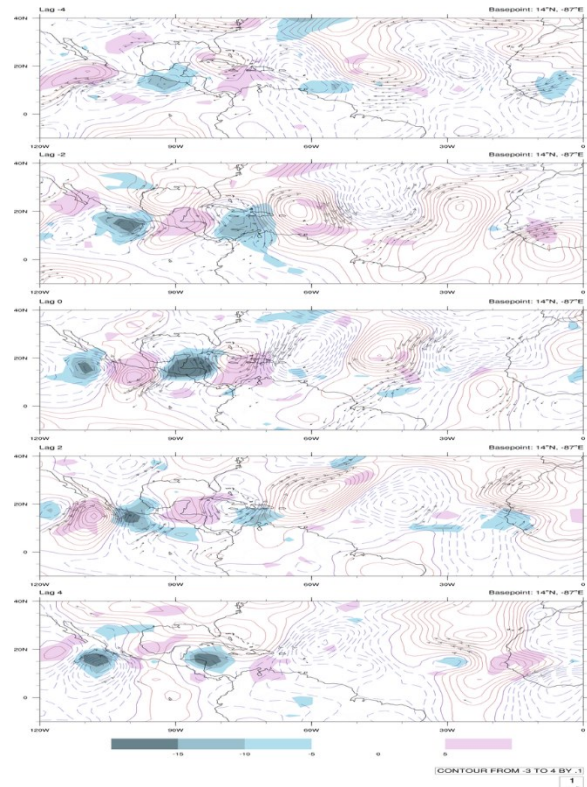

Figure 3. Maps of OLR (shading), 700-hPa stream function (contours) and 700-hPa wind (vectors) anomalies associated with the OLR variation of the TD wave at the base point 14ºN, 87ºW for the month of August, for day -4 to 4 every 2 days.

At subsequent lags the convective and dynamical signals move westward and have characteristic horizontal tilts that are consistent with barotropic growth.

Southerlies are located behind the region of enhanced convection, as can be seen at lags -2 and 0. At lag 0 the convection is over the western Caribbean and part of Central America, the winds associated influence the northwest Gulf of Mexico, eastern Pacific and central Caribbean. As the dynamical signature of the wave crosses Central America, at lag +2, a splitting of convection takes place with convection over the Gulf of Mexico and the eastern Pacific. Subsequent lags show a displacement of the wave parallel to the west coast of Mexico.

From this behavior and in agreement with TD variance in August, the TD storm track appears continuous between the tropical Atlantic and the Caribbean suggesting a link to AEWs, henceforth it can be stated that for the month of August, Easterly waves affecting the Caribbean arise primarily from African Easterly Waves.

Similar results are obtained for the months of June and July (not shown) but not for September.
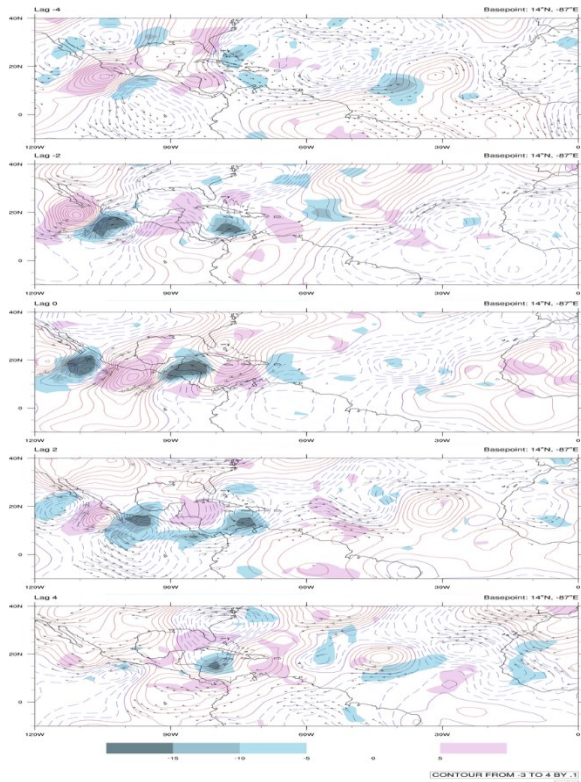
Figure 4. Same as figure 3 but for the month of September.

To compare the previous result against what is obtained for September we used the same regression point.

From variance maps it can be observed that the link to AEWs is weaker during this month. Regressions for September in figure 4 show that 4 days before the impact over Central America, the convection is not represented by a single center; and additionally, there is no clear link to AEWs. At lag -2 we observe a well-defined center of convection over the central Caribbean, the dynamical signature seems to be related to a northern influence and with no relation to the Atlantic. Over the eastern Pacific we start to see the onset of a wave train. At lag 0 it is possible to appreciate a well-defined wave train from the Caribbean developing into the eastern Pacific, the center of convection with north-westerlies ahead of the trough over the Central American and south-easterlies behind. At lag+2 we see that convection is southwest of the Isthmus of Tehuantepec with a well-defined trough over the eastern Pacific. At this time, we still observe a wave train well developed over the eastern Pacific and deflected to the northwest and a new development in the middle of the Caribbean. Finally at lag +4 the convective signal at the eastern Pacific has disappeared, but not the dynamical signal.
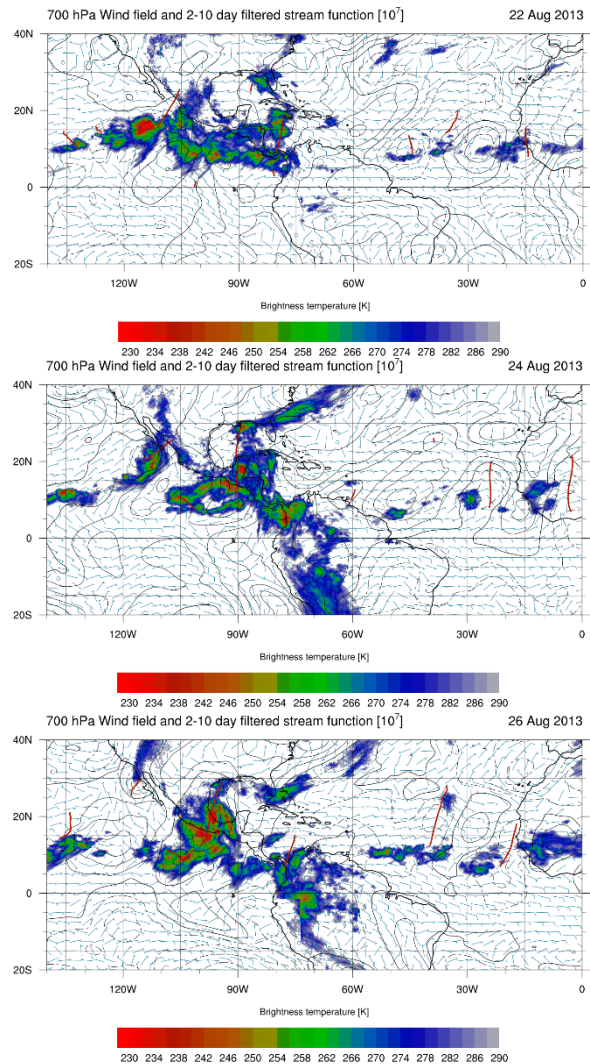

Figure 5. Observed Brightness Temperature (shading), 700 hPa actual wind field, and 2-10 day filtered stream function (contours) for 22-26 August 2013. Trough lines are shown in red.

This regression then allows us to infer a different origin for waves over the Caribbean, and that they are not originating from Africa but in the middle of the Caribbean instead, as shown from lags -4 to 0 for the month of September.

3.3 Relation to cyclogenesis

To illustrate the preceding regressions with real cases, we have selected two events from the 2013 Atlantic hurricane season, Tropical Storm Fernand (August 25-26) and Hurricane Ingrid (12-17 September). Selection of these cases was motivated by the fact that they could be tracked back to the Caribbean before making landfall. According to the tropical cyclone report of the National Hurricane Center (NHC), for the tropical storm Fernand:
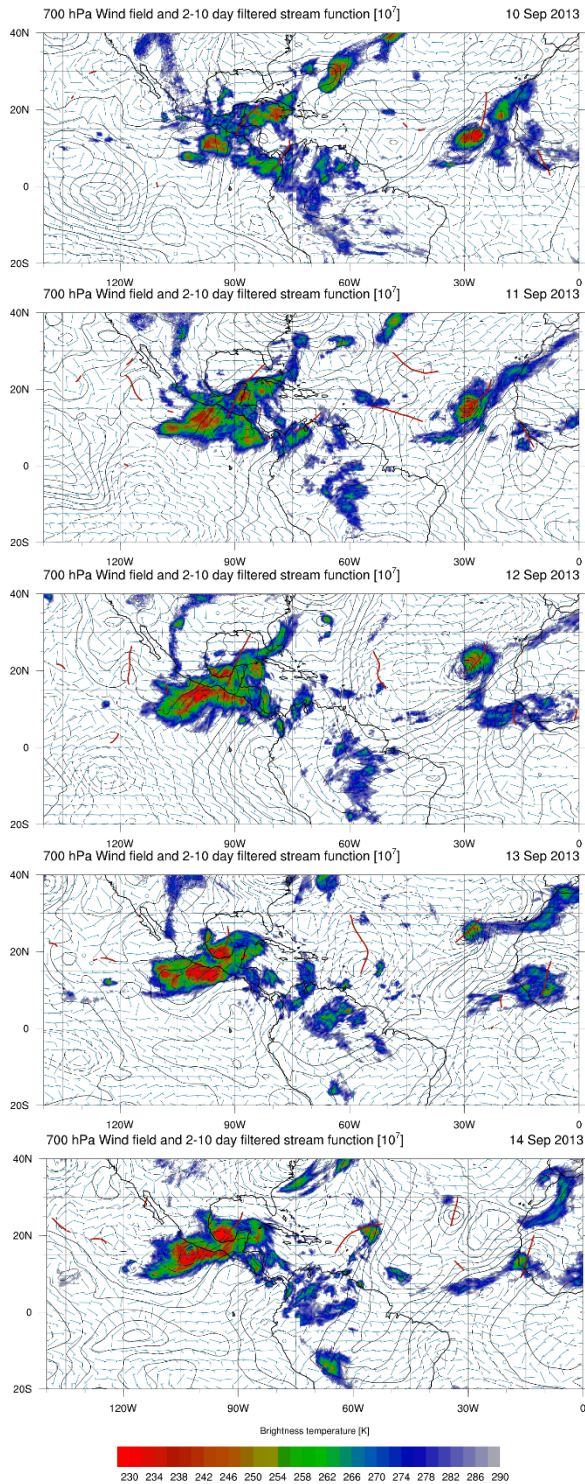
Figure 6. Observed Brightness Temperature, 700 hPa wind field, and 2-10 day filtered stream function for 10-14 September 2013.
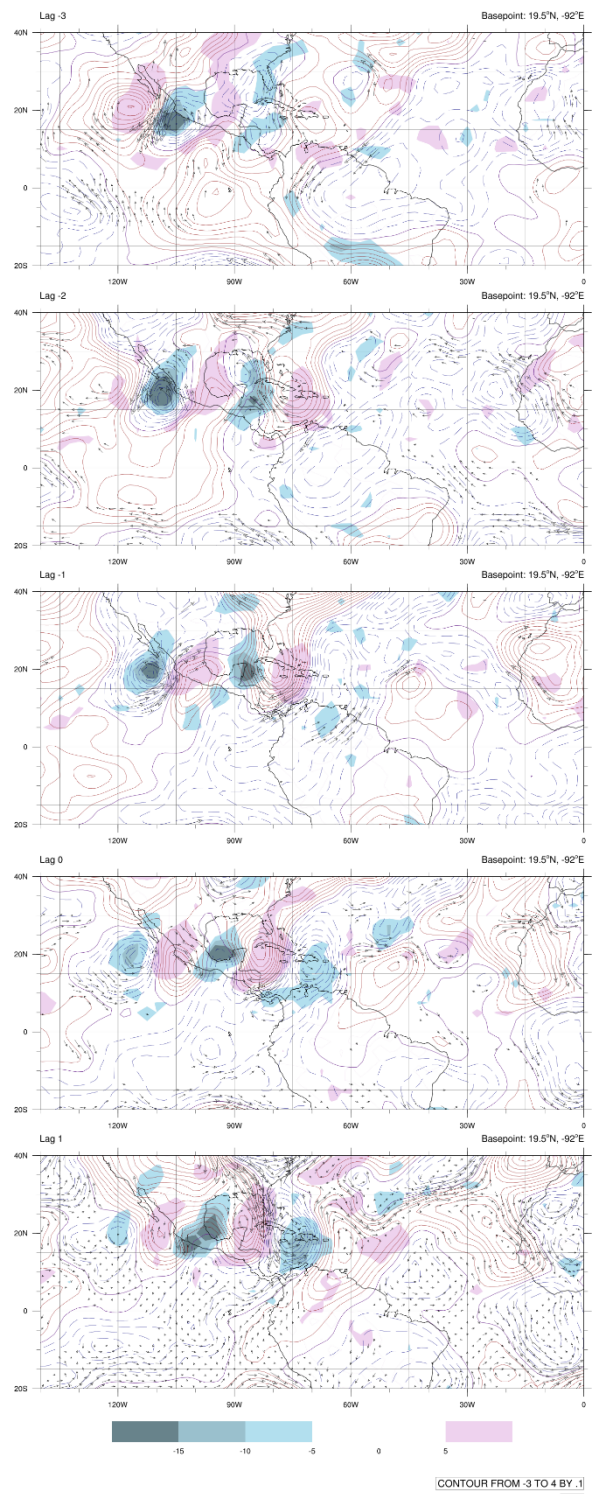
Figure 7. *Maps of OLR (shading), 700-hPa stream function (contours) and 700-hPa wind (vectors) anomalies associated with the OLR variation of the TD wave at the base point 19.5ºN, 92ºW for the month of September, for day -3 to 1.*

"…a single disturbance emerged just east of the Lesser Antilles and amplified over the eastern Caribbean Sea on 19 and 20 August… and reached the Yucatan Peninsula early on 24 August" (Berg 2013).

Wave filtering analysis between 2-10 day at 700 hPa for August 22, 24 and 26 (Figure 5) shows resemblance with lagged regressions from figure 3 for lags -2, 0 and +2, confirming that regressions performed, as described, are in good agreement with events on August, and that these kind of events are indeed induced by AEWs.

Continuing with the second case, Hurricane Ingrid took place on September 12-17 over the Gulf of Mexico, this case is of importance because the genesis of Manuel in the tropical northeastern Pacific is attributed to the same cause. According to the official cyclone report from the National Hurricane Center: "…*the southern part* (of an AEW) *moved into a large area of low-level cyclonic flow extending from the western Caribbean Sea across Central America into the eastern north Pacific (producing) two areas of disturbed weather…*" (Beven 2014).

Analysis of the wind field at 700-hPa level on September 8, 2013 shows horizontal shear because of Tropical Strom Gabrielle, but not the presence of an African Easterly Wave over the Caribbean. This clearly shows that an AEW was not responsible of future developments over the region for this event. Also a trough line is not identified for this date.

It is not until September 9 that a trough line starts to develop north of Honduras and it is more evident on September 10 (figure 6). From this date we can follow the evolution of this system, (also in Figure 6) and compare it with the regressions shown in Figure 4.

Figure 6 on September 10 shows enhancement of convection over Central America, north of Honduras and the Caribbean similar to what we can observe in the regression plots of figure 4 at lag 0, this suggests that north of Honduras region could potentially be a "hot spot" for the generation of waves over the Caribbean. Future development of these waves will enhance convection over the Gulf of Mexico and eastern Pacific as can be seen at lag +2 and on September 12, this is in good agreement considering convection.

However lag +4 shows a weak signal in convection that results mainly from linearity and do not reproduce accurately the observations on September 14. For this reason and considering that Ingrid intensified as a Hurricane over the Bay of Campeche, led us to consider a new regression point at this location.

Regressions for the point located at 19.5ºN, 92ºW for the month of September are shown in Figure 7 for days -3 to 1. These lags were selected to compare directly with observations in figure 6. The results indicate that systems intensifying over the Bay of Campeche (lag 0) cannot be tracked back to Africa but

to the Western Caribbean somewhere over northern Honduras (lag -3), however, the most interesting feature of the regression at this point is the fact that the westward progression at lag +1 shows increased convection over the western coast of Mexico having a result closely related to what was observed during the presence of Ingrid and Manuel during the 2013 hurricane season.

Making a one-to-one comparison between figure 6 and figure 7 there are some features to highlight:

i. At lag -3 the regression shows enhanced convection over Central America- western Caribbean and a well-defined trough over the western coast of Mexico. Observations indicate such enhancement, over the Caribbean, however, the western trough is not present at this time.

ii. However, observations show a trough south of the peninsula of Baja California which is in agreement in position at lag -1.

iii. Agreement in the stream function over the Atlantic at lag 0.

iv. Some discrepancy in the observed wind at lag 0 over the eastern Pacific.

v. Disagreement in wind field over Florida and Cuba at lag +2 and

vi. A slower westward motion in observed systems in general.

We attribute some of these discrepancies to the fact that a monthly linear regression composite cannot capture the whole dynamics by the linearity itself, the averaging of several events (compositing) and because this event is unique in complexity over the region; however, the point that these events are slower compared to regression hints that the window selected must be directed to lower frequencies in the range of Mixed-Rossby gravity waves or to explore if there was a change in magnitude of the trades in the month of September 2013 compared with a climatology.

4. CONCLUSIONS

Using a monthly approach of linear lagged regressions allowed us to identify two regimes of Easterly Waves over the Caribbean, these are the typical African Easterly Waves during the months of June, July and August and the waves originating over the Caribbean during the month of September, which we can call Caribbean Easterly Waves. These Caribbean waves are originated over the western Caribbean north of Honduras and could potentially serve as seeds of hurricanes developing over the Bay of Campeche and eastern Pacific at the western coast of Mexico such as was the case of Ingrid and Manuel in the 2013 hurricane season.

Even though monthly composites do not show a full and precise depiction of all processes taking

place over the Caribbean, they allow to recognize points of origin for these waves and to offer a new paradigm on the origin of Easterly Waves near to Central America.

Some question remain left as to the mechanisms originating these waves even though it is speculated that Mixed Rossby-Gravity waves could be triggering these Caribbean easterly waves, however, this is a topic in research that we still pursuing.

Acknowledgments

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