AFRICAN EASTERLY WAVES: INTERACTIONS OVER NORTHERN SOUTH AMERICA AND THE CARIBBEAN AND INTERANNUAL VARIATIONS

by

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SUMMARY

This Masters Thesis aims to understand the possible role of the African Easterly Waves (AEWs) on modulating precipitation over northern South America at different timescales from intraseasonal to interannual scales. The document is divided into two main parts: a first part addresses interactions associated to the activity of AEWs and their effects on the occurrence and inhibition of precipitation over northern South America whereas a second part aims to identify the interannual variability of AEWs related to El Niño - Southern Oscillation (ENSO) phenomenon. Both parts constitute independent papers that will be submitted for publication in indexed journals. This manuscript is divided into five sections, as follows: sections 1 and 2 introduce the state of the art and problem statement, respectively, guiding this Masters Thesis; section 3 presents the first paper (draft version) focused on the influence of AEWs on precipitation over northern South America; section 4 presents the second paper (near to submission), which addresses the interannual variability of AEWs related to ENSO; finally, section 5 presents the main conclusions and future work from this Masters Thesis. A brief summary of the two papers that constitute this Thesis is presented below.

Part I: AFRICAN EASTERLY WAVES AND PRECIPITATION OVER NORTHERN SOUTH AMERICA

Spatiotemporal conditions that rule hydro-climatology over northern South America and the Caribbean Sea are influenced by a large amount of phenomena taking place at different timescales. This is mainly due to the huge solar radiation income throughout the year as a result of their geographical location. Characterizing the activity of the AEWs over northern South America and the Caribbean is an imperative work to do in order to improve our understanding of the tropical atmospheric dynamics involved in hydrology and climate features over the region. The latter regulates the availability of very important resources such as water, which represents an important resource for economical activities and social dynamics of the populations that occupy these regions. Furthermore, AEWs activity plays an important role on air quality characteristics as a consequence of its connections with dust transport.

In order to approach an adequate characterization of the AEWs activity over northern South America and the Caribbean Sea, this work intends to address the relationship between these atmospheric perturbations and the occurrence or inhibition of precipitation, as well as possible connections with dust transport, when the AEW’s oscillations take place over northern South America and the Caribbean region. In particular, relative vorticity and outgoing long-wave radiation are used to identify the AEW’s activity during

the 1983-2013 period, together with daily precipitation anomalies, surface divergence, streamlines of total wind, and Aerosol Optical Depth, in order to understand how the passage of AEWs could influence meteorological interactions in the region. Our results suggest that most of the AEWs passing over northern South America enhance convective activity, favoring the occurrence of precipitation; while some dry AEWs are identified to influence local conditions not only by inhibiting precipitation over northern South America but also by transporting aerosols as they cross over the region.

Part II: INTERANNUAL VARIATIONS OF AFRICAN EASTERLY WAVES

AEWs are one of the major climatological features of the intraseasonal variability in the tropical Atlantic Ocean and the Caribbean regions. AEWs enhance convective activity over their influence regions throughout the westward displacement of these disturbances within the trade winds regime, favoring the occurrence of precipitation. El Niño - Southern Oscillation (ENSO) is the main interannual forcing mechanism of climate in the region. Previous studies suggest a possible influence of Sea Surface Temperature (SST) anomalies on the variability of these atmospheric perturbations. Furthermore, according to recent research, central and northern Colombian precipitation exhibits an intensification of the AEW-related spectral band during El Niño years, suggesting a possible modification on their development and typical trajectories.

In this work, we explore the interannual variability of AEWs related to SST anomalies variations. Particularly, we aim attention at the different phases of ENSO by comparing the AEW's activity depicted by the ERA-Interim reanalysis, as well as that according to the NOAA Interpolated Outgoing Long-wave Radiation anomalies throughout the 1979-2010 period. In addition, the African Easterly Wave Climatology dataset trajectories are used to identify possible modifications on the AEW's trajectories during the specific years of occurrence of El Niño and La Niña events. Moreover, we analyze the dynamical features of the AEW's track density modification during El Niño years in order to explore a physical mechanism explaining the interannual variability of the AEWs related to ENSO. Our results indicate that El Niño years are characterized by a southward shift of the main waveguide of the AEWs, allowing wave propagation over northern South America. Such shift during El Niño events is induced by the occurrence of more suitable conditions for AEWs propagation to the south of their typical path.

1. STATE OF THE ART

1.1 Regional climatology

Climate conditions over northern South America and the Caribbean Sea are influenced by a wide range of atmospheric processes acting on different spatiotemporal time scales. Due to their geographical position, atmospheric dynamics over these regions is complex (Poveda et al. 2006). In particular, the location of these regions allow them to receive a large amount of solar radiation throughout the year, inducing variability to the atmospheric circulation and favoring the occurrence of numerous atmospheric processes through different timescales. For instance, intraseasonal variability related to the Madden Julian Oscillation (MJO), as well as interannual variability induced by El Niño - Southern Oscillation (ENSO), directly/indirectly influence atmospheric dynamics over these regions (Poveda 2004; Poveda et al. 2011).

Notwithstanding the diurnal an semidiurnal cycle nature of Colombian precipitation (Poveda, Mesa et al. 2005), and among the wide range of atmospheric processes influencing climate conditions in the region, the meridional migration of the Intertropical Convergence Zone (ITCZ) has been pointed out as the first mode of variability, which regulates the hydrological cycle on an annual timescale. In particular, the behavior of precipitation over central and western Colombia is bimodal while in northern Colombia and to the north of the Amazon basin, precipitation regime is unimodal (Eslava 1993; Hastenrath 2002; Poveda and Mesa 1997; Poveda et al. 2006). Colombia exhibits some of the wettest but also driest regions of the world, due to its proximity to the Caribbean Sea and the Pacific Ocean as well as its tropical location and complex orography (Snow 1975).

In particular, ENSO constitutes the main forcing mechanism inducing interannual variability in the Andean region (Poveda et al. 2011). The ENSO phenomenon is a natural fluctuation of the ocean-atmosphere system that takes place with a periodicity of 3 to 5 years. This phenomenon occurs on the tropical eastern Pacific Ocean, where a variation of the sea surface temperature (SST) is seen, followed by an atmospheric response, determined by a variation on the wind intensity over the equatorial Pacific, resulting on an anomalous redistribution of humidity and precipitation fields (Trenberth 1997). El Niño and La Niña events, the two ENSO phases, are responsible for strong interannual fluctuations on the tropical region weather. For instance, in South America, the main effects of ENSO are related to the precipitation regime (Andreoli and Kayano 2005).

When taking into account lower timescales, the MJO, and the AEWs emerge due to their importance on regional climate features. The MJO is an ocean-atmosphere coupled system that propagates over the

Pacific Ocean along the equatorial region, with a velocity of about 5 m/s and a periodicity of 30 to 60 days (Madden and Julian 1972). The most important effects of the MJO are variations on precipitation, atmospheric circulation patterns and surface temperature, on tropical and subtropical regions; in Colombia, anomalies on precipitation are found during extreme phases of the MJO, with periods of around 30 days (Torres Pineda 2012).

The AEWs are undulatory perturbations originated on northern Africa with a westward displacement of about 8 m/s within the trade winds regime (Kiladis et al. 2006). Along their displacement, these perturbations reach continental territory on northern South America and the Caribbean region and have been observed to be frequent during the rainy season over northern Colombia (León et al. 2001), as well as in Puerto Rico, where they are the principal climate modulator during boreal summer (Levine 2008).

Together with the atmospheric phenomena pointed above, some important processes for northern South America and the Caribbean region are those produced as a consequence of the ocean-atmosphere interaction, leading to the existence of low-level circulation patterns, known as the low-level jets. These low-level jets act as humidity transport mechanisms toward northern South America, Central America, and the Caribbean region (Arias et al. 2015; Durán-Quesada et al. 2017). For instance, the Choco Jet is a low-level jet observed around 5°N, whose interactions with the mesoscale convective processes over the region condition the Colombian Pacific region to be one of the rainiest regions of the world (Poveda and Mesa 2000). The Chocó low-level jet consists on a surface current that blows from south to north over the northern South American Pacific coast, which deviates to the east over the Colombian Pacific region, with a maximum intensity observed between June and November (Poveda et al. 2006). On the other hand, the Caribbean low-level Jet (CLLJ) is another low-level circulation related to humidity transport in the region. This jet is observed around 10-12°N, with a maximum intensity between June and August (Amador 1998; Wang 2007), when the meridional wind component increases in the south-to-north direction. The latter explains why the CLLJ contributes to a reduction of precipitation over northern South America by transporting humidity to higher latitudes, especially toward Central America, where precipitation levels increase (Arias et al. 2015; Wang 2007).

1.2 The African Easterly Waves

The AEWs are synoptic processes that develop on the African Easterly Jet (AEJ), a mid-tropospheric feature of northern Africa summer as a consequence of the strong meridional temperature and geopotential height gradient over the Sahel (Hsieh and Cook 2005; Kiladis et al. 2006). AEWs are characterized by atmospheric undulatory perturbations exhibiting a quasi-periodic behavior. These perturbations take place within the trade wind regime in the Northern Hemisphere and are associated to cyclonic circulation linked to surface wind convergence (Burpee 1975; Mekonnen et al. 2006; Reed and Recker 1971). AEWs are recognized by the scientific community since the middle of the 20th century, when Dunn (1940) discovered what he defined as "isobaric centres that moves westward in the tropical Atlantic Ocean". However, Riehl (1945) located their origin over northern Africa, finding that the AEW's wave trough exhibits a northeast-southeast orientation. Moreover, Riehl (1945) also observed an increment of precipitation after the passage of these tropical waves.

At the end of the 1970's, thanks to the beginning of the satellite era, it was possible to identify patterns that resemble an inverted 'V' shape over the clouds band to the north of the ITCZ over the Atlantic Ocean, identifying the westward displacement of these clouds (Chang 1970). However, due to an apparent incoherence in the cloud patterns, a general description of the phenomenon was not performed. A couple of years later, it was demonstrated that it was possible to track those cloud patterns from Africa to the Pacific Ocean. It was also confirmed that those cloud patterns were associated with synoptic-scale wind perturbations that, although were not always intensified, could contribute to the formation of tropical cyclones in the Atlantic Ocean (Burpee 1972).

The AEWs have a periodicity of about three to six days and wavelengths between 2000 and 4000 km (Burpee 1972; Carlson 1969; Kiladis et al. 2006). These disturbances have a latitudinal extension between 10° to 15° and propagate westward over the Atlantic Ocean, traveling around seven longitudinal degrees per day with a velocity about 7/8 m/s (Pytharoulis and Thorncroft 1999). Besides, the AEWs have their maximum amplitude on the middle and lower troposphere, around the 850hPa and 700hPa levels (Mekonnen et al. 2006).

León et al. (2001) highlighted the importance of studying the activity of the AEWs over Colombia due to their effects on local meteorological conditions during their displacement. Most of the AEWs over northern South America are preceded by a reduction on atmospheric pressure, with a few clouds and absence of rain or fog. Cloudiness increases as the wave trough approaches a determined location and, from that point, it is possible to observe centers of middle-to-high clouds as well as some rain showers. Meantime, wind changes its direction from northeast to east, and temperature remains the same or slightly increases. To the west of the wave trough, the wind blows from east to southeast and some storms are present; the atmospheric pressure and the moisture content increases likewise. Once the wave moves to the west, crossing over determined locations, the atmospheric conditions go back to normal and the predominant trade winds impose again (León et al. 2001). Considering the effects of these disturbances on local meteorological conditions, AEWs represent an important component for climate of northern Africa, the Atlantic Ocean, and the Caribbean region, being also considered the main synoptic-scale perturbation to affect northern Africa during summer rainy season (Kiladis et al. 2006).

Burpee (1976) was the first to observe the relation between the AEW's displacement and the occurrence of precipitation. He proposed that precipitation between 30°S and 30°N was affected by the movement of AEWs, even though the stronger modulation was observed between the equator and 15°N. There has also been observed a marked belt of variability related to the activity of these tropical waves, between 5°N and 15°N, over northern Africa and the Atlantic Ocean. Furthermore, a second belt of variability related to the AEWs has been identified between 20°N and 25°N; notwithstanding, convectively coupled AEWs, those AEWs that induce surface convergence favoring clouds formation and some precipitation events, are more common between 5°N and 15°N than in northernmost regions (Agudelo et al. 2010; Burpee 1976).

On the other hand, Jones et al. (2003) highlighted the importance of AEWs in the genesis and transport of mineral dust from northern Africa, being one of the main summer climatological features on the distribution of aerosols over northern Africa and the Atlantic Ocean, where the incursion of mineral dust from the Sahara desert towards the Atlantic Ocean is modulated by the activity of the AEWs (Burpee 1972; Jones et al. 2003; Zuluaga et al. 2012).

In spite of the importance of the AEWs on the African continent as much as on the Atlantic Ocean and the Caribbean Sea, some details of their life cycle remain uncertain; even though there is a general consensus about the mechanisms that regulate the AEW's growth, it is not clear yet where do these waves form neither the physical mechanisms involved in the process (Ventrice and Thorncroft 2013; Vieira Agudelo 2010). Some authors suggest that the orographic processes added to a strong pressure gradient crossing the equator over western Africa have an important role in their genesis (Fink and Reiner 2003; Thorncroft and Rowell 1998). In particular, Berry and Thorncroft (2005) identified three phases of the AEW's life cycle: (i) an initial convective activity on high ground, (ii) a second phase of baroclinic growing of the wave, (iii) and a third phase of developing convective activity over the coast.

About the origins of the AEWs, it has been indicated that some of these waves can be tracked from their origin at 15°E in central Africa as well as during their displacement over the Atlantic Ocean in a period of about two weeks; however, some authors have postulated the origin of AEWs on further regions. Carlson (1969) suggested that AEWs could form over the Ethiopian highlands, while Albignat and Reed (1980) suggested their formation on even further regions to the east, over the Red Sea. The apparent discrepancy on the results of these studies should not be a problem for the identification of the place where these disturbances form, because for both of the studies mentioned above, different time periods were considered. For this reason, the difference on the results of those studies can be an indicator of a possible fluctuation on the genesis regions of the AEWs (Albignat and Reed 1980).

Some years later, and by using automatic tracking of vorticity centers with the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis, there was identified the presence of peaks of AEW's genesis over the Ethiopian highlands, a result that is consistent with previous studies. Nevertheless, another maximum of AEWs genesis was found on the western African coast over the ocean. Although this last feature is in disagreement with the conceptual models developed for the AEWs available by that time, it was suggested that this was not a place of wave origination but a place of AEWs intensification, reaching an amplitude enough to be detected (Thorncroft and Hodges 2001).

About the physical mechanisms explaining the AEW's formation, it was identified a region between 15°E and 30°E, with a strong temperature gradient among the Sahara desert and the relative fresh region of western Africa, and a maximum of trade winds on the lower troposphere with a large vertical and horizontal wind shear during the months of boreal summer (Thorncroft et al. 2008). In addition, a strong momentum transport was observed from the maximum of trade winds on the middle troposphere and heat transport towards the south, to the equatorial line of the African continent (Burpee 1974; Kiladis et al. 2006). It has been also suggested that both horizontal and vertical wind shear can act as sources of energy for the AEWs. The barotropic and baroclinic processes also constitute important energy sources for the formation of these tropical waves, as well as the momentum and heat transfer contribute to the growing of these disturbances (Burpee 1974).

Moreover, some authors suggest a plausible dynamic influence of convective processes over the western slope of central African mountains, that might have an important role on the origin and development of AEWs (Thorncroft et al. 2008); however Vieira Agudelo (2010) alluded a possible influence of the African continent orography on the development of these disturbances that has not been studied in detail. Therefore, it is not clear yet if the local relief plays an important role during the early stages of their life cycle.

1.3 AEWs interactions over northern South America and the Caribbean

It is known that AEWs favor convective activity, inducing surface convergence processes to the east of the wave trough and, therefore, precipitation events. It has been previously identified that the AEWs are frequent during the rainy season of northern Colombia. In particular, this is a region where the AEWs relate to an increase of precipitation levels while a reduction of precipitation is observed on the central region of Colombia, being more evident these effects when the AEWs evolve to reach tropical cyclone category (León et al. 2001). In places like Puerto Rico and Costa Rica, a permanent monitoring of AEWs is performed during the boreal summer due to the effects that the passage of an AEW over their territory imply for the meteorological conditions. For instance, it was established that AEWs are the leading meteorological modulator during the June-October period in Puerto Rico (Levine 2008).

In addition to the effects on the local meteorological conditions, AEWs are closely related to the occurrence of tropical cyclones not only in the Atlantic Ocean and the Caribbean Sea (Agudelo et al. 2010; Burpee 1972; Landsea 1993; Riehl 1945; Simpson et al. 1969) but also to the east of the Pacific Ocean (Avila and Pasch 1992). It is estimated that between 50% to 60% of the tropical cyclones on the Atlantic Ocean, including around 85% of these tropical cyclones reaching a major hurricane category, have their origin as AEWs (Agudelo et al. 2010).

Moreover, previous studies (e.g., Poveda 2004) indicate little or any difference on the behavior of AEWs between La Niña and ENSO-neutral years. By contrast, a greater AEWs-related power spectrum on precipitation is found over Colombian precipitation gauges during the same years. The latter could indicate that during El Niño years, the AEWs are less active over the Atlantic Ocean, in addition to a modification of their typical trajectory to the south, determining AEWs to be more frequent over northern South America while moving westward to the Pacific Ocean (Poveda 2004; Salas Parra et al. 2012). A more recent study using computer simulations highlights a statistical relation between SST anomalies and the activity of AEWs, exposing a strong influence of ENSO on the variability of these atmospheric perturbations over western Africa (Ruti and Dell'Aquila 2010). In relation to AEWs variability over the African landmass, Janiga and Thorncroft (2013) mentioned that AEW's activity tends to increase during wet periods while exhibiting a decrease during the dry seasons in northwestern Africa, both at intraseasonal and interannual scales.

About the AEW's trajectory, and despite of their high variability, two waveguides have been identified over western Africa. The first one is located around 8°N while the second is located between 17°N and 20°N. Some studies suggest that as the AEWs move away from the African continent, the two waveguides merge into a single one, around 17°N, when approaching the Caribbean Sea (Martin and Thorncroft 2015; Salinas-Prieto 2006). Regarding to the activity of AEWs over the Atlantic Ocean, it has been found a strong link between the initial intensity of the AEWs while leaving western Africa and the maximum amplitude of the waves during their life cycle (Hopsch et al. 2007). More recent studies, on the other hand, suggest a possible interaction between the AEWs and the CLLJ over the Caribbean region. Particularly, an intensification of the AEW's related to their passage over this low-level jet has been observed, together with a possible region of Easterly Waves (EW's) genesis associated to the same mechanisms that has been proposed as precursors of the AEWs over northern Africa, but related to the CLLJ activity (Serra et al. 2010). EW's (i.e. those waves with a genesis region away from the African continent) consist on significant features for the boreal summer precipitation over the Caribbean region and Central America as well as the North American monsoon region (Méndez and Magaña 2010; Serra et al. 2010).

2. PROBLEM STATEMENT

The spatiotemporal conditions that rule hydro-climatology over northern South America and the Caribbean Sea are influenced by a large amount of phenomena taking place in different timescales. For this reason, northern South America is a complex region for climate dynamics, mainly due to its geographical location and topography, which determine that the region receives a huge solar radiation income throughout the year. Intraseasonal features, such as the AEWs, are some of the main climatic features over northern South America.

In order to establish a complete characterization of the effects that the passage of these tropical disturbances have on the hydro-climatology of northern South America, it is indispensable to analyze the occurrence or inhibition of precipitation associated to the passage of these tropical waves over the region, as well as the physical mechanisms related to precipitation events during the westward propagation of the AEWs.

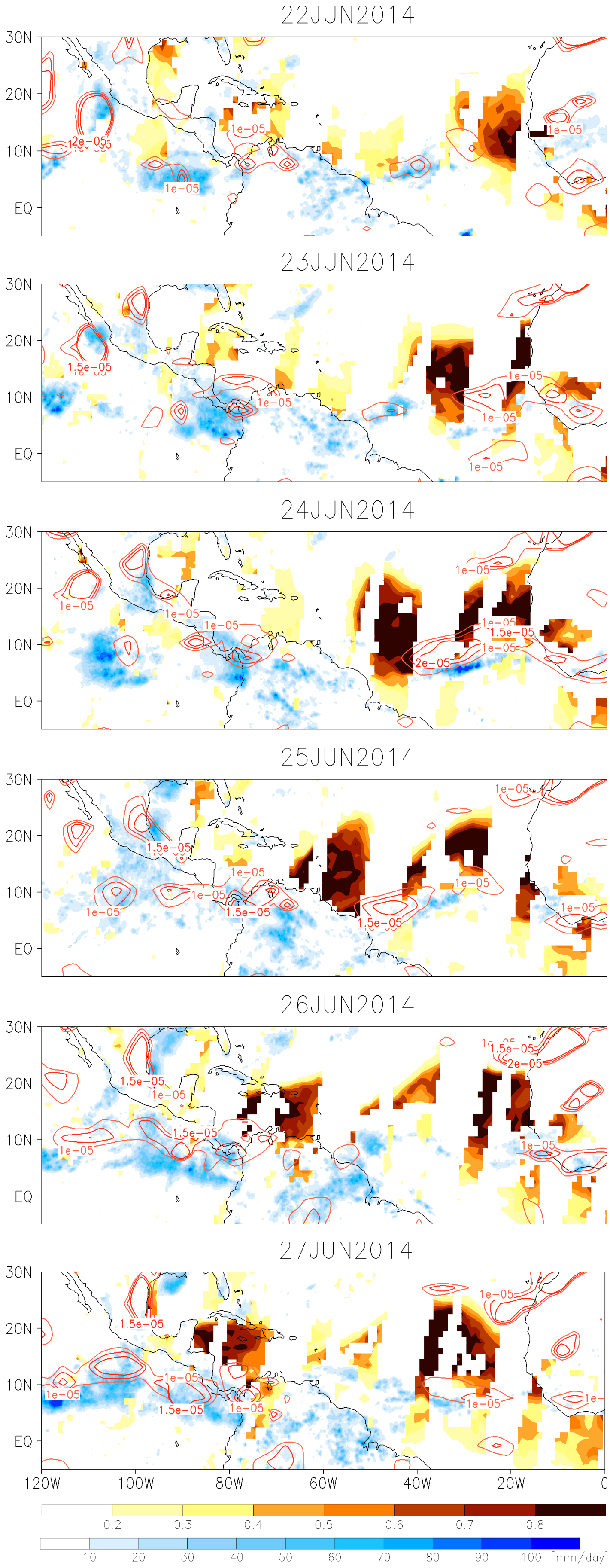

Figure 2.1: June 22 (top) – June 27 (bottom) composite for smoothed ERA Interim relative vorticity [s^{-1}] (red contour), TRMM total precipitation [mm/day] (blue shade), and MODIS Aerosol Optical Depth [1] (yellow/orange shade).

On June 27, 2014, large concentrations of atmospheric particulate matter (PM) were detected over central Colombia. Local environmental authorities linked this anomalous phenomenon with the passage of an AEW across the northern South American landmass (AMVA 2014). Although AEWs are thought to play an important role not only on the generation but also on the transport of mineral aerosols from the Saharan Desert (Prospero et al. 2014; Yu et al. 2015b), this transport and deposition is more evident over the Caribbean region rather than over the northern Andes, as occurred during this particular event, being the first Saharan dust plume event to be reported in Colombia. Figure 2.1 shows the AOD related to mineral dust transport between June 22 (top) and June 27 (bottom) 2014, as well as the AEW associated smoothed relative vorticity related to this transport and the daily cumulative precipitation within the dust plume. Dust transport is detected from Moderate Resolution Imaging Spectroradiometer (MODIS) Aerosol Optical Depth (AOD), AEWs are tracked from ERA-Interim filtered relative vorticity, and precipitation is depicted from Tropical Rainfall Measurement Mission (TRMM). Figure 2.1 suggests that throughout this mineral dust transport event, a dry regime allowed the dust plume to reach the northern South American landmass without being deposited over the Atlantic Ocean.

When analyzing the climate patterns during this particular mineral dust transport event, El Niño-like conditions were present on the eastern Pacific Ocean (Figure 2.2). Besides, previous studies suggest a possible influence of El Niño events on the AEW's activity with a possible modification of their trajectories to the south of their typical position; the latter could help to explain this particular dust transport and deposition event, the first of its kind to be reported in Colombia, on June 27, 2014. Consequently, it is important to study the relationship between the AEWs and El Niño events, aiming to identify a possible interannual variability of these tropical disturbances related to the warming of the SSTs on the eastern tropical Pacific Ocean.

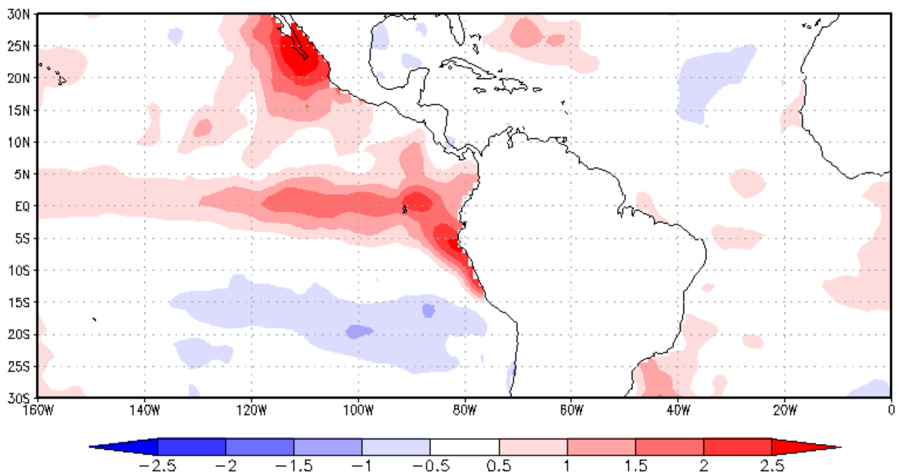

Figure 2.2: El Niño advisory: NOAA OI SST anomalies for June, 2014. Values are in °C.

Therefore, this Masters Thesis aims to address this possible relationship, as well as the effects of the AEWs on precipitation regime over northern South America. Section 3 presents a draft paper regarding the influence of AEWs on precipitation over northern South America and the Caribbean. Section 4 constitutes a second paper (near to submission) addressing the interannual variability of the AEWs and its link to ENSO. Both sections are independent papers, therefore each of them presents introduction, data and methodology, results, and discussion sub-sections. Thus, some abbreviations and definitions may be repeated throughout both sections.

3. AFRICAN EASTERLY WAVES AND PRECIPITATION OVER NORTHERN SOUTH AMERICA

3.1 Introduction

Due to its geographical location, the spatiotemporal conditions that shape the hydro-climatology over northern South America and the Caribbean Sea are influenced by a large amount of phenomena taking place at different timescales. The former determines that the region receives a huge amount of solar radiation throughout the year. Such tropical location, as well as the local topography, explains why northern South America is a complex region in terms of climate dynamics (Poveda et al. 2006).

The African Easterly Waves (AEWs), as suggested by spectral analysis of Colombian precipitation records, are among the intraseasonal features influencing the complex climate dynamics of northern South America (Poveda et al. 2002). AEWs consist on undulatory atmospheric perturbations with a quasi-periodic behavior. They occur within the trade winds regime in the Northern Hemisphere during boreal summer, and are related to cyclonic circulation and convergence of air masses in the lower levels (Burpee 1974; Reed et al. 1988). AEWs propagate westward across the Atlantic Ocean with a velocity of 7-8 ms^{-1}, equivalent to 7 longitudinal degrees per day, and exhibit a latitudinal extension around 10-15 degrees (Pytharoulis and Thorncroft 1999). These disturbances reach their maximum amplitude in the mid-troposphere between 850hPa and 700hPa (Mekonnen et al. 2006), with periods between 3 to 5 days and wavelengths around 2000 - 4000 km (Burpee 1972; Carlson 1969; Hall et al. 2006).

The importance of studying the AEWs and their relationship with precipitation over northern South America is highlighted by previous studies, where AEWs are studied with satellite imagery and the streamflow computed from the NCEP/NCAR reanalysis winds, stating that AEWs are frequent during the rainy season in northern Colombia (León et al. 2001). Besides, a strong signal of AEWs spectral band is observed in the wavelet spectrum of precipitation records in Colombia (Salas Parra et al. 2012). Furthermore, it is known that AEWs enhance convective activity by inducing surface convergence processes to the east of the wave, allowing the occurrence of precipitation events (Burpee 1976). Most of the AEWs are preceded by a reduction on precipitation with a few clouds while cloudiness and precipitation increase as the wave trough approaches a determined location; once the AEWs continue their displacement to the west, atmospheric conditions return to normal with the imposture of the predominant trade winds (León et al. 2001).

On the other hand, mineral dust incursion into the Atlantic Ocean and the Caribbean is one of the major climatological features of the distribution of aerosols in this region (Jones et al. 2003). Furthermore, such dust transport is considered as an important feature of the climate system (Knippertz and Todd 2010), mainly because aerosols modulate the radiation budget and the hydrological cycle by direct and indirect processes, playing a potential role in regional weather and climate variability (Ramanathan et al. 2001; Zuluaga et al. 2012). On the other hand, dust transport and deposition to the Amazon basin is higher during the boreal winter and is predominated by transatlantic transport in the northeasterly trade winds (Swap et al. 1992). During the boreal summer, most of the mineral dust is transported to the Caribbean Sea and North America (Prospero et al. 2014; Yu et al. 2015b). Burpee (1972) pointed out that mineral dust incursion into the Caribbean Sea and North America during this season is modulated by the activity of AEWs. The role of AEWs on mineral dust entrainment into the atmosphere, due to the strong winds during some phases of the waves life cycle, as well as the transport of the Saharan mineral dust across the Atlantic Ocean, have been discussed for years (Burpee 1972; Westphal et al. 1987; Zuluaga et al. 2012). It is considered that between 10% and 20% of desert dust that is transported across the Atlantic Ocean during the boreal summer is related to AEW's activity (Jones et al. 2003).

In this work, we intend to address the link between AEWs and the occurrence or inhibition of precipitation when these disturbances displace over northern South America and the Caribbean Sea, as well as possible connections with dust transport. Section 3.2 describes the data and methodology as well as the region of study. Section 3.3 presents the statistical link between AEWs and precipitation and how the identified AEWs are classified. Sections 3.3.1 and 3.3.2 present the AEWs that enhance and inhibit precipitation over the region, respectively. Section 3.3.3 presents the dry AEWs relationship to dust transport; finally, Section 3.4 summarizes the main results of this work and presents some concluding remarks.

3.2 Data and methods

The AEW's activity is identified, following the preprocessing methodology proposed by Hodges (1995) and improved by Serra et al. (2010), as smoothed relative vorticity anomalies exceeding a threshold of 10^{-6} s^{-1} while exhibiting a westward displacement over the Atlantic Ocean and the Caribbean Sea. Daily zonal and meridional components of wind from the ERA-Interim reanalysis with a spatial resolution of 1.5° X 1.5° (Uppala et al. 2005) are used to calculate the relative vorticity, which is vertically averaged between the 850hPa and 600hPa levels and smoothed to a T42 resolution, using a bilinear interpolation technique. The T42 resolution (approximately 280 km grid space at the equator) is used in order to filter variability in a smaller spatial scale than the AEW's typical wavelengths.

In order to complement the identification of the AEW's activity and its relation to precipitation, Outgoing Long-wave Radiation (OLR) anomalies exceeding a threshold of $-2Wm^{-2}$, computed from daily values of the National Oceanic and Atmospheric Administration (NOAA) Interpolated OLR dataset, with a spatial resolution of 2.5° X 2.5°, are used (Liebmann 1996). The OLR daily anomalies are filtered within 2 to 8 days applying a digital Lanczos bandpass filter in order to keep the variability related to the convectively coupled AEWs (Agudelo et al. 2010). Additionally, 0.25° X 0.25° daily precipitation anomalies from the NOAA Climate Data Record (CDR) of Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks (PERSIANN-CDR) (Sorooshian et al. 2014) are used to study the relationship between AEW's activity and the occurrence or inhibition of precipitation over northern South America. PERSIANN-CDR precipitation has shown to perform in a reasonable manner when compared to radar, ground-based observations and GPCP data over tropical and subtropical regions; moreover, PERSIANN-CDR precipitation is considered to have a length, continuity and consistency that is adequate to study trends and observed changes in global and regional precipitation patterns (Ashouri, Hsu et al. 2015).

The 1.5° X 1.5° surface divergence and U and V components of winds from the ERA-Interim reanalysis are also used in order to explore the dynamical response behind the passage of the AEWs and the relation between the AEWs displacement and the occurrence of precipitation over northern South America. The U and V components of winds are filtered by applying a digital Lanczos bandpass filter in order to retain variability between 2 to 8 days related to the activity of the AEWs. This work is focused on the June-to-September season (JJAS), the time of the year with the highest activity of these waves, during the period 1983-2013, which is the common period available for the different datasets mentioned above.

Combined land and ocean Moderate Resolution Imaging Spectroradiometer (MODIS) Aerosol Optical Depth (AOD) is used aiming to perform a daily trace of the mineral dust transport across the Atlantic Ocean related to AEW's activity. The MODIS aerosols retrieves are made at a spatial resolution of 10km X 10km using separate retrieval algorithms for ocean and land (Nowottnick et al. 2011). The AOD analysis is performed within the 2000-2013 period due to the availability of this dataset, allowing to find information not only about dust transport over the Atlantic Ocean related to the AEWs activity but also about the dry waves and their link with the inhibition of precipitation over northern South America.

3.3 Results and discussion

The link between AEWs and precipitation over northern South America was initially addressed aiming to identify the statistical relationship between AEW's activity over the region and the 5°N-15°N, 80°W-70°W domain average for PERSIANN-CDR precipitation anomalies. Precipitation anomalies were considered in order to filter interannual variability, which is the first mode of variability for precipitation over northern South America (Eslava 1993; Poveda et al. 2006). Figure 3.1 shows the point-by-point daily-lagged significant cross-correlation between the JJAS season precipitation anomalies and the smoothed relative vorticity anomalies during the 1983-2013 period. The correlation pattern exhibits a westward propagation of about 7 longitudinal degrees per day, a propagation that corresponds to the westward displacement of the AEWs, and the occurrence of precipitation (positive correlation) due to the enhanced convection activity related to these disturbances. Furthermore, a region of influence of AEWs on precipitation over northern South America is clearly identified between 50°W-90°W and 0°-20°N, as suggested by precipitation anomalies - smoothed relative vorticity cross-correlation patterns for the daily lagged PERSIANN-CDR precipitation.

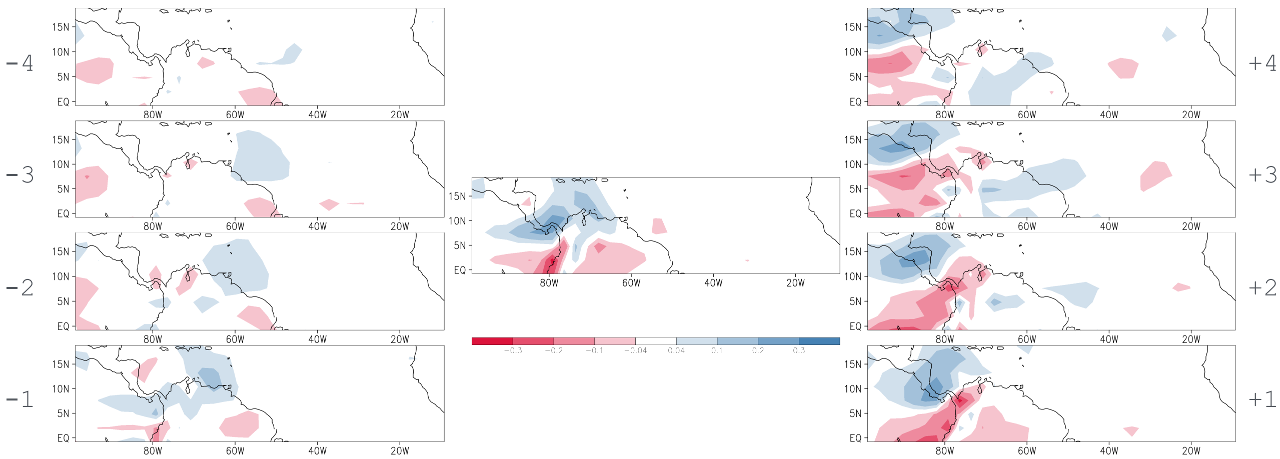

Figure 3.1: Significant lagged cross-correlation between precipitation anomalies and smoothed relative vorticity anomalies for the JJAS season.

Figure 3.2 exhibits the JJAS climatology of the smoothed relative vorticity over northern South America and the Caribbean Sea. In order to accomplish a better understanding of the existing relationship between the passage of AEWs over northern South America and the occurrence of precipitation, a daily composite analysis is performed after identifying the exact dates in which the AEWs, as depicted by the smoothed relative vorticity exceeding a threshold of 10^{-6} s^{-1}, cross over northern Colombia. The composite analysis is done using a lag of 4 days before to 4 days after the passage of an AEW over northern Colombia, the region of interest highlighted in Figure 3.2.

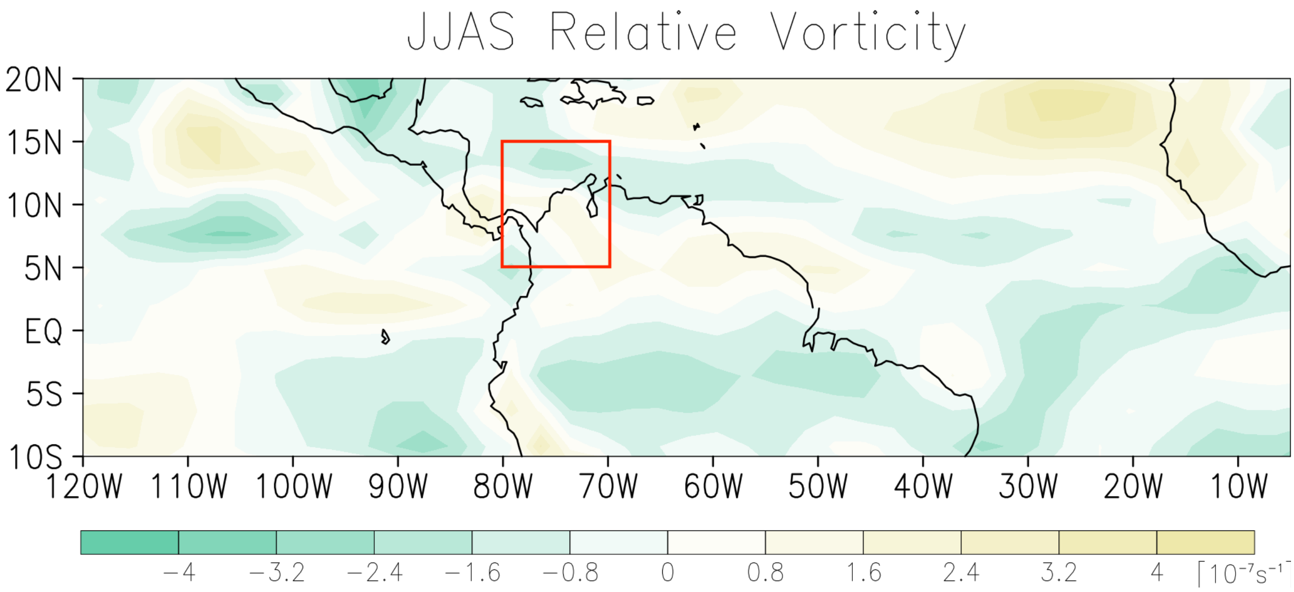

Figure 3.2: JJAS relative vorticity climatology during the 1983-2013 period. The region of interest for the identification of AEWs is marked within the red rectangle. Day 0 is defined as the date when an AEW is observed over this domain. Values are in $10^{-7}s^{-1}$.

Table 3.1 shows the total of AEWs identified as well as their classification into convective and dry waves. This identification was compared to the passage of AEWs reported by the Costa Rican Meteorological Institute (IMN) and the Colombian Meteorological Institute (IDEAM), finding a consistent pattern on the dates of the AEW's displacement over the region as depicted by the smoothed relative vorticity and the reports issued by these two national meteorological institutes. The available reports from these meteorological institutes are built by using real time satellite imagery, and have been reported since 2004 by IMN in Costa Rica and 2013 by IDEAM in Colombia.

AEWs were classified into convective and dry waves according to their effect on precipitation and OLR anomalies during day 0 (i.e., when the AEW is over the region marked in Figure 3.2). The waves characterized by negative precipitation anomalies and positive filtered OLR anomalies over the region marked in Figure 3.2 are classified as dry waves. On the other hand, waves with

AEWs		
Total	364	100%
Convective AEWs	312	85.7%
Dry AEWs	52	14.3%

Table 3.1: Amount of AEWs crossing over the 5°N-15°N, 80°W-70°W region during the 1983-2013 period and their classification into convective and dry waves.

positive precipitation anomalies and negative filtered OLR anomalies are identified as convective waves. As shown in Table 3.1, from the total of AEWs identified crossing over Colombia during the 1983-2013 period, 85.7% are related to a positive precipitation anomaly over Colombia (5°N-15°N and 80°W-70°W) while the remaining 14.3% AEWs have an opposite effect on precipitation. Thus, our analysis is detached into convective and dry AEWs.

3.3.1 Convective AEWs

The convective AEWs (i.e., those favoring precipitation) represent more than 85% of the total AEWs crossing over Colombia during the period 1983-2013, where the occurrence of precipitation is one of the main meteorological responses to the passage of these disturbances. Figure 3.3 (left) shows that convective AEWs influence precipitation in agreement with their physical characteristics. The AEWs, which are tracked using smoothed relative vorticity anomalies, displace together with a region of positive precipitation anomalies over the wave trough (that appears to correspond with the maximum values of the smoothed relative vorticity as discussed below), due to near-surface local convergence, while to the west and east of the wave trough, negative precipitation anomalies appear. Both types of anomalies are thought to be related with the AEWs effect on the wind field and are explored below. In addition, the convective AEWs relationship with OLR is shown in Figure 3.3 (right). OLR anomalies composite shows a more defined pattern than that related to precipitation, as precipitation is not taking place all along the AEWs trajectory while they do enhance near-surface local convergence as the AEWs move to the west. In particular, the relationship between AEWs displacement and precipitation appears to be noisy from 2 days before to 2 days after the passage of an AEW (Figure 3.3, left) while the influence of these disturbances on OLR anomalies is more consistent during the interval between 4 days before to 4 days after the wave passage (Figure 3.3, right). Negative values of OLR anomalies move simultaneously with the AEWs, as tracked from smoothed relative vorticity anomalies. Besides, a precisely delimited region of positive OLR anomalies, related to an absence of cloudiness, is located to the west as well as to the east of the wave trough. The latter is not only consistent with previous observations from satellite imagery of AEWs over Colombia (León et al. 2001) but also with the pattern exhibited by significant cross-correlation between smoothed relative vorticity and precipitation anomalies (Figure 3.1).

Thus, the occurrence of precipitation could be one of the main effects of the passage of an AEW, as the result of cloud cover induced by surface wind convergence due to the wave propagation. In order to illustrate this more clearly, Figure 3.4 (left) shows the relationship between smoothed relative vorticity and surface divergence. Results indicate that a region of negative surface

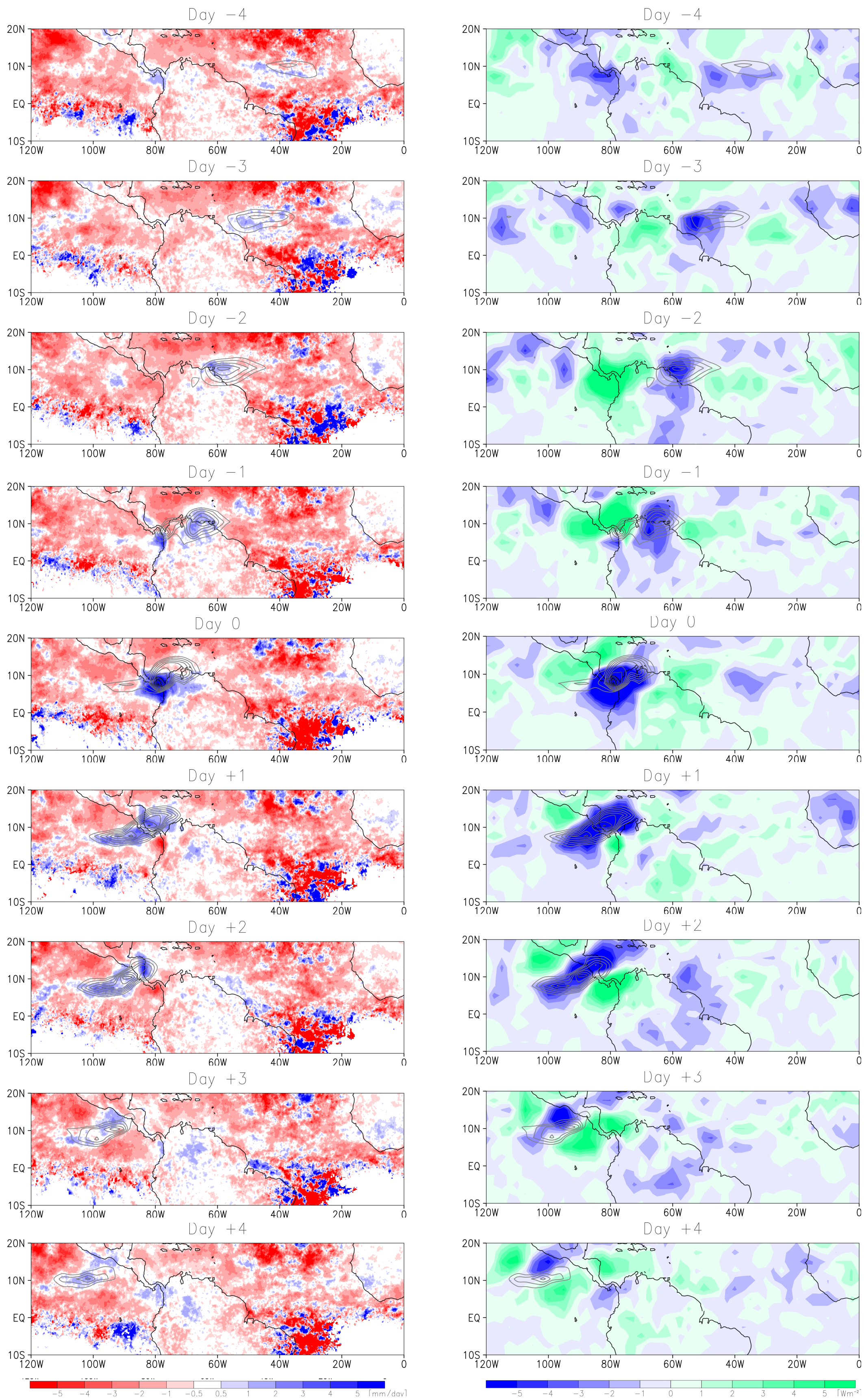

Figure 3.3: Left: composites of smoothed relative vorticity anomalies [s^{-1}] (black contour) and precipitation anomalies [mm/day] (shades). Right: composites of smoothed relative vorticity anomalies [s^{-1}] (black contour) and filtered OLR anomalies [$W \cdot m^{-2}$] (shades). Composites are shown from 4 days before (Day -4) to 4 days after (Day +4) the passage of the convective AEWs over northern South America.

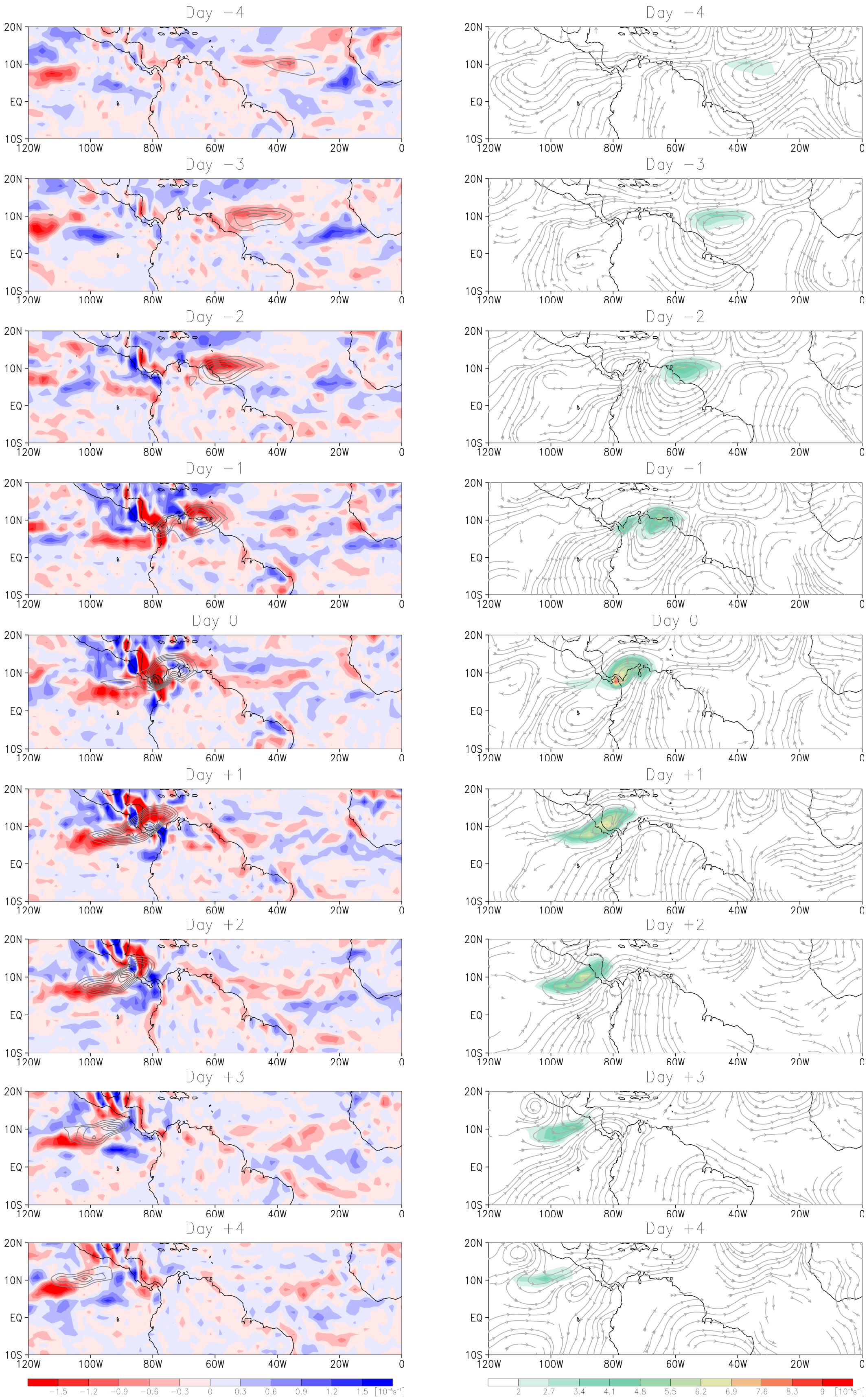

Figure 3.4: Left: composites of smoothed relative vorticity anomalies [s^{-1}] (black contour) and surface divergence anomalies [$10^{-6}s^{-1}$] (shades). Right: composites of streamlines of 700hPa filtered total wind and smoothed relative vorticity anomalies [$10^{-6}s^{-1}$] (shades). Composites are shown from 4 days before (Day -4) to 4 days after (Day +4) the passage of the convective AEWs over northern South America.

divergence anomalies (i.e., surface convergence) propagates westward simultaneously to the wave displacement while an area of surface divergence can be noticed to the west and to the east of the wave location. Although the surface divergence area surrounding the wave location is not as clear as the pattern related to surface convergence propagation, OLR anomalies composite suggests that the absence of cloud cover to the east as well as to the west of the AEWs location might be related to the surface divergence pattern observed over the same areas, inhibiting cloud formation.

In addition, the streamlines of total wind from the filtered U and V components of wind (Figure 3.4 (right)), reveals a clear pattern of cyclonic rotation on the 700hPa level, also seen on the 850hPa and 600hPa levels (not shown), that goes along with the smoothed relative vorticity maxima while the westward displacement is taking place. Similarly, a distinct pattern of anti-cyclonic rotation is also identified to the east and to the west of the smoothed relative vorticity that points out the AEW activity with a westward propagation. The latter suggests that the wave trough corresponds to the smoothed relative vorticity maxima (i.e., the variable used to identify the AEW activity appear to match the wave trough as the AEWs move to the west), and complement what is observed from precipitation, OLR and surface divergence anomalies, regarding to the surface convergence on the wave trough that favors the occurrence of precipitation. In addition, a region of divergence is found to be delimited to the west and to the east of the wave trough, and is in agreement with an absence of cloud cover and the inhibition of precipitation over these areas.

3.3.2 Dry AEWs

Whereas only 14% of the AEWs tracked during the 1983-2013 period were classified as dry waves, according to their link with precipitation anomalies over northern South America, it is still important to analyze their connection to local meteorological conditions. The latter is supported taking into account that previous studies highlight the occurrence of precipitation as the main effect of AEWs displacement over northern South America, particularly Colombia. Figure 3.5 (left) indicates that negative precipitation anomalies related to the dry AEWs propagation are evident on Day 0; nevertheless, the pattern is not clear on the lagged composites during the period between 4 days before and 4 days after the passage of the AEWs, exhibiting a noisy structure. Still, day -1 exhibits a noticeable difference between dry and wet AEWs in relation to the positive anomalies that dry waves seem to induce over northern Venezuela while negative anomalies are seen on the Colombian Pacific coasts (Figure 3.5), in contrast to the lower positive anomalies that those convective waves appear to relate to over northern Venezuela as well as over the Pacific coasts of Colombia, one day before the passage over Colombian

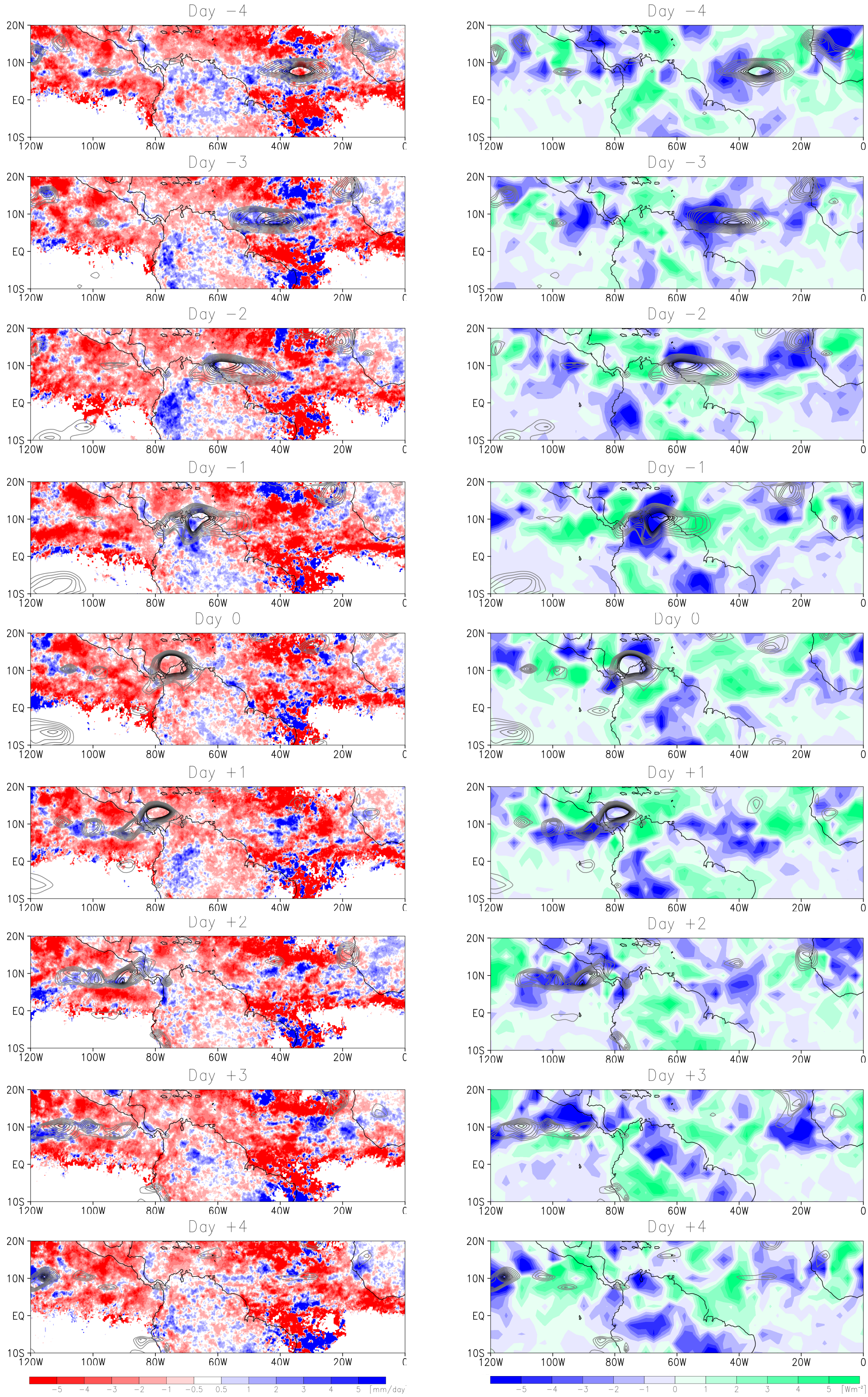

Figure 3.5: Same as Figure 3.3 but for dry AEWs.

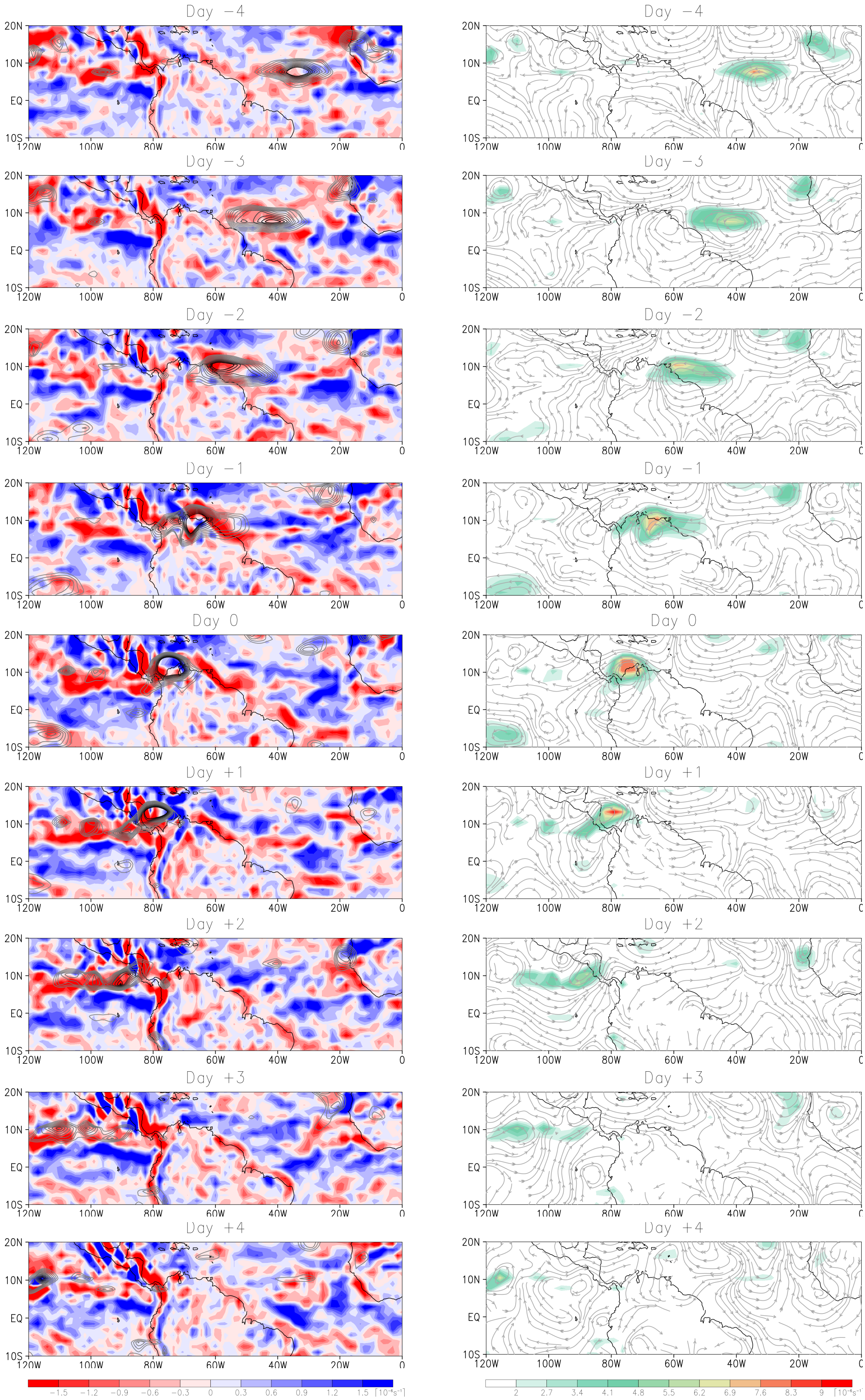

Figure 3.6: Same as Figure 3.4 but for dry AEWs.

territory.

Although the OLR anomalies composite pattern shown in Figure 3.5 (right) shows a less noisy pattern, the relationship between the propagation of dry AEWs and OLR anomalies is still not as clear as that for convective waves. In particular, a cloud propagation structure (negative OLR anomalies) can be seen over the Atlantic Ocean; however, this propagation is not unmistakable following the AEWs track, and more important, is not preserved once the dry AEWs approach South American landmass, in contrast to what is observed for convective waves (Figure 3.3).

Similarly, dry AEWs influence on surface divergence is not clearly identified. Figure 3.6 (left) shows surface divergence anomalies composite following the dry AEW path. Even though a region of surface convergence follows the AEWs displacement over the Atlantic Ocean, the pattern is not consistent over northern South America neither on the Caribbean. On the contrary, dry AEWs do display an influence on the wind field near the surface with both, cyclonic over the maximum values of the smoothed relative vorticity anomalies, along with anticyclonic rotation to the east and to the west of the wave trough, as depicted by the total streamlines of filtered U and V components of winds (Figure 3.6; right). The westward propagation of the dry AEWs is accompanied by both, cyclonic and anticyclonic rotation, emerging into a plausible inconsistent association between the circulation of winds and the observed divergence anomalies; therefore, the inhibition of precipitation related to the passage of dry AEWs indicates an unclear connection to convergence/divergence of air masses near the surface.

3.3.3 AEWs and dust transport

Although the relationship between dry AEWs, wind fields and surface convergence/divergence in northern South America and the Atlantic Ocean is not clear, the inhibition of precipitation during the westward propagation of such dry perturbations might be interconnected to the role of these waves on mineral dust transport over the Atlantic Ocean. Aerosols link to precipitation is complex, depending among others on the size of the cloud condensation nuclei (i.e. size of aerosols) and cloud microphysics; nevertheless, Saharan mineral dust has been identified to inhibit precipitation while being transported (DeMott et al. 2003; Prospero and Lamb 2003).

AEW’s role on mineral dust transport is a well-known feature of these tropical perturbations (Knippertz and Todd 2010; Zuluaga et al. 2012). In fact, all of the dry AEWs identified during the 2000-2013 period (21 perturbations in total) are related with dust transport. We consider this shorter period due to AOD data availability. Figure 3.7 suggests that dust is deposited throughout its transport across the Atlantic Ocean. Thus, aerosol concentration decreases as the dry wave propagates toward the west, being the dust plume more extensive across the Atlantic Ocean and the northeastern coast of South America, where AOD starts to decrease. The latter is in agreement with previous studies stating that large mineral dust particles are removed during atmospheric transport over the Atlantic Ocean, concluding into a redistribution of dust size (Maring et al. 2003).

These results provide further evidence on how the AEWs may affect not only precipitation but also air quality over northern South America, as observed over Central America and the Amazon (Prospero et al. 2014; Swap et al. 1992; Yu et al. 2015a).

3.4 Conclusions

A total of 364 AEWs where identified to displace over northern South America between the 1983-2013 period. These AEWs are then classified into convective and dry waves according to their effects on precipitation over the same territory. Composites of those dry and convective waves are used in order to study the effects of these AEWs from 4 days before to 4 days after their passage over northern South America.

The AEWs wave trough, as suggested by the cyclonic circulation seen on the streamlines of the 700hPa filtered U and V components of wind,

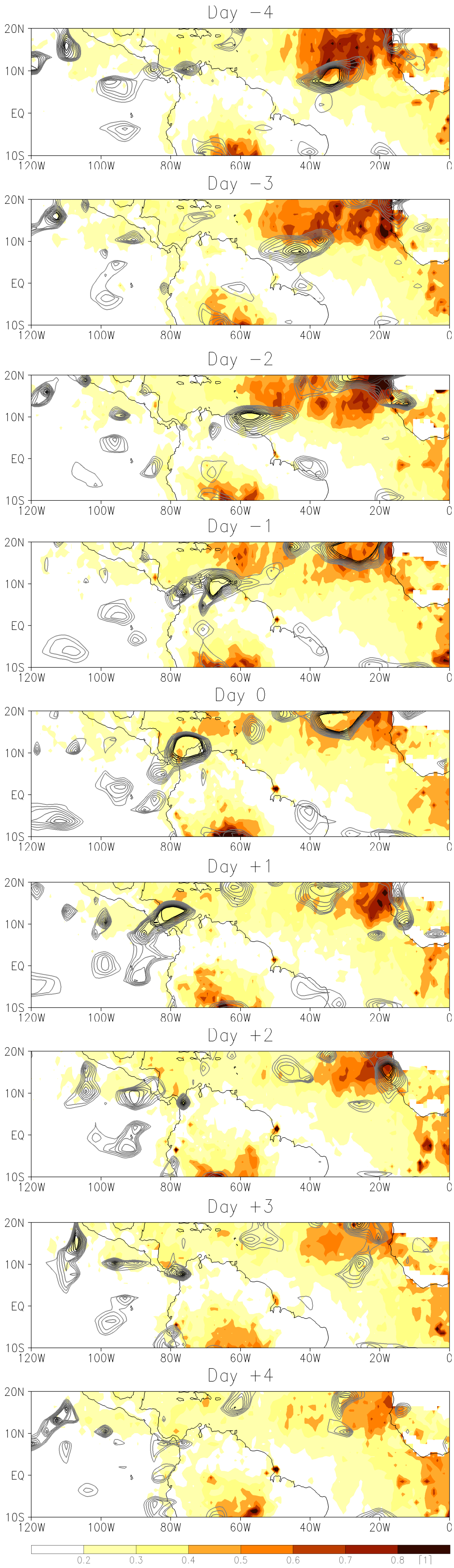

Figure 3.7: Composites of smoothed relative vorticity anomalies [s^{-1}] (black contour) and MODIS AOD [1] (shaded) from 4 days before (Day -4) to 4 days after (Day +4) the passage of dry AEWs over northern South America.

correspond to the maxima smoothed relative vorticity anomalies exceeding the threshold used to identify the activity of the AEWs over northern South America.

Most of the AEWs passing over northern South America that are identified in this study (~86%) appear to enhance convective activity, favoring the occurrence of precipitation over the region. The effect of these perturbations on precipitation over northern South America is evident approximately around 4 days before AEWs reaching northern South American territory.

Convective AEWs enhance precipitation while the wave trough is above northern South America. However, few days before and after the passage of the AEWs over this region, they inhibit precipitation over Colombia due to their effect on wind field.

Furthermore, according to surface divergence and OLR anomalies composites analysis, the occurrence of precipitation over northern South America when the wave trough is located over this region, appears to be a consequence of the convective activity due to the wave-induced surface convergence and its subsequent cloud cover formation, as water vapor condenses throughout its ascending movement.

While the convective AEWs enhance convective activity, favoring precipitation over northern South America, the dry AEWs are more related to the transport of mineral dust from northern Africa towards the Atlantic Ocean and the Caribbean Sea. Therefore, dry AEWs, which account for only the 14.3% of the total AEWs crossing over northern South America identified in this study, influence local conditions not only by inhibiting precipitation over northern South America but also by transporting aerosols as they cross over the region.

Although the occurrence of precipitation as a result of the convective activity induced by the convective AEWs is well explained when analyzing composites of OLR, surface convergence, and streamlines, the inhibition of precipitation related to dry AEWs follows a random and noisy pattern on these composites. Therefore, as all of the dry AEWs identified during the 2000-2013 period are related to mineral dust transport across the Atlantic Ocean, the inhibition of precipitation over northern South America during the passage of these dry waves might be related to the aerosols effects on precipitation in spite of the surface wind circulation and its related divergence anomalies inconsistence. However, further analyses are necessary in order to explain such behavior.

4. INTERANNUAL VARIATIONS OF AFRICAN EASTERLY WAVES

4.1 Introduction

The African Easterly Waves (AEWs) are among the main intraseasonal features of the tropical Atlantic Ocean, northern South America, and the Caribbean region during boreal summer (Burpee 1976; Poveda et al. 2002). AEWs consist on undulatory atmospheric perturbations with a quasi-periodic behavior. They occur within the trade winds regime in the Northern Hemisphere and are associated to cyclonic circulation and wind convergence in the lower levels of the troposphere (Burpee 1975; Mekonnen et al. 2006; Reed and Recker 1971).

AEWs travel with a velocity about 7/8 ms^{-1} and have a latitudinal extension between 10° to 15° (Pytharoulis and Thorncroft 1999), exhibiting a westward propagation across the Atlantic Ocean. These disturbances have a periodicity about 3 to 6 days with wavelengths between 2000 and 4000 km (Burpee 1972; Carlson 1969; Kiladis et al. 2006), and reach their maximum amplitude at the middle-to-lower troposphere around the 850hPa and 700hPa levels (Mekonnen et al. 2006). AEWs displacement over western Africa follows two previously identified waveguides: a first waveguide located around 8°N and a second guide located between 17°N and 20°N. Regarding their trajectory over the Atlantic Ocean, some studies suggest that as these waves leave western African landmass, the two waveguides merge into a singular guide around 17°N, especially when approaching the Caribbean Sea (Martin and Thorncroft 2015; Salinas-Prieto 2006). Moreover, Hopsch et al. (2007) suggested a strong relationship between the initial wave intensity while leaving western Africa and the maximum wave amplitude during its life cycle.

AEWs enhance convective activity throughout their westward displacement due to induced surface convergence processes to the east of the wave trough, favoring the occurrence of precipitation. AEWs also seem to be closely related to the occurrence of tropical cyclones, not only in the Atlantic Ocean and the Caribbean Sea (Agudelo et al. 2010; Burpee 1972; Landsea 1993; Riehl 1945; Simpson et al. 1969) but also in the eastern Pacific Ocean (Avila and Pasch 1992). It is estimated that between 50% and 60% of the tropical cyclones on the Atlantic Ocean, including around the 85% that develop into intense hurricanes, have their origins as AEWs (Agudelo et al. 2010).

An ENSO-related interannual variability in the amount of intense tropical cyclones has been recognized in the north Atlantic and northwestern Pacific oceans, as well as increasing frequency and intensity on Atlantic hurricanes during El Niño years (Tang and Neelin 2004). Thorncroft and Hodges (2001) suggested that Atlantic tropical cyclone activity may be influenced by a marked interannual variability in AEWs leaving west African coast. In addition, in the eastern Pacific Ocean, where tropical cyclogenesis is modulated by tropical waves from the Caribbean, more intense hurricanes are observed, life spans are longer, and tropical cyclogenesis shifts westward during the warm phase of El Niño-Southern Oscillation (ENSO) (Chu 2004). Concerning AEWs interannual variability, Ruti and Dell'Aquila (2010) found a statistical link between sea surface temperature (SST) anomalies and AEWs variability, suggesting a strong influence of ENSO and other SST fluctuations on the variability of these atmospheric perturbations. Thus, interannual variability of AEWs is explored from the perspective of important SST variability modes. In the first place, we consider the Atlantic equatorial mode or Atlantic El Niño (Lutz et al. 2013), which consists on fluctuations of the SST over the eastern Atlantic ocean, similar to the ENSO but with a shorter life cycle and exhibits significant impacts over land (Hirst and Hastenrath 1983; Keenlyside and Latif 2007). To represent this mode, we consider three regions over the Atlantic ocean: ATLN 1 (17°S—7°S, 8°E—15°E), ATLN 2 (10°S—3°S, 0°W-8°E), and ATLN 3 (3°S—3°N, 15°W—0°W), due to their appreciation as three subtypes of one comprehensive Atlantic El Niño, which fluctuations effects are felt on northwestern African landmass (Lutz et al. 2013). As a second mode of variability, we consider Caribbean Sea (12°N-16°N, 80°W-70°W) SST anomalies, as a way to explore a possible link between SST variations and AEWs activity, since the Caribbean Sea has been identified as an important region of AEWs intensification and tropical wave origination (Serra et al., 2010). Finally, we consider the Niño 3.4 (170°W-12°W, 5°S-5°N) and Niño 1+2 (90°W-80°W, 10°S-0°) regions as representation of the ENSO mode.

In particular, previous studies (e.g., Poveda 2004) indicate little or any difference on the behavior of AEWs between La Niña and ENSO-neutral years. By contrast, during El Niño years, a reduction on the precipitation power spectrum related to AEWs traveling over the Atlantic Ocean as they move westward is evident, although wavelet spectrum of precipitation records in Colombia exhibit a strong intensification of the variance associated to AEW-frequency bands (3-6 days) during El Niño years. The latter could indicate that during El Niño years, the AEWs are less active over the Atlantic Ocean, in addition to a modification of their typical trajectory to the south, determining AEWs to be more frequent over northern South America while moving westward to the Pacific Ocean (Poveda 2004; Salas Parra et al. 2012). Therefore, this study aims to identify whether AEWs exhibit a different path between El Niño and La Niña events, favoring a southward trajectory over northern South America during El Niño years. This paper is divided as follows: section 4.2 presents the data and methodology used in this study; section 4.3.1 describes the interannual variability of AEWs and its relation to ENSO; section 4.3.2 presents the dynamical features behind AEW's interannual variability and finally, section 4.4 summarizes the main results of this work and presents some concluding remarks.

4.2 Data and methodology

The longest AEWs trajectories for the ERA-Interim reanalysis, retrieved from the African Easterly Waves Climatology (AEWC) Version 1 dataset (https://data.noaa.gov/dataset/african-easterly-wave-climatology-version-1) are used to compute the AEWs track density during the period June to September (JJAS) 1980-2010. These trajectories are computed from the 1.5° X 1.5° ERA-Interim wind fields and its derived vorticity; the trough axis of an easterly wave is identified from the advection of curvature vorticity anomalies, where the maximum zonal wind does not exceed 2.5 ms^{-1}, and must be located within a region of curvature vorticity in excess of the the 55th and 66th percentile of the coarse and fine curvature vorticity. The easterly wave must last a minimum of two days. All waves are also checked to ensure that over the course of their lifetime they have a median minimum propagation speed of 2 ms^{-1}, and that the easterly wave has a maximum propagation speed at all time steps less than 25 ms^{-1} (Belanger, Jelinek et al. 2016). The longest trajectories are considered in order to filter those waves that do not last long enough to reach northern South America, as well as not to take into account more than once the AEWs that intensify while traveling over one of the seven easterly wave generation regions (Figure 4.1).

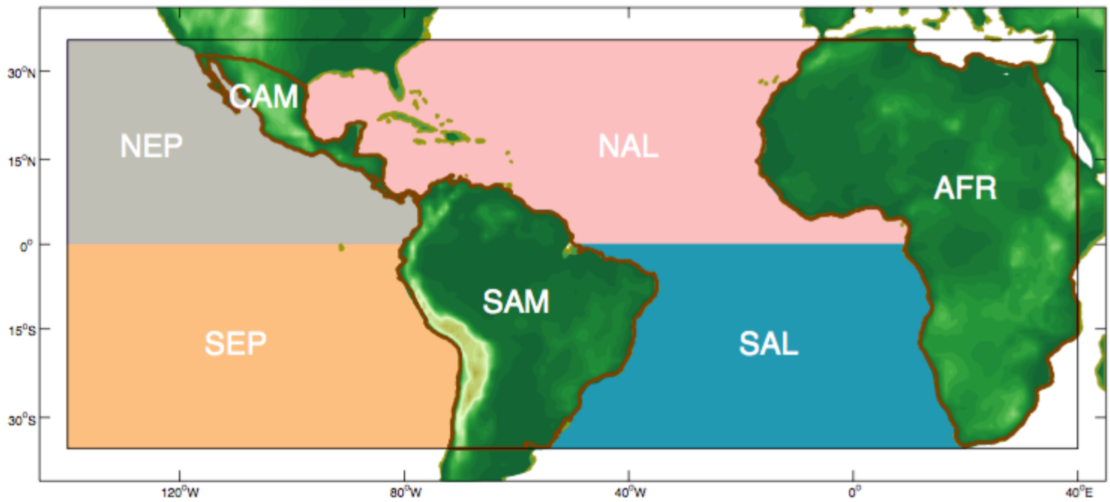

Figure 4.1: AEWs generation regions from the AEWC dataset.
Source: Belanger et al., 2016.

In addition, AEWs amplitude as depicted by the smoothed relative vorticity and the OLR filtered anomalies during the JJAS season is used as the spatial distribution of the average amplitude of an AEW is a good indicator of its waveguide (i.e., the region where wave oscillations take place) (Agudelo et al. 2010). AEWs amplitude, defined as the standard deviation of the smoothed relative vorticity and the OLR filtered anomalies, is computed using the relative vorticity anomalies that are vertically averaged between the 850hPa and 600hPa levels (Serra et al., 2015) from the ERA-Interim reanalysis U and V components of winds, and the Outgoing Long-wave Radiation (OLR) anomalies from daily values of the NOAA OLR dataset provided by the Earth System Research Laboratory Physical Science Division (NOAA/OAR/ESRL PSD), from their web site at http://www.esrl.noaa.gov/psd/. The OLR daily anomalies are filtered within 2 to 8 days applying a digital Lanczos bandpass filter in order to keep the variability related to the convectively coupled AEWs (Agudelo et al. 2010).

Regarding the relationship between AEWs and SST anomalies, and therefore their link to ENSO, monthly 1.0° X 1.0° SST anomalies from the NOAA_OI_SST_V2 dataset provided by the NOAA/OAR/ESRL PSD (http://www.esrl.noaa.gov/psd/) are used. It is shown later in Figure 4.3 that the primary statistical relation between AEWs and SST anomalies is seen over the Niño 1+2 region. Hence, the categorization of ENSO phases and neutral years is done by considering the SST anomalies within the Niño 1+2 region (90°W-80°W, 10°S-0°). El Niño years are selected as those when SST anomalies over the Niño 1+2 region are higher than 0.5°C while La Niña years are recognized as the years when SST anomalies over the Niño 1+2 region are lower than 0.5°C, during a period of three successive months. This study is focused on the El Niño and La Niña years' JJAS season since it corresponds to the season when these disturbances exhibit their strongest activity. The Bootstrap test, which consists on an alternative cumputer-intensive resampling procedure that uses empirical distribution to estimate any function from the observed distribution assuming independence of samples (Wilks 2011), was used in order to test significance of the observed differences between El Niño and La Niña years.

4.3 Results and discussion

4.3.1 AEWs interannual variability

As a first exploration of AEWs interannual variability, Figure 4.2 shows a histogram of the number of annual convective and dry AEWs crossing over northern South America landmass (5°N-15°N, 80°W-70°W); convective and dry AEWs are classified into convective and dry waves according to their effect on precipitation and OLR anomalies over the same region. The waves with negative precipitation anomalies and positive filtered OLR anomalies, averaged over the region marked in Figure 4.2, are classified as dry waves, while waves with positive precipitation anomalies and negative filtered OLR anomalies are then classified as convective ways. This identification was compared to the passage of AEWs reported by the Costa Rican Meteorological Institute (IMN) and the Colombian Meteorological Institute (IDEAM), finding a consistent pattern on the dates of the AEW's displacement over the region, as depicted by the smoothed relative vorticity, and the reports issued by

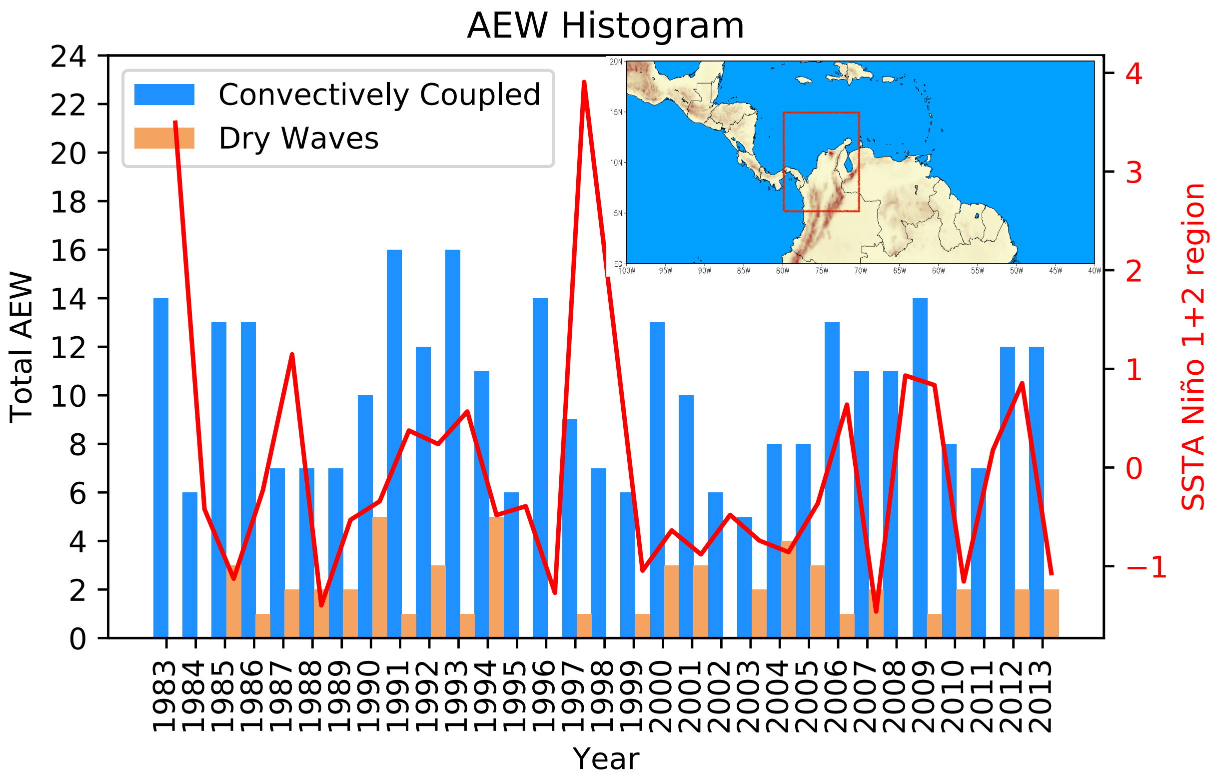

Figure 4.2: Histogram of convectively coupled (blue bar) and dry (orange bar) AEWs crossing over northern South America (5°N-15°N, 80°W-70°W). Red line corresponds to the Niño 1+2 SST anomalies time series.

these meteorological institutes despite the short period of tropical waves reported by these institutions, since 2004 by IMN in Costa Rica and 2013 by IDEAM in Colombia. As shown in Figure 4.2, AEWs exhibit a clear interannual variability; however, there is not a discernible pattern either a periodicity that can be deducted from the histogram. Niño 1+2 SST anomalies suggest that some years with the lowest quantity of AEWs over northern South America match those with negative Niño 1+2 SST anomalies, although there is not a clear correspondence among other years.

Since a recognizable pattern is not found in the number of AEWs captured by the smoothed relative vorticity, concerning their interannual variability, AEWs track density from the AEWC dataset is used in order to identify the statistical relationship between SST anomalies and AEWs observed trajectories over different oceanic regions; thus, a correlation approach is performed (Figure 4.3). AEWs track density is computed from the AEWC dataset as the probability of AEWs trajectories to cross over each 1.5° grid point per year. The JJAS climatology of AEWs track density is presented next in Figure 4.5a.

SST anomalies averaged over the Niño 1+2 (90°W-80°W, 10°S-0°) and Niño 3.4 (170°W-120°W, 5°S-5°N) regions are considered in order to explore an statistical relation between ENSO and AEWs interannual

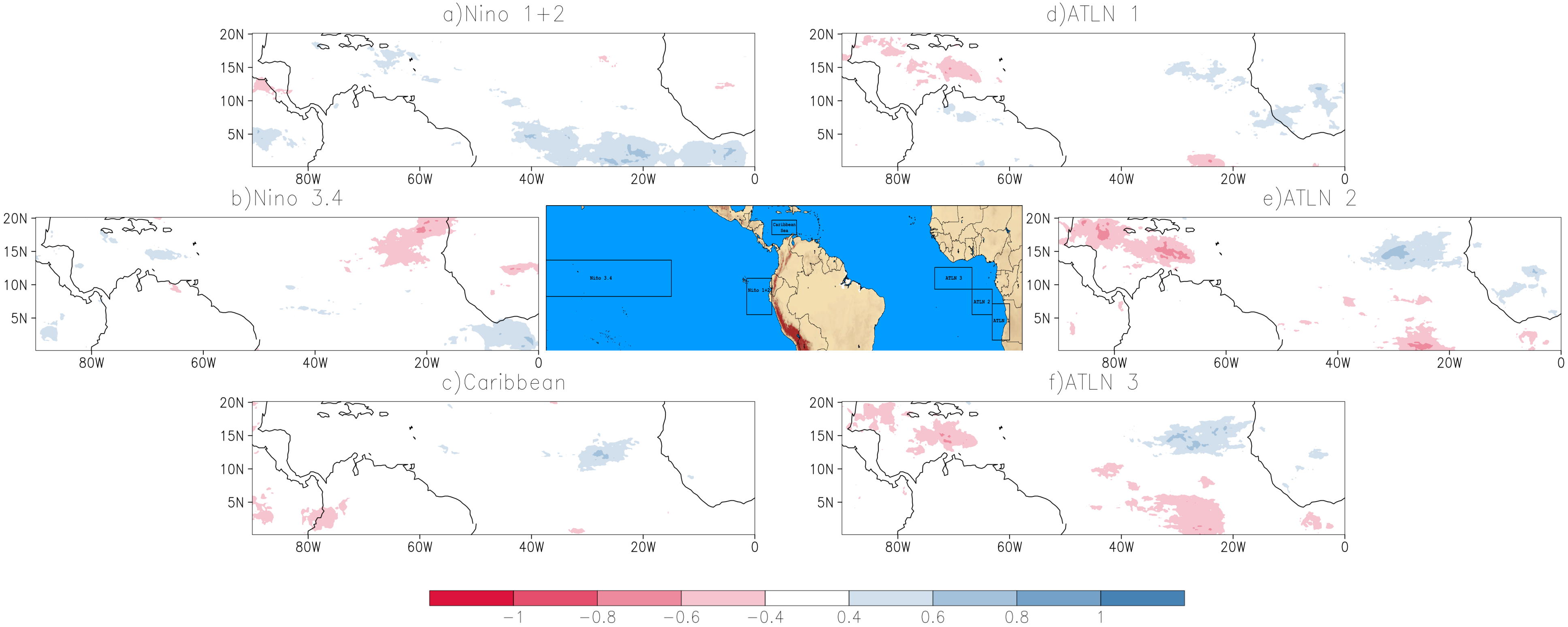

Figure 4.3: Significant correlation between AEWs track density and SST anomalies over the regions: a) Niño 1+2, b) Niño 3.4, c) Caribbean Sea d) ATLN 1, e) ATLN 2, and f) ATLN 3. Boxes in the central image of the panel indicate the domain used to compute SST anomalies.

variability (Figures 4.3a and 4.3b). The Caribbean Sea (12°N–16°N, 80°W–70°W) is also considered as a way to explore a possible link between SST anomalies and AEWs track density over the region of tropical waves origination and intensification suggested by Serra et al. (2010). The correlation between SST anomalies averaged over the Caribbean Sea and AEWs track density is shown in Figure 4.3c. Additionally, Figures 4.3d to 4.3f show the significant correlations between AEWs track density and SST anomalies over three tropical Atlantic regions, in order to explore a possible interaction between these waves and the Atlantic equatorial mode, a mode of variability similar to ENSO with shorter life cycle that exhibits significant impacts over land (Hirst and Hastenrath 1983; Keenlyside and Latif 2007). The three Atlantic regions considered to extract the SST anomalies indexes where: ATLN 1 (17°S–7°S, 8°E–15°E), ATLN 2 (10°S–3°S, 0°W-8°E), and ATLN 3 (3°S–3°N, 15°W–0°W), according to what is presented by Lutz et al. (2013).

Although significant correlation between SST anomalies and AEWs track density during the 1980-2010 period are observed over all of the six oceanic regions considered for this analysis, the region with the largest correlations is the Niño 1+2 region, suggesting an statistical relation between El Niño years and the AEWs track density upon the eastern tropical Atlantic ocean. Nevertheless, no statistical relation was found between AEWs track density over Colombia and the oceanic regions here considered, as suggested in previous studies regarding the variability of AEWs activity related to the different phases of ENSO (Poveda 2004; Salas Parra et al. 2012).

Since the most statistically significant relationship between SST anomalies and AEWs track density is observed when considering the

ENSO years (Niño 1+2 SST anomalies)	
Warming [El Niño years]	**Cooling [La Niña years]**
1982	1984
1983	1985
1987	1988
1993	1989
1997	1994
1998	1996
2006	1999
2008	2000
2009	2007

Table 4.1: El Niño and La Niña years classification according to the Niño 1+2 region (see methodology section for more details).

Niño 1+2 region, our analysis will focus on the activity of these tropical atmospheric perturbations within both phases of ENSO: El Niño and La Niña, as depicted by the SST anomalies averaged in the Niño 1+2 region. Table 4.1 shows the warming (El Niño) and cooling (La Niña) events on the Niño 1+2 region observed during the period 1980-2010.

Figure 4.4 shows the track density for the AEWs observed for the 1980-2010 period during El Niño and La Niña years. The JJAS AEWs track density climatology shown in Figure 4.4a exhibits a curved path along the Atlantic Ocean, with most of the AEWs leaving Africa near 20°N that deviates to the south over the Atlantic Ocean while the track density is greater around 12°N; AEWs track density appears to shift northward, up to 15°N when approaching the South American landmass, to the Caribbean Sea. A difference can be noticed between El Niño (4.4b) and La Niña (4.4c) years with the appearance of a region of high track density nearby the South American landmass during El Niño years. Besides, AEWs track density appears to be larger over northwestern Africa during La Niña years, while over the Atlantic Ocean, near the northern South American coast, the AEWs track density seems to be similar during La Niña years and the JJAS climatology. The latter could indicate reduced AEWs activity over northwestern Africa during El Niño years, although this activity intensifies when approaching the South American landmass. In addition, the largest track density over the Atlantic Ocean appears to intensify southward 12°N during El Niño years.

To observe more clearly such possible modification of the AEWs trajectories during the different phases of ENSO, Figure 4.4d shows the difference of the AEWs track density between El Niño and La Niña years; contours illustrate statistically significant differences computed from the 1000 times resampling procedure Bootstrap test. The observed differences between El Niño and La Niña years indicate that during El Niño, it is more likely for the AEWs to be located southward of their position during La Niña years, over the central and eastern tropical Atlantic Ocean. The AEWs track density is also larger over northern Colombia, western tropical Atlantic Ocean near the South American landmass and the Caribbean Sea (around 70°W) during El Niño years, a pattern that is in agreement with the intensification of the 3-6 days band of the wavelet spectrum of Colombian rain gauges during El Niño (Salas Parra et al. 2012). However, negative differences can be noticed over Venezuelan territory as well as over the Caribbean Sea about 80°W, indicating, on the contrary, more AEWs track density during La Niña years.

Figure 4.4d also shows that the regions of larger AEWs track density correspond to those with positive significant correlation coefficients between AEWs track density and the Niño 1+2 SST anomalies (Figure 4.3a). The latter confirms that the AEWs trajectories shift to the south of their typical position during

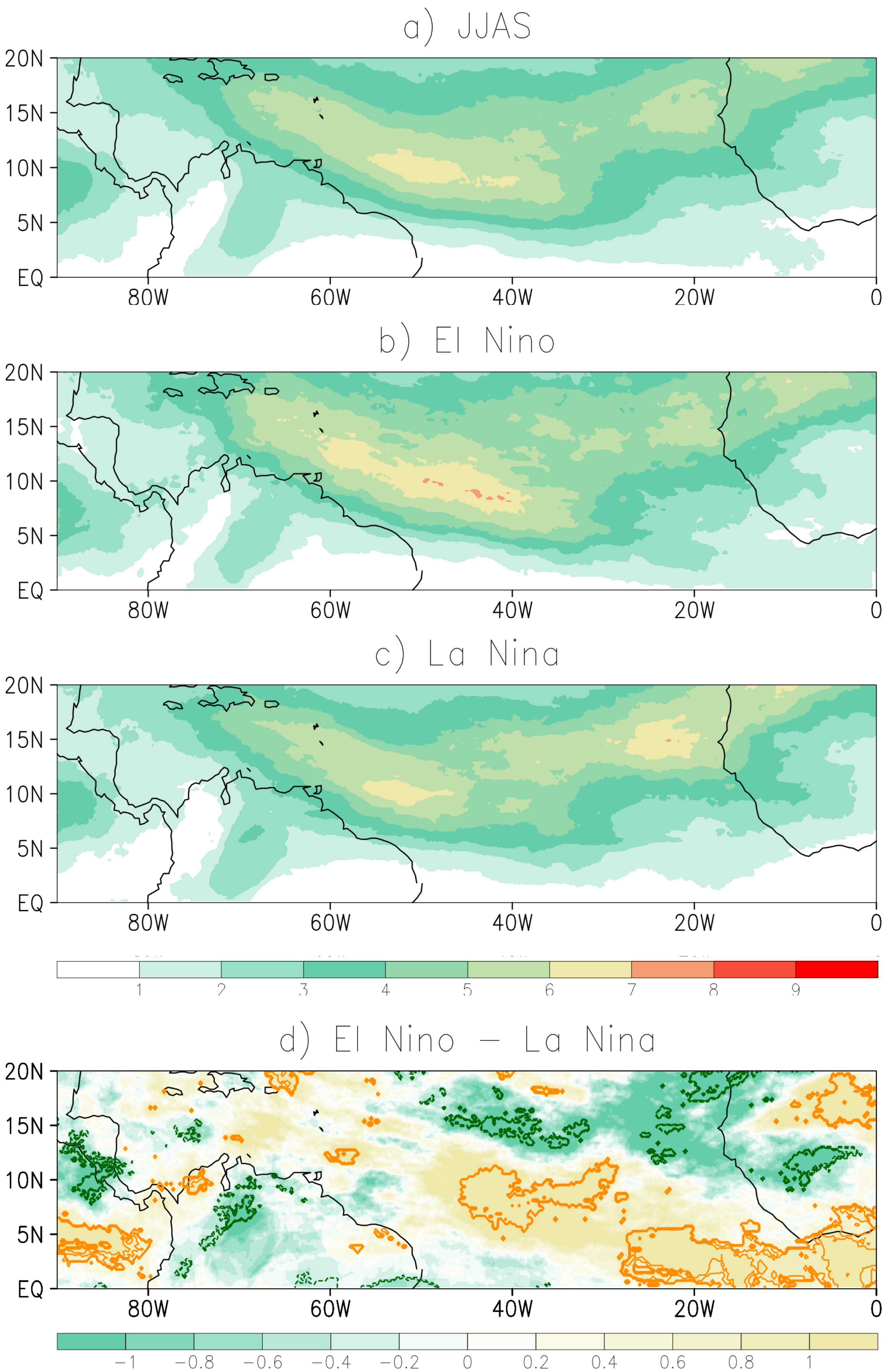

Figure 4.4: a) JJAS 1979-2010 AEWs track density climatology. b) Same as a) during El Niño years. c) Same as a) and b) but for La Niña years. d) Differences of AEWs track density between El Niño and La Niña years (shades), and statistically significant differences (contours).

El Niño years. Moreover the AEWs may become more frequent over the Atlantic Ocean surrounding northern South America as well as over northern Colombia and the southeastern Caribbean Sea during this ENSO phase.

The spatial distribution of the average amplitude of an AEW is a good indicator of its waveguide (i.e., the region over where wave oscillations take place) (Agudelo et al. 2010). Significant AEWs amplitude differences between El Niño and La Niña years are shown in Figure 4.5. AEWs amplitude is defined as the standard deviation of the variable used to identify its activity; therefore, it is computed from the smoothed relative vorticity and the OLR filtered anomalies during the JJAS season. Results indicate that El Niño years are related to negative OLR anomalies (Figure 4.5, top) and positive relative vorticity anomalies (Figure 4.5, bottom) on the eastern tropical Atlantic Ocean, suggesting that larger AEWs amplitudes occur during El Niño events. This patterns suggests that AEWs with larger amplitude over the Atlantic Ocean, during El Niño Years, are convective waves, which favors the occurrence of

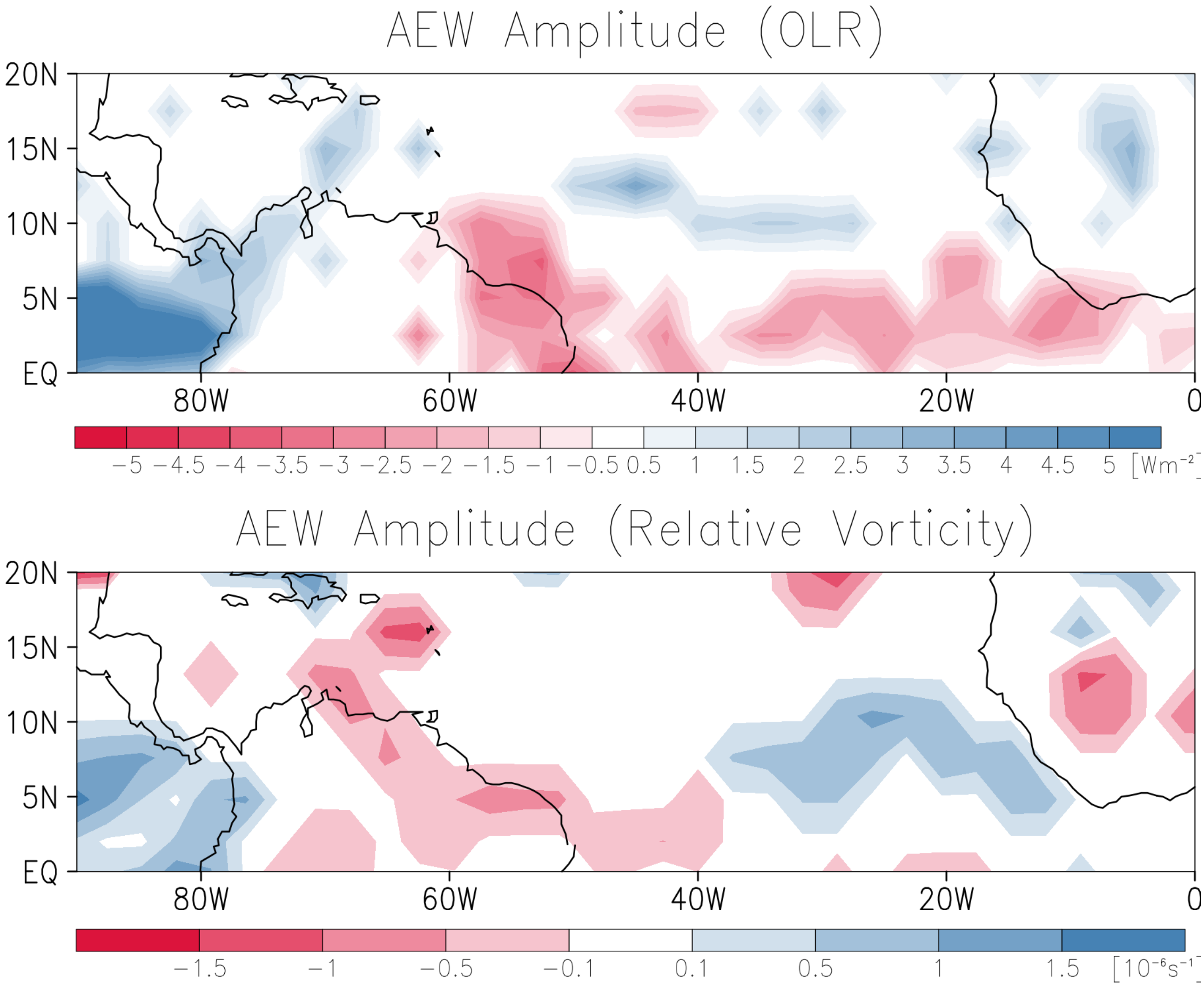

Figure 4.5: Significant AEWs amplitude differences between El Niño and La Niña years for digital band-pass filtered OLR (top) and smoothed relative vorticity (bottom). Values are in $W \cdot m^{-2}$ and $10^{-6}s^{-1}$.

precipitation, enhancing surface convergence over the wave trough; hence cloud cover is larger and the OLR tends to reduce. On the other hand, over western Colombia and the Pacific Ocean, positive OLR anomalies correspond to positive smoothed relative vorticity anomalies, indicating the existence of dry AEWs whose activity is not related to the occurrence of precipitation. Although this pattern is also evident on the OLR anomalies over the Caribbean Sea, Figure 4.5 (top) suggests that those AEWs that intensify over these region as well as those easterly waves that originate on the Caribbean Sea (Serra et al. 2010) displace towards Colombia and the eastern tropical Pacific Ocean rather than towards Central America. The latter is not consistent with what is observed from the smoothed relative vorticity waveguide that exhibits non significant anomalies over northern Colombia or even isolated positive anomalies over the Caribbean Sea.

It can be also noticed from Figure 4.5 that, during El Niño years, the average AEWs amplitude is larger southward of the previously recognized typical waveguide position over the Atlantic ocean, which is nearly around 17°N (Martin and Thorncroft 2015; Salinas-Prieto 2006). Furthermore, the AEW's track density pattern observed for the significant differences between AEWs track density during El Niño and La Niña years (Figure 4.4d) match the AEWs amplitude pattern (i.e., regions with the largest amplitudes, not only for the smoothed relative vorticity standard deviation but also for the OLR anomalies standard deviation, shown in Figure 4.5). Thus, the shift of AEWs trajectories to the south of their typical location during El Niño years appears to be a feature that is consistent among different analysis (e.g., point-by-point significant correlations and composite analysis during the different phases of ENSO) as well as among different variables here considered (e.g., relative vorticity, OLR and AEWs track density from the AEWC dataset). Additionally, these findings are consistent with previous studies regarding the influence that SST anomalies fluctuations might imply to the AEWs activity (Ruti and Dell'Aquila 2010).

4.3.2 Dynamical features behind AEWs interannual variability

In order to explore the physical mechanisms that could explain the southward shift of the AEWs trajectory during El Niño years, Figure 4.6 shows the significant differences of the vertical zonal wind shear, defined as the magnitude of the difference between U component of wind at 850hPa and 200hPa, during El Niño and La Niña years. A negative vertical wind shear is one of the necessary conditions for a suitable background environment for the formation of these tropical waves (Burpee 1972; Ventrice and Thorncroft 2013). Results show that negative values of the vertical zonal wind shear tend to be more negative during El Niño years. Thus, during El Niño years, a favoring environment for the development of these atmospheric perturbations occurs over the southern region

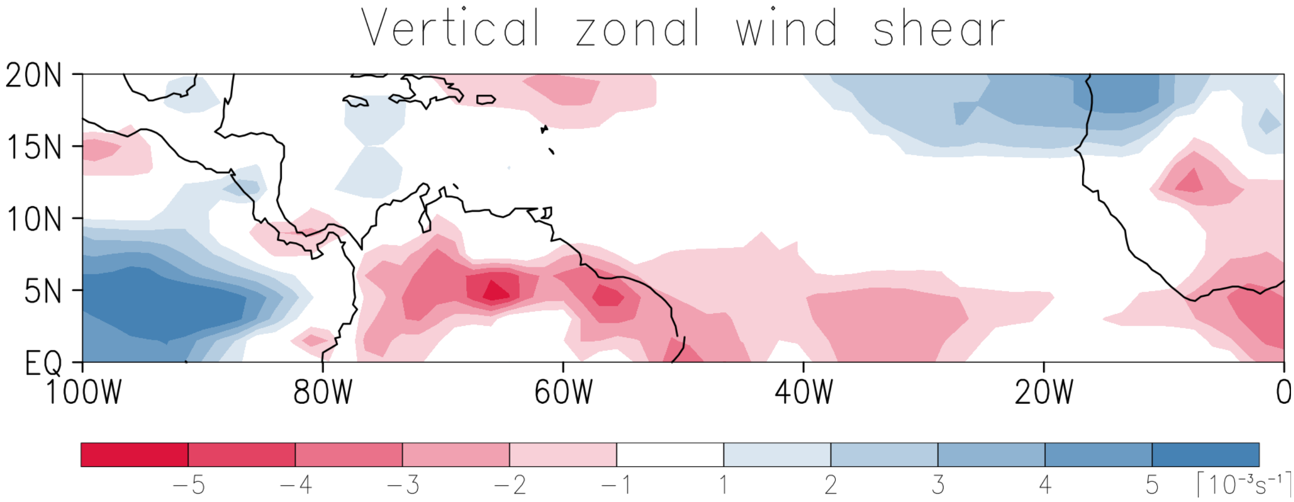

Figure 4.6: Significant differences of vertical zonal wind shear between El Niño and La Niña years. Values are in $10^{-3}s^{-1}$.

of the northern Atlantic Ocean, being consistent with those regions where the AEW's oscillations take place during El Niño years, as shown in section 4.3.1. Therefore, these negative values of vertical zonal wind shear support our finding of a shift of the AEWs trajectory to the south of their typical position during El Niño years; with a more favorable environment, to the south of 10°N, for the development of AEWs during El Niño. During La Niña events, no significant differences in terms of vertical zonal wind shear are found over the tropical Atlantic Ocean neither over northern South America.

In addition to a negative vertical zonal wind shear, Burpee (1972) pointed out baroclinic instability as a necessary condition for the formation of the AEWs. The Charney-Stern condition consists on the existence of a reversed meridional gradient of potential vorticity (PV) (Charney and Stern 1962), computed as the partial derivative of PV with respect to Y (Equation 1) (Hsieh and Cook 2008; Molinari et al. 1997). In particular, we compute the PV meridional gradient reversals on the 300-315-330K ERA-Interim isentropic levels, besides, an interpolation to the 310K isentropic level, which is typically used, is performed.

$$\frac{\partial(PV)}{\partial y}=\frac{\partial q}{\partial y}=\frac{\partial}{\partial y}\left[f+\nabla^2\Psi+\frac{\partial}{\partial P}\left(\frac{Pf_0^2}{RS_P}\frac{\partial\Psi}{\partial P}\right)\right]\partial t \qquad (4.1)$$

Figure 4.7a indicates that the region where the PV meridional gradient reverses sign along the 310 K isentropic level (i.e., the region with a favorable instability condition for the formation of the AEWs) strengthens southward, over the tropical Atlantic Ocean and northwestern Africa, during El Niño years. Figures 4.7a and 4.7c show a slightly southward strengthening of the region where

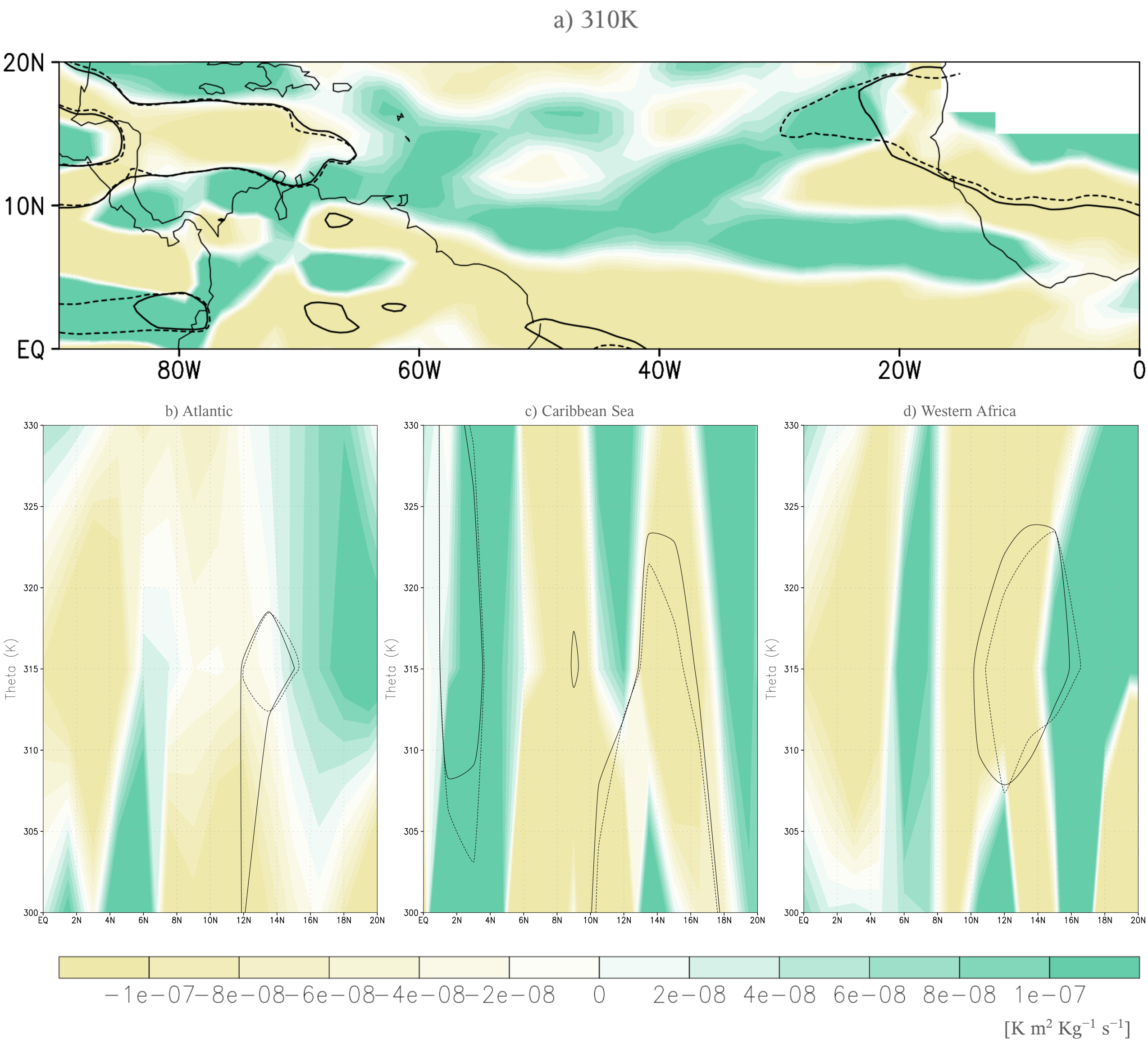

Figure 4.7: Potential vorticity gradient difference between El Niño and la Niña years on the 310K isentropic level (top), and north-south cross section of the potential vorticity gradient difference between el Niño and La Niña years between: b) 80°W and 0°W, c) 85°W and 75°W, d) 15°W and 5°W. Values are in K m^2 kg^{-1} s^{-1}. Solid and dashed lines show the 0 K K m^2 kg^{-1} s^{-1} contour during El Niño and La Niña years, respectively.

PV meridional gradient reverses sign over the Caribbean Sea, a domain of intensification and genesis of AEWs (Molinari et al. 1997; Serra et al. 2010). Meridional cross-sections also show a deepening of the PV meridional gradient reversal over the Atlantic Ocean (Figure 4.7b), together with a southward strengthening and displacement of the PV meridional gradient reversal over the western African coast (Figure 4.7d), in agreement with changes of AEWs amplitude (Figure 4.5) and AEWs track density (Figure 4.4).

4.4 Conclusions

Our work shows that AEWs exhibit interannual variability related to ENSO; specifically, the AEW's activity appears to correlate with the SST anomalies over the Niño 1+2 region. Although a general link of the AEW's activity and the SST anomalies over the Atlantic and Pacific Oceans had been suggested in previous studies, the significant correlation between the SST anomalies over six different oceanic regions and the AEW's track density identified in this study suggests a particularly important link emerging between the Niño 1+2 region and the AEW's track densities, rather than with other oceanic regions in the Pacific and Atlantic Oceans, as well as the Caribbean Sea.

Our analysis is consistent with previous studies regarding the intensification of the AEW - related precipitation power spectrum over Colombia, during El Niño years (Poveda 2004; Salas Parra et al. 2012). However, our work makes further contributions since it identifies a larger density of trajectories on the western tropical Atlantic Ocean near the South American landmass during El Niño years, in addition to a larger AEW's track density over the southern region of the eastern tropical Atlantic Ocean and, more interestingly, over the northern and central region of Colombia as well as the eastern Caribbean Sea. The recognized shifting to the south of the AEW's typical position during El Niño years is further verified with the smoothed relative vorticity and OLR anomalies amplitude. This means that not only the trajectories of the AEWs suffer a modification during El Niño years but also the activity of these waves detected by the wind field's relative vorticity from the ERA-Interim reanalysis and the cloud cover related to the AEWs derived from the NOAA interpolated OLR.

In addition, vertical zonal wind shear, together with potential vorticity meridional gradient reversal on the 300-330K isentropic levels, suggest a more suitable environment for the AEWs development during El Niño over a domain located to the south of the region where the AEW's oscillations typically take place. The region exhibiting a more favorable environment for baroclinic instability and wave propagation during El Niño years correspond to the same region with higher AEW's track density and amplitude, in agreement with the shifting to the south of these tropical disturbances during El Niño years found with other variables. This suggests the development of a dynamical background enhancing AEW's activity southward of their typical location during El Niño years, which has not been reported before according to our literature review.

This work provides new insights on the ENSO-related variability of the AEWs, suggesting more suitable conditions for AEWs displacement and intensification in the more equatorial North Atlantic Ocean, reaching regions as southward as northern South America during El Niño years. The latter could imply intraseasonal variations of precipitation over northern South America related to ENSO, via changes in AEWs activity. This is particularly important in a region highly influenced by tropical phenomena, such as northern South America, where weather prediction and intraseasonal forecast needs to be improved.

5. GENERAL CONCLUSIONS AND FUTURE WORK

Most of the AEWs crossing over northern South America turned out to enhance convective activity, favoring the occurrence of precipitation over northern South America. In particular, convective AEWs enhance convective activity over northern South America whereas dry AEWs are related to mineral dust transport from northern Africa towards the Atlantic Ocean and the Caribbean Sea. Therefore, the effects of dry AEWs, which account for only the 14.3% of the total AEWs crossing over northern South America, are not only related to the inhibition of precipitation as they cross over the same territory.

AEWs exhibit interannual variability that seems to be related to the ENSO phenomenon, specifically with the Niño 1+2 SST region. There is a larger density of trajectories near the South American landmass during El Niño years, in addition to a larger AEW's track density over the southern region of the North Atlantic Ocean. A shifting to the south of the AEW's typical position during El Niño years is not only verified with the AEW's track density during El Niño years but also with the smoothed relative vorticity and OLR anomalies amplitude. In addition, the vertical zonal wind shear together with the potential vorticity reversal on the 315 K isentropic level, suggest a more favorable environment for the AEWs development during El Niño over a region that is located to the south of the region where the AEW's oscillations take place typically.

Identifying possible dynamical or mesoscale interannual features behind the displacement of convective and dry AEWs during ENSO is of great interest, not only for Colombia but also for the northern South American region, and must be considered in a future work. Possible interactions within AEWs, trade winds, and water vapor with northern South American orography is thought to be the next step in this research, in order to achieve a better understanding of the passage of an AEW and the occurrence or suppression of precipitation in the region.

This Masters Thesis constitutes an effort to understand climate variability in northern South America at intraseasonal and interannual timescales. In particular, the influence of AEWs in this region has not been widely addressed and this work aims to provide a first step toward such goal.

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