Large-scale flow patterns conducive to Central American extreme precipitation events during autumn

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LARGE-SCALE FLOW PATTERNS CONDUCIVE TO CENTRAL AMERICAN EXTREME PRECIPITATION EVENTS DURING AUTUMN

by

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Extreme precipitation events (EPEs), characterized by daily widespread heavy rainfall exceeding the 95th percentile across Central America, can have large impacts on agriculture, life, and property during the rainy season. EPEs during the Northern Hemisphere (NH) autumn, however, have been observed to be influenced by both tropical and extratropical originating phenomena such as easterly waves and cold surges, respectively. Given the limited research in this area, the novelty of this work is to apply a systematic approach for identifying and better understanding EPEs, and investigating their associated synoptic-scale variability using daily high-resolution observations and reanalysis products over Central America.

An examination of Central American EPEs during the autumn, defined by exceeding the 95th percentile of daily precipitation, was performed using the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Climate Data Record (PERSSIAN-CDR). Additionally, a climatology of the associated large-scale flow features related to the formation and evolution of EPEs from 1983–2018 was objectively categorized and extracted using self-organizing maps (SOMs) using the NCEP Climate Forecast System Reanalysis (CFSR) reanalysis. A time-lagged composite analysis of thermodynamic and dynamic variables (e.g., K-index, integrated vapor transport, and moisture flux convergence) using SOMs was then performed on binned EPEs to document the evolution of the dominant fields that generally lead to EPEs identified in the constructed climatology. Diagnostic fields used to investigate the evolution of EPEs were applied to two representative case studies included in this thesis for consistency and comparison purposes.
The monthly frequency of daily EPEs over Central America during autumn is generally confined to enhanced terrain where upslope flow is highly favored. Based on the observed local synoptic features throughout autumn, EPEs are commonly associated with two dominant scenarios characterized by the presence of Central American gyres (CAGs) or cold surges prior to an EPE onset. CAG patterns favor EPE precipitation along the Pacific coastline of Central America as opposed to cold surges that favor heavy precipitation along the Caribbean coastline of Central America.

Finally, the representative case studies further demonstrate the evolution and processes associated with CAG and cold surge patterns as depicted by SOMs. The first representative case study that was associated with a CAG featured the interactions of a potential vorticity streamer (PVS), a Southern Hemisphere (SH) dry air surge, and two tropical cyclonic circulations that precluded widespread heavy rainfall primarily the Pacific-facing slopes of Central America. The second representative case study highlighted the importance of NH extratropical influences that manifested in the form of a cold air surge within a convectively favorable environment that supported widespread heavy rainfall across Central America.
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<td>CAG</td>
<td>Central American Gyre</td>
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<td>CJ</td>
<td>Chocó Jet</td>
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<td>CLLJ</td>
<td>Caribbean Low-Level Jet</td>
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<td>EPAC</td>
<td>Eastern North Pacific</td>
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<td>EPE</td>
<td>Extreme Precipitation Event</td>
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<td>EW</td>
<td>Easterly Wave</td>
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<td>IVT</td>
<td>Integrated Vapor Transport</td>
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<td>MFC</td>
<td>Moisture Flux Convergence</td>
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<td>MJO</td>
<td>Madden-Julian Oscillation</td>
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<td>MSLP</td>
<td>Mean Sea Level Pressure</td>
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<td>NH</td>
<td>Northern Hemisphere</td>
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<td>PV</td>
<td>Potential Vorticity</td>
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<td>PVS</td>
<td>Potential Vorticity Streamer</td>
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<td>PWAT</td>
<td>Precipitable Water</td>
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<td>RH</td>
<td>Relative Humidity</td>
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<td>SH</td>
<td>Southern Hemisphere</td>
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<td>SOM</td>
<td>Self-Organizing Maps</td>
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<td>SST</td>
<td>Sea Surface Temperature</td>
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<td>TC</td>
<td>Tropical Cyclone</td>
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1. Introduction

1.1 Motivation

The purpose of this thesis is to objectively link and summarize key synoptic features that facilitate extreme precipitation events (EPEs) across Central America in the autumn. EPEs, characterized by daily widespread heavy rainfall, can have large impacts on agriculture, life, and property. EPEs account for nearly half of all natural disasters and for more than 90% of the total number of casualties and economic loss in Central America (EM-DAT international database, Guinea-Barrientos et al. 2015). Previous cases of EPE activity during the autumn have been recorded in the literature (Fernández and Barrantes 1996; Bell et al. 1999; Hellin et al. 1999; Rapp et al. 2014). For example, an EPE in the autumn associated with tropical cyclone (TC) Mitch (1998) produced extreme rainfall across the entire Central American region causing more than 18,000 fatalities, predominantly from flooding in Honduras and Nicaragua due to its slow movement of less than 2 m s\(^{-1}\) (4 kt) over a period of seven days and the topographic enhancement of rainfall. As a result, heavy rainfall with a maximum of 911 mm was recorded in the region and produced large-scale mudslides, which buried or swept away entire villages. Such an occurrence has been reflected in previous cases in areas that have an observed relative maxima of climatological precipitation along the Pacific and Caribbean slopes in Central America during the wet season.

The rainy season in Central America, defined from May through October, exhibits a definitive period of precipitation before abruptly becoming dry for the rest of the year (Hastenrath 1967; Portig 1976). Seasonal precipitation is generally characterized by a bimodal distribution along the Pacific slopes of topography in Central America with maxima centered in early June and September, respectively. In contrast, precipitation is characterized by a relatively
more uniform distribution along the Caribbean slopes, suggestive of different dynamical mechanisms of rain production (e.g., Maldonado et al. 2016a). For example, the secondary maximum of precipitation along the Pacific slopes has been shown to contain a relatively high frequency of EPEs in countries like Costa Rica (Alfar o et al. 2010; Maldonado et al. 2013). However, the generalized occurrence of EPEs linked to the varying rainfall distributions along the topography of Central America during the autumn have not been well explored. Thus, there continues to be a need for an objective evaluation and further understanding of Central America precipitation extremes linked to large-scale flow patterns.

1.2 Literature Review

1.2.1 Large-Scale Influencers of Central American Rainfall during the Autumn

1.2.1.1 The Caribbean Low-Level Jet (CLLJ)

Maximized at approximately 925 hPa, the CLLJ is characterized by easterlies exceeding 12 m s\(^{-1}\) around 13.8°N, 73.8°W and poleward of Colombia. The CLLJ is a westward extension of the Bermuda high, and its winds are largely influenced by the locally varying meridional temperature gradients and orography in the Caribbean (Amador 1998; Amador et al. 2010; Cook and Vizy 2010). Despite its annual presence, the CLLJ exhibits a semiannual cycle of intensity with peaks occurring in February and July, and a minima in May and October that are in phase with the semiannual cycle of the largest meridional pressure gradient across the Caribbean Sea (Wang et al. 2007; Munoz et al. 2008). With a peak during summer, the CLLJ is part of the circulation that flows from the Caribbean Sea through the Gulf of Mexico, transporting moisture into both Central America and the continental United States. During the latter half of the rainy season, the CLLJ acts as a primary conveyor of regional moisture and a key contributor to
defining the seasonality of large-scale forced rainfall (Durán-Quesada et al. 2010; Durán-Quesada et al. 2017).

1.2.1.2 The Chorro del Occidente Colombiano (Chocó) jet (CJ)

The CJ is defined as a low-level, westerly jet that is characterized by southwesterly cross-equatorial flow that converges over the EPAC and western Colombia. During autumn, the CJ peaks in strength and transports moisture from the Pacific to Panama and southwestern Costa Rica (Poveda and Mesa 2000). The governing source of its variability and existence has been linked to its sensitivity to the gradient of SSTs between the Niño-1+2 region and the Colombian Pacific (Poveda and Mesa 1999, 2000; Poveda et al. 2014). Form a Lagrangian standpoint, the CJ has been quantified in previous studies to be a secondary source for transporting low-level moisture into the region with the CLLJ being the primary source (e.g., Durán-Quesada et al. 2017). Despite being a secondary moisture source, the CJ has been suggested to act a primary source for the development of deep convection near Panama and southwestern Costa Rica due to its interactions and enhancement induced by the nearby topography gap known as the Mistrató Pass (Durán-Quesada et al. 2010, 2016; Rapp et al. 2014).

The observed linkage of deep convection to the CJ has been attributed to low-level moisture convergence by the CJ in association with upper-level easterly trade winds, orographic lifting, and low-level cyclonic disturbances (Poveda and Mesa 2000). The relationship between deep convection and the CJ can, therefore, be modulated by nearby sources depending on the background environment. For example, TC Otto (2016), while developing over the western Caribbean following a cold surge in late November, aided in the persistence and intensity of an anomalously strong CJ (Yepes et al. 2019). As TC Otto moved away from Central America, a
more zonal and southwesterly low-level flow was established, with enhanced southwesterly moisture flow favoring moisture flux convergence and orographic forcing. A consequence of the aforementioned flow pattern and enhanced CJ led to a period of enhanced precipitation, particularly in Nicaragua where 160 mm of rain was observed in association with anomalously high convective available potential energy (CAPE) and helicity (or vertical wind shear). Despite TC Otto making direct landfall in Nicaragua, rainfall totals were relatively large in magnitude for nearby countries such as Miravelles Volcano, Costa Rica, where a 1-day rainfall total of 300 mm was reported on 24 November. The observed heavy rainfall associated with an anomalous CJ following a cold surge and TC Otto’s formation suggests an important linkage to the multiple extratropical and tropical interactions that can occur in the late autumn in proximity to Central America.

1.2.1.3 Central American Gyres (CAGs)

CAGS are broad, low-level, cyclonic circulations that are observed over Central America during the warm season. CAGs typically occur in conjunction with enhanced convective activity and can result in heavy rainfall throughout the Central American region (Papin et al. 2017). The origins of CAGs have been shown to be associated two distinct categories, those that form with or without the presence of an upper-tropospheric trough, which are categorized as forming through baroclinic and non-baroclinic processes, respectively. In a less common baroclinic mode, CAGs form in the presence of high potential vorticity (PV) air manifesting in the form of an upper-tropospheric trough centered northwest of the gyre’s center similar to PV streamers produced via Rossby wave breaking. The direct consequence of the nearby trough shifts any nearby heavy precipitation to the east of the CAG circulation where deep tropospheric ascent is
most favored. Within non-baroclinic modes, upper-level PV throughout the gyre circulation is comparatively much lower and favors a warm-core vertical structure in the lower troposphere. Consequently, non-baroclinic CAGs contain a more uniform precipitation distribution in an area stretching east–west across its circulation center.

Despite the differences in upper-level PV between both CAG categories, CAG formation is typically preceded by low-level westerly wind bursts in the eastern North Pacific (EPAC) that result in more favorable conditions for a CAG to form through the conversion of zonal kinetic energy to eddy kinetic energy (Papin et al. 2017). Extreme precipitation has been shown to be observed over multiple days in all CAG cases, most commonly along the Central American coastline and, on average, over a large fractional area (25%) during all CAG formations (e.g., Papin et al. 2017). The aforementioned finding suggests that the occurrence an EPE may be particularly sensitive to, and dependent on, CAG formation and the accompanying large-scale flows that are conducive for their existence.

1.2.1.4 Monsoon Westerlies and ITCZ

In most basins, the local monsoon trough has been commonly associated with tropical cyclogenesis and can act as a source for enhanced rainfall. The monsoon trough zone is characterized by the near equatorial seasonal westerly winds and enhanced lower tropospheric vorticity. In contrast, the ITCZ area is dominated by easterly trade winds and can initiate convection where there is enhanced low-level convergence. The confluence zone between the monsoon trough westerlies and ITCZ trade easterlies has been shown in previous studies to be linked to the development of tropical cyclones that produce heavy rainfall over land (e.g., Landsea and Gray 1992).
The presence of monsoon westerlies and lack thereof have been attributed to the intraseasonal migration and variability of the ITCZ (e.g., Alfaro 2002). However, a recent study by Schreck et al. (2015) suggested that the presence of anomalous, low-level westerlies typically occurred in the wake of Kelvin wave passages and active phases of the Madden–Julian Oscillation (MJO) in all oceanic basins. The consequence of low-level westerlies was shown to aid in the formation of a low-level deformation zones exhibiting enhanced vertical relative vorticity, thus favoring tropical cyclogenesis for nearby tropical disturbances. Thus, a mutual feedback between tropical disturbances and anomalous low-level westerlies is established, and reinforces stronger westerly flow locally that can potentially lead to orographically enhanced heavy precipitation along the Pacific slopes of Central America and increase the likelihood for an EPE to occur.

1.2.2 Extratropical Connections to Extreme Rainfall

1.2.2.1 Potential Vorticity Streamers (PVS)

Potential vorticity streamers (PVSs) that extend into the tropics during the rainy season are often dynamically important to the generation of organized heavy rainfall. (Appenzeller and Davies 1992; Browning 1993; Appenzeller et al. 1996; Postal and Hitchman 1999; Wernli and Sprenger 2007; Galarneau et al. 2015). Similarly, PVSs have been found in numerous studies to aid in the initiation of EPEs (e.g., Massacand et al. 1998; Knippertz et al. 2005; Martius et al. 2006; Moore et al. 2019). As suggested by previous work, PVSs can have positive influences on tropical disturbances and low-level circulations that are conducive for heavy precipitation (Galarneau et al. 2015; Papin et al. 2017, 2020). For example, Papin et al. (2017) showed that high PV air northwest of a baroclinically originating CAG was associated with an upper-tropospheric trough that was characteristic of a PVS. Additionally, moisture anomalies observed
near PVSs as pre-existing moisture is advected by cyclonic nondivergent flow around the PVS in the form of an atmospheric river (Hoskins et al. 1985; Moore et al. 2019). In combination with moisture transport, synoptically forced ascent that favors the production of heavy precipitation has been observed ahead of the PVS trough axis where cyclonic vorticity advection is generally favored (Davis 2010).

### 1.2.2.2 Cold Air Surges

Cold surges originating from the midlatitudes (also known as “Nortes”) have been shown to significantly impact much of the weather and climate for Central America and the surrounding tropics (Reding 1992; Schultz 1998). Cold surges occur most frequently in the cool season (October–April) and are typically associated with an equatorward-moving anticyclone along the eastern slopes of the Sierra Madre and with amplified upstream ridging and blocking (e.g., Rex 1950; Reding 1992; Konrad 1996; Schultz et al. 1997). Typical cold air surges last 2–6 days, producing northerly winds over the Gulf of Mexico that generally induce anomalous cold air advection (Schultz et al. 1998). Cold surges that can persist for more than two days can lead to atmospheric destabilization at lower latitudes as low-level cool air moves over warm waters. The aforementioned atmospheric destabilization is commonly associated with enhanced cloud cover and rainfall throughout Central America, particularly when the equatorward extent and persistence of cold air surges can influence and interact with the surrounding area.

Previous studies have documented the dynamic and localized effects cold surges impose over Central America. For example, Reding (1992) showed that precipitation associated with cold surges and surface pressure features in the Mexico–Central American region accounted for 70–90% of winter precipitation. Similarly, the cold surge’s associated frontal boundary and
cooler air mass has been shown to effectively lower the surface air temperature and SSTs, increase surface pressure, decrease dew point, and induce heavy rainfall (Reding 1992; Schultz et al. 1997; Passalacqua et al. 2016). Though their occurrence and accompanying dynamics are well understood, their impacts on Central America during the transition from the warm season (October–April) to the cold season (November–May) and vice versa are less understood.

1.2.3 Tropical Disturbance Linkages to Extreme Rainfall

1.2.3.1 Easterly Wave Disturbances

Tropical easterly waves (EWs) are commonly observed in the Atlantic and EPAC basins and can produce locally heavy rainfall during the wet season as short-lived, intense, convective events (Mapes et al. 2003; Warner et al. 2003; Houze et al. 2004). The origins of passing EWs have been attributed primarily to African easterly wave activity; however, recent studies have suggested that EWs can locally form in situ in the EPAC rather than originating solely from the tropical Atlantic (Serra et al. 2008; Toma and Webster 2010a,b; Rydbeck et al. 2017). For example, Torres et al. (2021) showed from an idealized framework that EWs originating from the EPAC, particularly near the Panama Bight, could form close to the entrance region of the CLLJ when shallow convection is active. The aforementioned EW development was shown to be most supportive when the meridional PV gradient was increased at low levels during the active convective phase of MJO. The increased meridional gradients of PV generated from shallow convection in the idealized framework were shown to generate and sustain EW growth over the EPAC as a result.

When incoming EWs are able to carry low-level moisture from oceanic areas to the Central American landmass, sufficient thermal instability and surface moisture convergence near
the EW trough axis can play an important role for triggering and strengthening localized convection. Furthermore, a deep mesoscale vortex can potentially develop as passing EWs move downwind of Central American mountains, thereby further enhancing and maintaining strong convection in the presence of low-level easterly flow. The aforementioned processes associated with EW activity in Central America have been shown to produce more than 60% of the rainfall observed during the wet season (May–November) and contribute substantially to interannual regional rainfall variability (e.g., Domínguez et al. 2020). Costa Rica and Panama, for example, receive up to 700 mm per year from EWs alone (Fig. 1.4b; Domínguez et al. 2020), especially when EWs synergistically interact with the ascending branches of the exit regions in the CLLJ and CJ (Arias et al. 2015). Additionally, heavy rainfall associated with passing EWs is aided by moisture transport into Costa Rica and Panama, which peaks during the autumn under modest 200–850-hPa wind shear (~10 m s\(^{-1}\)) and increases the likelihood for an EPE to occur.

1.2.3.2 Indirect and Direct Effects of TCs on Regional Precipitation

Tropical cyclones (TCs), characterized by a low-pressure center and strong winds, are commonly exhibited in the EPAC during the wet season. TCs can produce heavy rainfall over Central America in its eyewall or surrounding rainbands. Heavy rainfall produced by TCs in the aforementioned manner have been referred to as the direct effects of TC on precipitation (Wang et al. 2009). In contrast, rainfall produced from large distances (> 500 km) away from the TC itself have been commonly classified as being the indirect effects of an evolving nearby TC (e.g., Peña and Douglas 2002). The direct and indirect effects of TCs on precipitation during the wet season are, therefore, relevant to the occurrence of EPEs across large areas of the region.
Consequently, the duration of an EPE can be linked to the evolution of TCs, which is dependent on the large-scale flow pattern that is steering the tropical systems.

TCs in the EPAC generally occur from May to November, with the greatest frequency in June and September–October. Notably, daily rainfall is relatively higher during the peak frequency of TC occurrence and reflects the bimodal rainfall distribution for areas along the Pacific slopes, which accounts for approximately 15% of average annual precipitation for areas along the Central American Pacific slopes (Waylen and Harrison 2005). In the presence of TCs, rainfall produced along the Pacific slopes from TCs are typically associated with low-level onshore flow that leads to enhanced rainfall where orographic ascent is favored (Vargas and Trejos 1994; Waylen and Laporte 1999; Peña and Douglas 2002). In contrast to the Pacific slopes, the western Caribbean Sea adjacent to Central America and the Bay of Campeche Sea generally receives rainfall directly from TCs rainbands that extend over the region (e.g., Zhou and Matyas 2018). Heavy rainfall directly produced from TCs in the northwest Caribbean was determined to be more sensitive to the distance of the TC’s center position and relative storm motion rather than the TC’s magnitude as suggested by previous studies (Alfaro and Quesada 2010; Pérez-Briceño et al. 2016). Hernández-Castro et al. (2021) and Hidalgo et al. (2022) further establish a relationship between EPEs and a TC’s relative location, such that direct (indirect) impacts are more common in the northern countries along the Caribbean (Pacific) slopes. However, the direct and indirect effects of TCs on precipitation within the presence of other large-scale circulations (e.g., cold surges, PVSs, CAGs, etc.) and their associated interactions during the autumn have not been well explored.

1.3 Research Goals and Thesis Structure
EPEs exhibited in Central America during the autumn have been shown to occur within a broad spectrum of large-scale flow regimes containing both extratropical and tropical originating features. Much of the recent progress in connecting EPEs and large-scale regimes over Central America has primarily used climate modes of variability and teleconnections, either over the specific domain or over extended areas (e.g., into the eastern Caribbean). Given the existing research in the area, the novelty of this work aims to apply a systematic approach for identifying and better understanding EPEs and the associated synoptic-scale variability using daily high-resolution observations and reanalysis over Central America. Therefore, the goals of this research are to: 1) capture and investigate the frequency, magnitude, and intensity of EPEs in Central America by constructing a climatology of all EPEs that occur in the autumn; 2) improve the understanding of extratropical and tropical interactions that produce EPEs in Central America through representative case study analyses of EPEs; and, 3) summarize the frequency and magnitude of the aforementioned interactions and dominant large-scale flow patterns that are linked to EPEs.

The organization of the subsequent sections of this thesis is as follows: Data and methodology are described in chapter 2. The climatology of EPEs is presented in chapter 3. Results of the objective composite analyses are discussed in chapter 4. Case studies of representative EPEs are discussed in chapter 5. Research, conclusions, and future work suggestions are discussed in chapter 6.

2. Data and Methodology
2.1 Candidate EPEs

The Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Climate Data Record (PERSIANN-CDR) dataset (Ashouri et al. 2015) provides daily rainfall estimates at a spatial resolution 0.25° x 0.25° from 1983–2018 and is used to identify EPEs. PERSIANN-CDR is produced using the PERSIANN algorithm on GridSat-B1 infrared satellite data and the training of the artificial neural network is done using the National Centers for Environmental Prediction (NCEP) stage IV hourly precipitation data (see Ashouri et al. 2015 for details). All PERSIANN products were evaluated over the continental United States using the NOAA Climate Prediction Center (CPC) Unified Gauge-Based Analysis of Daily Precipitation. Among all the PERSIANN products, the PERSIANN-CDR better reflected the precipitation patterns observed in the CPC data based on root-mean-square error and bias since PERSIANN-CDR is a bias adjusted product utilizing the Global Precipitation Climatology Project (GPCP) data (https://hess.copernicus.org/preprints/hess-2018-177/hess-2018-177.pdf). However, key weaknesses of the PERISANN-CDR are its inability to resolve the diurnal cycle and some short-lived, intense rainfall events.

EPEs that locally impact the Central America were extracted using a grid constructed over Central America with an identical resolution of PERSSIAN-CDR as shown in Fig. 2.1. To identify large-scale patterns conducive to extreme rainfall in Central America, our study chose to define daily EPEs as the 95th percentile of all precipitating days at each grid point throughout autumn observed within the PERSSIAN-CDR climatology from 1983–2018. We further defined a daily EPE based on the total distribution of daily grid points that exceeded the 95th percentile of precipitation to capture a larger extent of areal coverage and impact on the region. In our study,
we chose to objectively extract EPEs that exceed the 90\textsuperscript{th} percentile of total grid points that satisfied the aforementioned criteria (Fig. 2.2).

2.2 SOMs and EPE Climatology

Self-organizing maps (SOMs) have been demonstrated as useful and robust analytical tools for studying synoptic-scale variability using observational and model data (e.g., Sheridan and Lee 2011; Hewitson and Crane 2002; Liu and Weisberg 2011; Loikith et al. 2016). Such an application of SOMs is typically used in large datasets to objectively classify modes of variability that cover the primary large-scale patterns of interest. To further classify modes of variability, a user of SOMs has the options to utilize a single variable or multiple variables to organize the chosen dataset. The advantage of using one input variable is that it can aid in justifying a first-order perspective on generalized patterns describing the dataset. Additionally, inputting multiple variables that may be related to each other in a highly nonlinear fashion into a SOM algorithm can add complexity for describing the general patterns or phenomena of interest. The aforementioned nonlinear relations can, thus, be simplified and made interpretable through the unsupervised learning process specified by the user. A benefit for using an unsupervised learning process is that it can define clusters of similar inputs when no previous knowledge exists using the number of the desired clusters. In contrast, the supervised learning process commonly involves training a model to “learn” specific relationships within a given dataset to predict relationships within another dataset of similar variables.

The principle of the SOM applied in this study can simply be defined as a mapping from the input data space onto a regular two-dimensional array of nodes (Kohonen 1995). In previous studies, the number of nodes chosen is often motivated by balancing the interest of
interpretability and sufficient representation of a reasonably complete range of major patterns in the dataset subjectively by the user (Loikith et al. 2016). This thesis utilizes standardized mean sea level pressure (MSLP) and precipitable water (PWAT) anomalies centered at 1200 UTC as the chosen SOM variables in order to determine the characteristic synoptic flow patterns during EPEs.

We utilize the aforementioned variables for organization purposes to capture transient tropical variability and midlatitude intrusions in proximity to Central America that are commonly well observed in the lower troposphere. The standardized PWAT and MSLP anomalies derived from the NCEP Climate Forecast System Reanalysis (CFSR) 0.5° gridded dataset (Saha et al. 2010) are inputted into the SOM algorithm simultaneously to construct a multi-variate SOM analysis. We qualitatively assessed the results obtained using both smaller and larger SOM arrays and found that a 2 x 2 configuration captured the range of synoptic-scale variability with sufficient detail to distinguish among different variants of the same regime while being manageable for physical interpretation. To account for signatures and influences of upper-tropospheric variability, we conduct a composite analysis utilizing the information provided by the SOMs as outlined in this section.

Composite analyses are constructed for EPEs placed into each node produced by the SOMs algorithm over a Central American domain (Fig. 2.1). The aforementioned composites are constructed using the following variables within each node to describe the large-scale flow patterns associated with EPE regimes: MSLP, 1000–500-hPa thickness and 250-hPa wind speed; 850-hPa temperature, wind anomalies, and standardized temperature anomalies; 850-hPa equivalent potential temperature; 700-hPa geopotential heights and integrated vapor transport; 700–500-hPa layer averaged ascent, relative humidity (RH), and winds; and, 850–600-hPa layer
averaged cyclonic relative vorticity, winds, and K-index. Similarly, we composite and investigate precipitation patterns associated with EPEs within each SOM node using PERSIANN-CDR. The characteristics of each of the SOM nodes will be discussed in detail in section 4.

2.3 Case Study

EPEs observed in November 2014 and October 2018 were shown to be associated with two and three consecutive days of widespread heavy rainfall respectively over Central America and represented three of the four SOM nodes referenced in section 2.2. The NCEP CFSR is utilized to investigate synoptic-scale tropospheric conditions for the EPE events in November 2014 and October 2018. The aforementioned EPEs were identified from PERSIANN-CDR using SOMs and subjectively chosen based on their resemblance and broad representation of the extracted SOMs. The PERSIANN-CSS-CDR is utilized to further investigate the daily intensity and evolution of the precipitation during the EPEs. For consistency, the same variables chosen to organize and composite EPEs are used for the representative case studies. The characteristics and details of the November 2014 and October 2018 EPE cases are further discussed in more detail along with their affiliated SOM nodes in section 4.
FIG. 2.1. Domain and total grid points used to organize and extract EPEs throughout Central America.

FIG. 2.2. The total distribution of grid points satisfying EPE conditions. The 90th percentile of the total number of grid points is highlighted (red dashed line).
3. EPE Climatology

3.1 Intraseasonal Rainfall Variability

The intraseasonal rainfall variability during autumn in Central America exhibits widely varying spatial distributions during the progression of the season. On average, cumulative rainfall throughout the autumn ranges between approximately 50–500 mm. Cumulative rainfall can also vary largely depending on the given month during autumn, with larger amounts of precipitation increasing equatorward during the transition into the cool season (November–April).

During September, the maximum monthly rainfall is generally observed in proximity to enhanced topography on both the Pacific and Caribbean slopes of Central America (Fig. 3.1a). More specifically, a localized maxima of rainfall ranging from 400–500 mm is observed along the Pacific topographic slopes of Guatemala, El Salvador, Panama, and Costa Rica. The aforementioned area of large rainfall amounts extends further offshore near the aforementioned countries, suggestive of a potential linkage to external processes and/or features that play a role in producing enhanced rainfall over land. For example, MCSs that develop in, and originate from, the Panama Bight have been shown in extreme cases to produce rainfall amounts that exceed the annual precipitation total for Costa Rica and Panama along their Pacific facing slopes, particularly during October.

Monthly rainfall amounts are spatially more homogenous in magnitude along the Caribbean coast of Central America during October when compared to September rainfall. Additionally, a relative maximum of rainfall along the Pacific facing slopes near Guatemala, El Salvador, and Nicaragua on the Pacific side is comparatively more localized ranging from 300–450 mm (Fig. 3.1b). During October, larger monthly rainfall amounts are confined to the region.
equatorward of 15°N. The aforementioned region depicts the rainfall in Costa Rica and Panama to be largest along the Pacific facing slopes and is fairly similar to the overall distribution of monthly rainfall observed in September. Larger rainfall amounts confined equatorward of 15°N during October is suggestive of a shifted convergence zone (i.e., ITCZ) that is associated with lower-tropospheric westerly winds along the Pacific facing slopes.

A stark decrease in November precipitation totals along the Pacific side of the orography is much less when compared to October (Fig. 3.1c). Despite the rapid decrease in monthly rainfall of approximately 300–500 mm from October to November along the Pacific facing slopes poleward of 10°N, monthly rainfall along the Caribbean facing slopes of Central America remains relatively unchanged. Additionally, monthly rainfall in November is relatively largest along the western slopes of the Caribbean mountains in Nicaragua, Costa Rica, and Panama when compared to the rest of autumn.

3.2 Characteristics of 95th Percentile Distributions

Among all months in autumn, daily rainfall values at the 95th percentile typically range from 20–60 mm and are characterized by a bimodal distribution (Fig. 3.2). The 95th percentile of all grid points in Central America during the autumn has a mean of 35.3 mm, median of 33.8 mm, and standard deviation of 8.12 mm. Within the bimodal distribution, two relative maxima are observed to occur at 31.8 and 40.6 mm, respectively, with a peak frequency of approximately 6.6% observed at 31.8 mm.

Throughout the autumn, daily rainfall exceeding the 95th percentile is generally largest along the Pacific and Caribbean slopes as suggested by the seasonal rainfall distribution (Fig. 3.3a). The relative maxima of daily rainfall exceeding the 95th percentile along the Pacific
(Caribbean) facing mountain slopes generally ranges from 28–44 mm (34–50 mm). Belize particularly exhibits the largest daily rainfall 95th percentile rainfall with some local areas exceeding 50 mm. In contrast, areas containing relatively lower daily rainfall amounts with less than 20 mm at the 95th percentile are generally observed directly over higher terrain.

In September, the daily rainfall exceeding the 95th percentile generally reflects the rainfall pattern observed throughout the autumn (Figs. 3.3a,b). September’s daily rainfall at the 95th percentile contains a mean of 26.6 mm, median of 26.6 mm, and standard deviation of 4.2 mm. Areas along the Caribbean slopes are comparatively less in daily rainfall extremes, particularly over Honduras. Nevertheless, the Pacific facing mountain slopes along much of the Central American coastline are characterized by rainfall values that are equivalent in magnitude to the 95th percentile of precipitation observed throughout all of SON.

The magnitude and distribution of daily rainfall at the 95th percentile is largest in October, which is consistent with the monthly rainfall climatology (Figs. 3.1b and 3.3c). October’s daily rainfall at the 95th percentile has a mean of 31.4 mm, median of 30.4 mm, and standard deviation of 5.8 mm. The relative maximum of daily rainfall generally exceeds values of 46 mm along all slopes poleward of 10°N; however, rainfall along the Pacific facing slopes equatorward of 10°N in Costa Rica and Panama are relatively larger than values exhibited in September.

Daily rainfall maxima at the 95th percentile is maximized along the Caribbean facing slopes during November (Fig. 3.3d). Though relatively less homogenous across Central America than October’s daily rainfall at the 95th percentile, November rainfall has a mean of 32.4 mm, median of 30.9 mm, and standard deviation of 10.5 mm. A relatively larger standard deviation of daily rainfall at the 95th percentile compared to September and October is owed to the relatively
enhanced rainfall amounts along the Central American coastline bordering the Caribbean Sea. Characteristically, the Pacific facing slopes are relatively similar in distribution and magnitude when considering the entire season holistically. Areas along western Nicaragua and throughout El Salvador, however, exhibit a lesser rainfall magnitude compared to October.

3.3 Monthly EPE Distribution

A total of 265 EPEs were observed throughout the constructed climatology using the methods outlined in section 2.1. On average, approximately eight EPEs occur each year with most EPEs occurring in October. EPEs have no observable trend throughout the climatology though there is some suggestion that a decadal oscillation may exist for October EPEs particularly (Fig. 3.4). For any given month in autumn, EPEs are observed to most frequently occur for one day. Consecutive days of EPEs are relatively less common and drop rapidly when comparing 1- and 2-day EPEs (Fig. 3.5). When comparing among all EPEs, 1- and 2-day EPEs make up 49.8% and 14.3% of the total number of events identified in the climatology, respectively. In general, October particularly contains the largest total number of EPEs when considering all EPE types cumulatively.

In their respective order, the total number of EPEs throughout the climatology are 57, 133, and 75 for September, October, and November respectively. As shown Fig. 3.4, seasonal variability is large when comparing among all years. For example, there are zero EPEs observed in 2013, which occurred within a 5-y period in which the total number of EPEs were low in value. The largest number of events exhibited in the climatology occurred in October 1998, which is largely attributed to TC Mitch, suggestive of the impacts of TCs on the observed EPE climatology.
Broken down by locality and month, EPEs are most often observed in eastern Guatemala, western Honduras, eastern El Salvador, and northern Nicaragua with respect to the total number of EPEs that occur within the September climatology (Fig. 3.6a). The aforementioned locations generally reflect areas that have lower daily 95th percentile rainfall values and occur along enhanced topography. Similarly, the aforementioned areas that contain higher frequencies of EPEs experience less than 150 mm of accumulated monthly rainfall and do not necessarily reflect relatively large rainfall compared to the overall daily 95th percentile distribution in September (Figs. 3.1a, 3.3b, and 3.6a). When considering the 95th percentile of daily rainfall, the areas experiencing the most frequent EPE activity in September receive at least 20 mm in cumulative rainfall for any given event. Nevertheless, when comparing the surrounding areas to the most frequently observed EPEs in September, locations along the Pacific and Caribbean slopes of western Honduras and Nicaragua exhibit a relative maximum as well at higher minimum amounts at approximately 37 mm.

The EPE frequency relative to the total number of October EPEs are observed more than 30% of the time in eastern Honduras and throughout much of western and northern Nicaragua (Fig. 3.6b). Minimum daily rainfall values of EPEs exceeding the 30% frequency typically range from 22–46 mm. Compared to September, areas along both the Pacific and Caribbean facing slopes experience EPEs are more frequent and are larger in rainfall magnitude. Similarly, unlike the observed September EPE frequency, EPEs are not observed over mountainous areas with lower 95th percentile values. When considering the EPE distribution holistically, most EPE frequencies exceeding 20% of the total number of October EPEs are generally widespread and observed within most countries except for Panama. A relatively homogenous distribution of EPE frequency exceeding 20% suggests that: 1) multiple processes or features may be inducing
widespread heavy rainfall, 2) one unique feature or process is playing a large role in facilitating a widespread EPE over most of the Central American region, or 3) a combination of both.

Upon transitioning into the cool season, November EPE activity is generally confined east of 85°W along the eastward-facing mountains along the Caribbean coastline, particularly along Nicaragua’s coastline bordering the Caribbean Sea (Fig. 3.6c). Despite large values of daily 95th percentile rainfall in November observed along the northern coastline of Central America, EPEs are more likely to occur further equatorward as suggested by November’s monthly rainfall distribution. Relatively less frequent EPE activity along all westward-facing mountains along the Pacific coast aligns with the rapid decrease of seasonal precipitation that generally occurs after October. Additionally, Costa Rica and Panama exhibit a notable increase in EPE activity, which agrees with the results shown by Rapp et al. (2014) for Costa Rica specifically. The higher EPE frequency of Costa Rica and Panama in November when compared to the EPE climatology of September and October suggests that a specific feature and/or process is either typically less common in earlier autumn to the surrounding area or influencing areas further poleward more often. In order to identify features and physical mechanisms responsible for the spatially changing EPE frequencies throughout the autumn, an investigation of the variables chosen in section 2 will be used to assess the linkages to heavy rainfall will be discussed in section 4.
FIG. 3.1. Map of monthly rainfall (shaded, mm) and topography (white contours, m(?)) and what is contour interval?) during 1983–2018 for (a) September, (b) October, and (c) November.
FIG. 3.2. The total distribution of rainfall across the Central American domain (see Fig. 2.2) at the 95th percentile of daily rainfall.

FIG. 3.3. The 95th percentile of daily rainfall (mm) for (a) SON, (b) September, (c) October, and (d) November.
FIG. 3.4. The total number of EPEs in SON during 1983–2018.

FIG. 3.5. The total number of EPEs that occur on consecutive days in SON during 1983–2018.
FIG. 3.6. A map of the relative frequency of EPEs that occur during (a) September, (b) October, and (c) November.
4. SOM Analyses

4.1 Multivariate SOM

As discussed in sections 2 and 3, 265 EPEs were observed and extracted to be used with SOMs during September – November from 1983–2018. Upon implementing SOMs as outlined in section 2.2, four nodes were chosen to organize the combined MSLP and PWAT standardized anomaly fields of the environment and illustrate the temporal evolution of EPE events. In respective order, Nodes 1–4 contained N = 29 (10.9%), N = 110 (41.5%), N = 105 (39.6%), and N = 21 (7.9%) EPEs (Fig. 4.1). When breaking down the SOMs intraseasonally, all nodes for SON predominantly occur in October as indicated in Figure 4.2. Though October dominates in frequency among all nodes, Nodes 4, 3, and 2 represent the largest relative frequencies for September, October, and November, respectively (Fig. 4.2). For example, for a given case in Node 2, one would expect a November EPE to occur at a higher frequency (N=34, 30.9%) when compared among Nodes 1, 3, and 4 which depict lower frequencies and number of cases. Nevertheless, the monthly frequency distributions among all nodes are roughly similar. Composites of the total events relative to each node centered at 1200 UTC are composited and interpreted using the selected variables mentioned in section 2.2 and are discussed below in detail.

4.2 SOM Composite Analyses

4.2.1 MSLP and PWAT

The combined MSLP and PWAT standardized anomaly fields used to organize all EPEs suggest an important linkage to westward-moving low pressure systems originating from the Caribbean Sea that are accompanied by above normal PWAT values depicted among all nodes.
The spatial extent and magnitude of the aforementioned westward-moving low pressure disturbances and accompanying above normal PWAT values, however, vary among all nodes throughout the evolution of an EPE (Figs. 4.3–4.7) Nodes 1 and 3 depict a broad, anomalous cyclonic circulation centered over Central America between \( t_0 - 48 \) h and \( t_0 \) (Figs. 4.3–4.5a,c). The aforementioned circulation is identical to CAG circulations discussed in section 1.2.1.3, which have been shown to be associated with above heavy rainfall across the region. Notably, westward-propagating disturbances appear to propagate into the CAGs, suggesting an enhancement to the broad cyclonic circulations by \( t_0 \). Nodes 1 and 3 depict MSLP and PWAT standardized anomalies that increase in magnitude over the region leading up to the onset of the EPE at \( t_0 \) (Figs. 4.3a,c and 4.3a,c). Nodes 2 and 4, nevertheless, depict an above normal PWAT signature confined equatorward of 15°N that generally increases in magnitude over a 48-h period (Figs. 4.3b,d and 4.4b,d). Additionally, below normal values of MSLP in the western Caribbean in Node 4 are associated with anomalous surface high pressure anomalies and lower PWAT anomalies in the Gulf of Mexico between \( t_0 - 48 \) h and \( t_0 \) (Figs. 4.3d–4.5d) unlike Node 2, which show a MSLP anomaly >0.25 throughout the domain. The anomalously low pressure in all nodes begins to weaken in amplitude and break down by \( t_0 + 24 \) h (Fig. 4.6). The low-pressure anomalies associated with evolving westward-propagating disturbances embedded within the broader low circulation propagate over land and positive PWAT anomalies transition into the EPAC in Nodes 1 and 3 (Fig. 4.6a,c). To a lesser extent, Node 4 depicts a similar evolution; however, the primary low moves northwest towards higher surface pressure observed in the Gulf of Mexico and a secondary low accompanied by positive PWAT anomalies forms in the EPAC at \( t_0 + 48 \) h near 95°W (Fig. 4.7d).
4.2.2 Precipitation

Large spatial variability is observed in the composited average EPE precipitation across Central America within each SOM node (Fig. 4.8). The spatial variability of precipitation associated with EPEs largely reflects the differences in the environmental conditions and their favorability towards producing orographically enhanced rainfall across the region. When comparing among all nodes, Nodes 1 (Fig. 4.8a) and 3 (Fig. 4.8c) depict precipitation maximized throughout Belize, Guatemala, Nicaragua, and western Costa Rica. In contrast, Nodes 2 (Fig. 4.8b) and 4 (Fig. 4.8d) depict a maximum of precipitation along the Caribbean facing slopes throughout most of the region. Notably, Node 3 shows much more uniform and widespread amounts of precipitation with exception to Panama, though that may be due to having the largest number of EPEs that potentially aliases the areas containing higher precipitation amounts (Fig. 4.8c).

The combined MSLP and PWAT standardized anomaly fields used to generate four modes of variability with SOMs and the accompanying regional precipitation patterns at $t_0$ suggest two dominant scenarios. The first scenario illustrated in both Nodes 1 and 3 depicts a broad cyclonic circulation centered over Honduras and Nicaragua at $t_0$ with widespread precipitation along the Pacific coast of Central America and along the northern Caribbean coastline bordering the Gulf of Honduras. In contrast, a second scenario depicted in Nodes 2 and 4 highlights low MSLP anomalies and above normal PWAT anomalies further south near Costa Rica with an indication of above normal surface high pressure over the Gulf of Mexico. Additionally, larger values of precipitation in scenario 2 are generally depicted over the Caribbean coastlines of Nicaragua and Costa Rica, suggestive of a direct influence from the aforementioned low-pressure anomalies. To better understand the two primary scenarios and
their evolutions, Nodes 1 and 3 and Nodes 2 and 4 will be grouped and categorized as “Scenario 1” and “Scenario 2”, respectively, hereafter using time-lagged composites as similarly shown in Figures 4.3–4.7.

4.2.3 Large-Scale 250-hPa Jet, 1000–500-hPa Thickness, and MSLP

To better understand the evolution of the regional scale features pertaining to MSLP anomalies depicted in Figures 4.3–4.7, large-scale time-lagged composites were constructed to examine the potential extratropical contribution towards EPEs as suggested by relevant large-scale phenomena discussed in section (Fig. 4.9). As previously discussed, Scenario 1 features a westward-moving surface low from the Caribbean Sea into a broad, anomalous surface low centered over Central America. The westward-moving surface lows are subsequently steered into either a purely westward or northwestward trajectory by the onset of the EPEs and make up a closed low of 1010 hPa and warm thicknesses of 576 dam in proximity to Central America. The aforementioned differences in steering are not obvious at the regional scale, though a more symmetric and weaker low-pressure anomaly exhibited in Node 1 when compared to Node 3 suggests a potential linkage to the strength of the initial surface circulation as the westward-moving surface low evolves and interacts with the downstream environment.

The low pressure centered over Central America leading up to t0 in Scenario 1 appears to be linked to the configuration of the Bermuda High as suggested by values of higher MSLP (> 1012 hPa) extending into the Caribbean Sea (Fig. 4.9a–f). The steering of the westward-moving low pressure systems in the Caribbean Sea is associated with a meridional surface pressure gradient of ~4 hPa along 25°N near the Gulf of Mexico and Caribbean Sea. Additionally, the aforementioned pressure gradient is associated with an extension of the Bermuda High in the
presence of a low-pressure anomaly centered over Central America (Figs. 4.6 and 4.9a–f). The variability of Scenario 1 as suggested by differences in MSLP at $t_0$ between Nodes 1 and 3 are associated with differences in the structures and magnitudes of the broad cyclonic circulation centered over Central America, the Bermuda High, and a Rossby-wave train along 50°N (Fig. 4.9e,f). The Rossby-wave train centered over Canada is associated with the formation of low-pressure systems over the Hudson Bay and Labrador Sea as depicted between $t_0 - 48$ h and $t_0$ (Fig. 4.9b,d,f). In Node 1 particularly, the aforementioned extratropical low-pressure systems are associated with strong thickness gradients over the north-central U.S. and south of Greenland. Additionally, upper-level jets (> 30 m s$^{-1}$) are depicted in the aforementioned enhanced thicknesses and are largest in magnitude south of Greenland. The depiction of a stronger Bermuda High within the equatorward exit region of the upper-level jet south of Greenland in Node 1 leading up to $t_0$ suggests the effects of localized subsidence over the Bermuda High that yields higher pressure in the tropospheric column and, thus, at the surface. While similar in pattern, Node 3 features surface lows over the Hudson Bay and south of Greenland, a Bermuda High, and an upper-level jet south of Greenland at a comparatively weaker magnitude between $t_0 - 48$ h and $t_0$. (Fig. 4.9a–f). After $t_0$, the aforementioned pattern is manifested as a progressive upper-level wave pattern in Node 1, while Node 3 depicts an upper-level jet that increases over the central U.S. Therefore, a Scenario 1 EPE suggests a potential linkage and sensitivity to the state of the Bermuda High and to baroclinic development along the midlatitude waveguide near the North Central U.S. and Atlantic, though the aforementioned linkages would need to be tested using statistical significance.

As suggested by Fig. 4.3, Scenario 2 exhibits above normal surface pressure and below normal PWAT anomalies near the Gulf of Mexico, particularly in Node 4. When examining the
large-scale evolution of Scenario 2 depicted in Fig. 4.10, Nodes 2 and 4 depict a western U.S. thermal ridge at $t_0 - 48$ h and a trough that develops and centers over the eastern US by $t_0$. (Fig. 4.10a–f). The wave packets depicted in the thickness fields are characterized by longer and shorter wavelengths in Nodes 2 and Node 4, respectively. Furthermore, Node 2 (Node 4) exhibits a weaker (stronger) thickness gradient over British Columbia (northeastern U.S.) compared to Node 4 two days prior to the onset of an EPE event (Fig. 4.10a,b). The aforementioned jet streak over British Columbia favors the formation of a thermal trough centered near 100°W by $t_0 - 24$ h in Node 4 and is associated with lower MSLP on the lee side of the Rockies near 90°W (Fig. 4.10d). In contrast, Node 2 depicts a widespread surface high over the central U.S. and a low-pressure system offshore of the Carolinas just downstream of the thermal trough centered over the eastern U.S. by $t_0$ (Fig. 4.10f). The difference in location of the aforementioned thermal troughs and their respective downstream surface lows is associated with differences in MSLP over the Gulf of Mexico with higher pressure entrenched against the Sierra Madre Oriental in Node 2 (Fig. 4.10f,h,j). Therefore, Scenario 2 suggests a key difference between Nodes 2 and 4 in not only the evolution of a surface high-pressure system that migrates equatorward along the Rockies, but the presence of a low-pressure system that plays a role in modifying the orientation of the localized MSLP gradient poleward of Central America.

4.2.4 Large-Scale 850-hPa Temperature and Wind Anomalies

To further assess changes in the MSLP and thickness fields, anomalous 850-hPa temperature and wind fields are examined to elucidate any potential linkages to large-scale patterns that influence the evolution of EPEs within each scenario. Similar to the Bermuda High depicted within the MSLP and thickness fields, Scenario 1 features higher 850-hPa geopotential heights (>156 dm) extending from the western Atlantic to the Southeast U.S. Notably,
anomalous easterlies (> 5 m s$^{-1}$) are depicted over the Caribbean Sea between $t_0 - 48$ h and $t_0$ (Fig. 4.11a–f). The aforementioned easterlies are more zonal and larger in magnitude between $t_0 - 48$ h and $t_0$ in Node 3 compared to Node 1, which are relatively weaker and more poleward oriented. The differences in easterlies between Nodes 1 and 3 correspond to an increase in geopotential heights over the western Caribbean is exhibited between $t_0 - 48$ h and $t_0$ in Node 1 while Node 3 depicts a slight reduction in geopotential heights for values > 156 dm. Likewise, lower geopotential heights (< 153 dm) extend over a larger area in the EPAC (140°W–80°W) and further poleward near 20°N in Node 3 when compared to Node 1, which depicts a smaller closed 153 dm low centered over Central America. The differences in geopotential height gradients between Nodes 1 and 3 over the EPAC leading up to the onset of the EPE are crucial for enhancing the low-level easterlies that steer any westward-propagating low pressure systems (Fig. 4.11e,f). An additional artifact of the larger meridional pressure gradient is the comparatively stronger gap wind observed over the Gulf of Tehuantepec, which is more enhanced in Node 3 and increases in magnitude throughout the evolution of the EPE (Fig. 4.11b,d,f).

As shown in section 4.2.4., Scenario 2 suggests the development of surface baroclinic cyclones downstream of eastward moving low-level troughs as depicted by the 850-hPa geopotential heights and temperatures leading up to the onset of the EPEs. The aforementioned troughs depict differences in phasing and depth, owed to the differences in the upstream ridges over the western U.S. (Fig. 4.12a–f). A key distinction of the upstream ridges in Scenario 2 is their associated 850-hPa temperature and geopotential height magnitudes that evolve from $t_0 - 48$ h to $t_0$. For example, Node 2 depicts above normal temperature anomalies and southerly flow upstream of the 850-hPa ridge while Node 4 features below normal temperature anomalies and
northerly flow near the crest of the ridge (Fig. 4.12a,b). By time $t_0$, the ridge in Node 2 weakens in amplitude while Node 4 features a ridge that weakens and rebuilds within a 48-h period, indicative of a more progressive pattern (Fig. 4.12e,f). Additionally, widespread below normal temperature anomalies ranging between $-0.25$ and $-0.75$ are observed over the eastern U.S. in Node 2 unlike Node 4 that depicts a rapid progression of cold air along the Rockies into the Gulf of Mexico associated with cold air damming along the Rockies (Fig. 4.12e,f). Nevertheless, cold air damming is exhibited throughout Scenario 2 but there is a suggestion of differences in the magnitude and relative advection of the cold air mass. The aforementioned differences in the effects of cold air damming are depicted after the onset of the EPE, which shows below normal temperature anomalies in the Gulf of Mexico and Bay of Campeche in Node 4 (Fig. 4.12h,j). The below normal temperatures in Node 2, however, weaken in magnitude by $t_0 + 48$ h within the Gulf of Mexico and Bay of Campeche (Fig. 4.12e,g,i).

4.2.5 Regional 850-hPa Equivalent Potential Temperature, Geopotential Heights, and Winds

The equivalent potential temperature ($\theta_e$) at low levels can be a useful proxy for detecting thermal boundaries where surface air temperature gradients may be relatively weak in both the subtropics and tropics. The $\theta_e$ can aid in identifying boundaries between tropical and extratropical air masses that contain strong moisture gradients since temperature gradients can be weak in the subtropics and tropics during SON. Similarly, $\theta_e$ incorporates sensible temperature as well as temperature variations due to latent heat release that aids in identifying areas where convection is playing a role in modifying the local thermal gradient across the region. EPEs are observed in areas over Central America where the $\theta_e$ at 850 hPa is relatively higher in magnitude ($> 340$ K) than the surrounding tropical airmass. The overall distribution of $\theta_e$ depicts warmer
air to the south and cooler air to the north of Central America, though the landmass induces zonal asymmetries in the $\theta_e$ distribution across the region (not shown).

At $t_0 - 48$ h, $\theta_e$ air masses exceeding 340 K are generally observed in the western Caribbean Sea and along the Caribbean coastlines of Nicaragua, Costa Rica, and Panama (Fig. 4.13a,b). The aforementioned air masses advect westward by $t_0 - 24$ h, though Node 1 within Scenario 1 exhibits a poleward motion of relatively high $\theta_e$ air and a lowering of 850-hPa geopotential heights centered over Nicaragua and eastern edge of Honduras (Fig. 4.13c,d). At the onset of the EPE events, the warmest $\theta_e$ air masses are observed along the Central American shorelines and over the entire Central American region, though to a lesser extent in Node 3 (Fig. 4.13e,f). More specifically, high $\theta_e$ values in Scenario 2 are concentrated near Costa Rica and Panama and lack a closed, cyclonic circulation as suggested by the 850-hPa wind fields (Fig. 4.14). A relatively cool $\theta_e$ air mass ranging from ~330–338 K between ~20–25°N is observed over the western Gulf of Mexico in Scenario 1, though the aforementioned $\theta_e$ air mass is comparatively higher in temperature when comparing to Scenario 2 that exhibits lower $\theta_e$ values ranging from ~326–332 K (Figs. 4.13e,f and 4.14e,f). Notably, Scenario 2 exhibits some spatial variability such that $\theta_e$ values < 328 K are observed poleward of 20°N in Node 2 and depict a broader distribution of both low $\theta_e$ air < 332 K and higher geopotential heights east of 90°W when compared to Node 4 (Fig 4.14e,f). By $t_0 + 48$ h, 850-hPa geopotential heights lower over the EPAC in Scenario 1 and form broad cyclonic circulations as indicated by the wind fields, particularly in Node 3 (Fig 4.13i,j). Scenario 2 does not depict the aforementioned broad circulations, however, Node 4 depicts $\theta_e$ values concurrently increasing by ~2 K in 48 h after the EPE onset over the Gulf of Honduras with an inverted trough associated with the northwest
movement of the embedded PWAT and MSLP anomalies originating from the Caribbean Sea (Fig 4.14i,j).

4.2.6 Regional 700-hPa Geopotential Height and Integrated Vapor Transport

Moisture transported from the regional low-level jets discussed in sections 1.2.1.1 and 1.2.1.2 is critical for the development of an EPE. Scenarios 1 and 2 depict enhanced integrated vapor transport (IVT) at the onset of EPEs over the Caribbean Sea where the highest values of IVT are embedded within a lower-tropospheric inverted trough. In the presence of relatively lower geopotential heights at 700 hPa and cyclonic flow centered over Central America or an enhanced meridional geopotential height gradient between 10°N and 25°N, low-level moisture can oftentimes become directed through the region’s mountain gaps as easterly flow from the Caribbean and westerly flow from the EPAC (see Figure 2.3 for geographical reference). The aforementioned moisture transport when associated with a cyclonic circulation centered over Central America aids in redirecting moisture from the EPAC into the Caribbean. Consequently, high IVT can then either be used to produce precipitation over terrain along the Pacific facing slopes or is transported efficiently through the topographic gap near the Gulf of Papagayo into the Caribbean Sea. When the 700-hPa geopotential height field is zonally oriented and its gradient is enhanced by higher pressure poleward of 20°N, EPEs in general are more likely to occur along the slopes facing the Caribbean.

As discussed in section 1.2.1.1, the CLLJ has been shown to act as a primary source of moisture transport for rainfall in Central America during SON. At t₀ – 48 h, all nodes exhibit the aforementioned source of moisture at mid-levels where the CLLJ maximizes and IVT is high in value, thus illustrating its role in providing the necessary conditions for EPEs to occur (Figs.
4.15a,b and 4.16a,b). Areas of high IVT begin to diverge spatially by $t_0 - 24$ h with Scenario 1 depicting most moisture transport further north as opposed to Scenario 2 that depicts a zonal moisture transport over the Caribbean Sea (Fig. 4.15c,d). Interestingly, the primary source of high IVT begins “branching” in all nodes by $t_0$ and provides secondary modes of transport due to land and topographic interactions that divert the low-level winds (Fig. 4.15e,f). For example, Scenarios 1 and 2 depict moisture transport in the form of IVT through the Chivela Pass and Nicaragua mountain gap into both the EPAC and Caribbean Sea (Figs. 4.15 and 4.16). Therefore, the aforementioned IVT is crucial for resupplying moisture to the Caribbean Sea from the EPAC and increases in magnitude as shown in Scenario 1 by $t_0$ unlike Scenario 2 that transports moisture from the Caribbean Sea to the EPAC (Figs. 4.15e,f and 4.16e,f). Between $t_0 + 24$ h and $t_0 + 48$ h, Scenario 1 depicts a more homogenous distribution of IVT values compared to $t_0$, which is indicative of a broad envelope of concentrated moisture contained within a cyclonic gyre circulation centered over Central America (Fig. 4.15g–f). In contrast, Scenario 2 primarily shows IVT decreasing in magnitude over the 24-h period after the onset of the EPE, though Node 2 depicts an IVT corridor split into two corridors of moisture transport, with one over the Caribbean facing slopes poleward of 15°N and the other into Gulf of Papagayo through the mountain gap in Nicaragua (Fig. 4.16g–f).

4.2.7 **Regional 700–500-hPa Layer-Averaged ascent, Relative Humidity, and Winds**

Areas throughout Central America favoring enhanced precipitation are generally associated with westward-propagating disturbances characterized by 700–500-hPa layer-averaged ascent $<-5 \times 10^{-3}$ hPa s$^{-1}$, RH $>80\%$, and areas where upslope lifting is favored along local terrain. The aforementioned areas can aid in identifying where sufficient vertical motion
and RH in the mid-troposphere (~700–500 hPa) produce precipitation when located in a conditionally unstable background environment.

A relatively confined region of enhanced 700–500-hPa layer-averaged ascent < \(-5 \times 10^{-3}\) hPa s\(^{-1}\) and RH > 80% in Scenario 1 is observed along the Caribbean coastlines of Costa Rica and Panama between \(t_0 - 48\) h and \(t_0\), suggesting the development and presence of deep convection (Fig. 4.17a–f). At a smaller magnitude than Scenario 1, an axis of 700–500-hPa layer-averaged ascent and RH in Scenario 2 is prominent along the Caribbean coastlines of Costa Rica and Nicaragua, and the Gulf of Honduras by \(t_0\) (Fig. 4.18a–f). Additionally, Scenario 2 exhibits comparatively drier air within the 700–500-hPa layer over the Caribbean Sea and for most areas poleward of 15°N. The mid-tropospheric variability depicted in both Scenarios 1 and 2 suggests a linkage to the poleward movement of westward-moving low-pressure anomalies poleward of 15°N after the EPE onset given that Nodes 1 and 4 (Figs. 4.17e,g,i and 4.18f,h,j) depict a poleward shift of vertical ascent and increased mid-level RH from the Caribbean Sea into the Gulf of Honduras unlike Nodes 2 and 3 (Figs. 4.17f,h,j and 4.18e,g,i). Though Node 1 corresponds to a similar signature of poleward shifted RH and mid-tropospheric ascent, the broad low-level cyclonic circulation depicted throughout Scenario 1 induces an opposite effect over the region after the EPE onset and depicts widespread values of combined enhanced RH and mid-tropospheric ascent along the entire Pacific coastline of Central America and over Belize (Fig. 4.17g–j). Similarly, while a westward-propagating disturbance is suggested in Node 2, areas of combined 700–500-hPa layer-averaged ascent and RH are relatively suppressed after the EPE onset, indicative of a short-lived EPE (4.18e,g,i). Therefore, the poleward (westward) migration of the western Caribbean originating disturbances in Scenario 1 (2) is associated with a relatively less widespread EPE.
4.2.8 Regional 850–600-hPa Layer-Averaged Cyclonic Relative Vorticity, Winds, and K-index

The westward-moving disturbances originating from the Caribbean Sea depicted within both Scenarios 1 and 2 are indicative of easterly waves or developing tropical cyclones. To acquire a better idea of the structure associated with each disturbance and the favorability for convection within downstream environment, the mid-level cyclonic relative vorticity structure and K-index are utilized. Adapted from Serra et al. (2010), the 850–600-hPa layer-averaged cyclonic relative vorticity was chosen to capture not only the cyclonic circulation associated with the westward-propagating disturbances, but any contributions of cyclonic relative vorticity within the environment downstream in proximity to Central America.

The K-index (George 1960), which has traditionally proved to be useful in short-term forecasting of thunderstorms, is defined as:

\[ \text{K-index} = (T_{850} - T_{500}) + T_{d, 850} - (T_{700} - T_{d, 700}). \]

The K-index was chosen as a suitable metric for considering the favorability of convection within a given environment since it considers the vertical temperature lapse rate and moisture within the mid-troposphere. The aforementioned variables are linked to the important role that thermodynamics can have in the tropics when considering changes in static stability near Central America. For example, the consideration of 700-hPa moisture, highlighted by the third term of the K-index equation, has been shown in the tropics to add skill for predicting convection (Caesar 2005) since it serves as a fair proxy for assessing buoyancy and dry air entrainment in the tropical mid-troposphere. Some limitations of its performance, however, have been observed over elevated terrain and in areas within the deep tropics where the index can be too spatially
homogeneous. Therefore, the aforementioned conditions are cautiously considered over the Central American landmass and compared to other metrics illustrated and discussed in section 4.2.7.

Scenario 1 is characterized by a regional scale cyclonic circulation within the mid-tropospheric at $t_0 - 48$ h and suggests an indication of a CAG circulation (4.19a,b). Similarly, a confined area of cyclonic relative vorticity is observed over the western Caribbean though there are differences in the structure of nearby cyclonic vorticity maxima between Nodes 1 and 3 (4.19a,b). The aforementioned differences are depicted by cyclonic vorticity near the Bay of Campeche in Node 1 while Node 3 depicts cyclonic vorticity over the Gulf of Tehuantepec as a result of shear vorticity induced by northerly gap winds through the Chivela Pass (4.19a,b). All cyclonic vorticity maxima are generally in regions of K-index values $> 26$ (or $>50\%$ likelihood of convection) which is indicative of a higher favorability environment for convection. By $t$, the maximum of cyclonic relative vorticity over the western Caribbean in Node 1 moves northwestward into an environment of K-index values $> 30$ and eventually moves over the Bay of Campeche by $t_0 + 48$ h where the feature becomes enhanced based on the increase in cyclonic relative vorticity (Fig. 4.19a,c,g,e,i). Similar to Node 1, Node 3 depicts a northwestward propagation of cyclonic relative vorticity that reaches the Gulf of Honduras and Gulf of Papagayo from the western Caribbean, though a closed circulation appears more robust offshore of Nicaragua in the EPAC within a deformation zone along $12^\circ$N (Fig. 4.19b,d,f,h,j). The aforementioned deformation zone, indicated by the 850–600-hPa layer-averaged wind field throughout the EPE, is associated with westerlies equatorward of $10^\circ$N and located within K-index values $>30$ (Fig. 4.19f,h).
Scenario 2 depicts the aforementioned characteristics of symmetric cyclonic relative vorticity structures over the western Caribbean between $t_0 - 48$ h and $t_0$; however, Node 2, which is associated with positive standardized MSLP and PWAT anomalies, does not depict the presence of an easterly wave (Fig. 4.20a–f). Additionally, the western Caribbean in Node 2 exhibits a maximum of cyclonic relative vorticity that is concentrated near $13^\circ$N as opposed to Node 4, which depicts a vorticity maximized near $10^\circ$N due to differences in the meridional geopotential height gradient. Nevertheless, the depiction of a westward-moving low-pressure system and poleward moving PWAT anomaly (> 0.75) as discussed in section 4.2.1 is well depicted within the cyclonic relative vorticity field particularly in Node 4 by $t_0$ (Fig. 4.20b,d,f).

Notably, the Gulf of Papagayo features increasing values of cyclonic relative vorticity between $t_0 - 24$ h and $t_0$ throughout Scenario 2; however, Node 4 depicts the presence of an organized low-pressure system offshore of Nicaragua in the EPAC as suggested by the cyclonic signature in the wind field (Fig. 4.20c–f). The cyclonic relative vorticity maxima depicted over the Gulf of Papagayo in Node 2 is associated with the easterly low-level gap winds induced by local topography (see Fig. 2.3 for geographical reference) due to horizontal wind shear. Thus, the depiction of a secondary low-pressure system in Node 4, as suggested by the cyclonic relative vorticity field and MSLP anomaly over the Gulf of Papagayo between $t_0$ and $t_0 + 48$, highlights a linkage to the cyclonic circulations originating from the western Caribbean. The aforementioned secondary tropical low formation is a key feature in the context of a widespread EPE as indicated by larger values of precipitation observed along the Pacific coastline of Nicaragua and Costa Rica when comparing Nodes 2 and 4 (Fig. 4.3b,d).

4.3 Linkages Among the SOM Composites
As discussed in section 4.2, westward-propagating disturbances manifested as low-pressure systems or above PWAT anomalies originating from the Caribbean Sea can largely influence the spatial distribution and likelihood for an EPE during SON. The evolution of the aforementioned westward-propagating disturbances manifested as low-pressure systems or areas of above normal PWAT appear to be largely governed by the relative timing, phasing, and presence of lower $\theta_e$ air and higher surface pressure in the Gulf of Mexico associated with early season extratropical originating cold surges. Since the presence of cooler and drier air along 20°N is inversely proportional to the higher surface pressure in proximity to Central America, the CLLJ strengthens due to an increased meridional pressure gradient and can act to induce enhanced rainfall along the Caribbean-facing slopes. Similarly, the aforementioned presence of cold surges during the autumn, though relatively weak when compared to cold surges in the winter, can act to increase lower-tropospheric stability and hinder the ability for deep convection to form. For example, Scenario 2 depicts strong mid-tropospheric vertical ascent ($<-5 \times 10^{-3}$ hPa s$^{-1}$) and high RH (> 80%) at the mid-levels along the shorelines of Central America below 15°N downstream of strong easterlies. Alternatively, Scenario 1 depicts a similar signature of the aforementioned features linked to the convergence of low-level westerlies (easterlies) from the EPAC (Caribbean) over land. It hypothesized that the initial cold surges observed during the autumn are relatively warmer and moister than those later in the season. We further hypothesize that the latitudinal extent of extratropical originating, low $\theta_e$ air is not only sensitive to the magnitude of the cold air mass itself but to the magnitude of the SST values over the Gulf of Mexico that acts to modify the low-level cool air through upward heat fluxes.

An interesting artifact of EPEs involves their association with CAGs without the presence of a strong cold surge. The CAGs depicted in Scenario 1 are centered over the Gulf of
Honduras and Nicaragua, respectively, at the onset of an EPE, which not only changes the local rainfall across the region but changes the development and evolution of westward-propagating disturbances embedded within the circulation. The CAG circulation coupled with the response of low-level winds in the presence of strong, cyclonic circulations provides a unique opportunity for increasing the likelihood of an occurrence of an EPE to occur across the region. The wind field in the EPAC reflects the indirect contribution on precipitation from westward-propagating disturbances through lower-tropospheric westerly and southwesterly flow over the EPAC, which is conducive for orographic upslope along the Pacific facing terrain. A consequence of the aforementioned westerly flow regime is the direct sensitivity and linkage to not only the strength of the CAG but the evolution of westward-propagating disturbances that initially develop in the Caribbean Sea and continue developing in the EPAC.

In summary, two scenarios of EPEs during the autumn can be extracted among all SOMs and are a function of the environmental large-scale circulation prior to EPE onset. As schematically illustrated in Figure 4.21, both scenarios feature westward-propagating disturbances in the Caribbean Sea that are carried westward by the CLLJ into Central America. The aforementioned westward-propagating disturbances diverge into multiple directions or further organize in multiple locations as they move into an environment associated with: 1) strong high surface pressure and low $\theta_e$ air observed over the Gulf of Mexico and northern Caribbean, or 2) an environment characterized by strong westerlies near 10°N in the EPAC and a CAG circulation centered near the Yucatan Peninsula and Nicaragua prior to the onset of an EPE.

In Scenario 1, the symmetry and strength of the initial CAG circulation two days prior to EPE onset initially governs the steering direction of the westward-propagating disturbance that
aids in the production of heavy rainfall. The strength and spatial extent of the aforementioned CAG circulation is partly dependent on the presence, magnitude, and latitude of cold air at low levels into the Gulf of Mexico and relatively higher lower-tropospheric pressure near Cuba. However, the discriminating feature that governs the motion of the westward-propagating disturbance in Scenario 1 appears to be the observed low-level westerlies along 10°N in the EPAC leading up to the onset of an EPE event. It is hypothesized that the low-level westerlies act as a mechanism for enhancing the CAG circulation before westward-propagating disturbances originating from the Caribbean Sea further enhance the CAG circulation.

Scenario 2 depicts a difference in magnitude of the low \( \theta_e \) air poleward of 20°N and does not exhibit a CAG circulation centered over Central America. Relatively higher surface pressure observed across the Gulf of Mexico is associated with westward-propagating disturbances that continue to move westward and weakly develop in the EPAC. However, westward-propagating disturbances tend to move northwest and decay near the Gulf of Honduras 48 h after EPE onset. Scenario 2 is similar to subtropical gyre formations which are consistent with findings discussed and shown by Molinari and Vollaro (2012), Crandall et al. (2014), and Papin et al. (2017).
FIG. 4.1. The partitioning and organized distribution of EPEs using SOMs.

FIG. 4.2. (left) The total frequency of EPEs throughout SON classified by each SOM node and (right) the relative frequency of total EPEs (N = 265) within each SOM node as defined by month.
FIG. 4.3. Multivariate SOMs of standardized MSLP (contours) and PW anomalies (shaded) valid 1983–2018 centered at 1200 UTC at $t_0 - 48$ h before EPE onset ($t_0$) defined relative to (a) Node 1, (b) Node 2, (c) Node 3, and (d) Node 4. Dashed (solid) contours represent negative (positive) anomaly values.

FIG. 4.4. As in Fig 4.3, but for $t_0 - 24$ h
FIG. 4.5. As in Fig 4.3, but for $t_0$

FIG. 4.6. As in Fig 4.3, but for $t_0 + 24$ h
FIG. 4.7. As in Fig 4.3, but for $t_0 + 48$ h
FIG. 4.8. The average EPE daily rainfall (mm) at $t_0$ defined relative to (a) Node 1, (b) Node 2, (c) Node 3, and (d) Node 4.
FIG. 4.9. Composited fields of mean sea level pressure (black contours, hPa), 1000–500-hPa thickness (blue/red dashed contours, dam), and 250-hPa wind speed (shaded, m s$^{-1}$) defined relative to Scenario 1.
FIG. 4.10. As in Fig. 4.9., except for Scenario 2.
FIG. 4.11. Composited fields of 850-hPa temperature (contours, °C), wind anomalies (vectors, m s⁻¹), and standardized temperature anomalies (shaded) defined relative to Scenario 1.
FIG. 4.12. As in Fig. 4.11., except for Scenario 2.
FIG. 4.13. Composited fields of 850-hPa geopotential heights (contours, dam), winds (barbs, m s$^{-1}$), and equivalent potential temperature (shaded, K) at $t_0 - 48$ h before EPE onset ($t_0$) defined relative to Scenario 1.
FIG. 4.14. As in Fig. 4.13., except for Scenario 2.
FIG. 4.15. Composited fields of 700-hPa geopotential heights (contours, dam) and IVT (shaded, kg m\(^{-1}\) s\(^{-1}\)) (vectors, kg m\(^{-1}\) s\(^{-1}\)) at \(t_0 - 48\) h defined relative to defined relative to Scenario 1.
FIG. 4.16. As in Fig. 4.15., except for Scenario 2.
FIG. 4.17. Composited fields of 700–500-hPa layer-averaged ascent (red contours, every $1 \times 10^{-3}$ hPa s$^{-1}$), relative humidity (shaded, %), and winds (barbs, m s$^{-1}$) defined relative relative to Scenario 1.
FIG. 4.18. As in Fig. 4.17., except for Scenario 2.
FIG. 4.19. Composited fields of 850–600-hPa layer-averaged cyclonic relative vorticity (blue contours, x 10^{-5} s^{-1}), winds (barbs, m s^{-1}), and K-index (shaded) defined relative to Scenario 1.
FIG. 4.20. As in Fig. 4.19., except for Scenario 2.
FIG. 4.21. Schematic of two primary scenarios of EPEs based on the SOMs used in this study. The two directions within each scenario that westward-propagating above normal precipitable water anomalies (black “L” symbol) typically migrate are represented by the gray filled arrows (green and blue outlines) based on the details described in section 4.2 and 4.3. Solid filled arrows and labels represent the lower-tropospheric wind fields linked to their associated features, respectively. The blue and green “H” and “L” symbols represent the variability and presence of higher surface pressure in relation to evolution of the lower-tropospheric above normal precipitable water anomalies.
5. Representative Case Study Analyses

5.1 Overview

Two representative case studies are analyzed to investigate the detailed evolution of Central American EPEs that correspond to Scenarios 1 and 2 as described in section 4. A representative Scenario 1 EPE features a Central American Gyre (CAG) circulation and the formation of embedded cyclonic disturbances over the EPAC and western Caribbean during 4–6 October 2018. Similarly, a representative Scenario 2 EPE during 18–19 November 2014 features the presence of an extratropical originating cold air surge that extends into the tropics. These case study analyses will examine the large- and regional-scale flow patterns that are associated with Scenarios 1 (i.e., Nodes 1 and 3) and 2 (i.e., Nodes 2 and 4) to better describe the dominant patterns and highlight hidden features and processes that are not depicted well in SOMs.

5.2 Representative Case Study of a “Scenario 1” EPE

5.2.1 Case Overview

During 4–6 October 2018, a widespread three-day EPE occurred in response to a CAG circulation that contained multiple mesovortices located in the Gulf of Honduras, Gulf of Papagayo, and western Caribbean. The aforementioned mesovortices were associated with a westward moving remnant of TC Kirk in the western Caribbean and subsequent formation of TC Michael in the western Caribbean (Fig. 5.1). More specifically, this EPE corresponded to Node 1 from 4–5 October and Node 3 on 6 October, which made it an ideal candidate for representing a Scenario 1 evolution as discussed throughout section 4. The EPE led to observed rainfall values exceeding 100 mm along the Pacific coastlines extending from Guatemala to Costa Rica and the Caribbean coastlines of Belize and Honduras (Fig. 5.2). Additionally, 12 fatalities and $100
million of economic losses in Central America were reported according to the European Union’s Directorate-General for European Civil Protection and Humanitarian Aid Operations (DG-ECHO) during the first week of October 2018.

5.2.2 Case Analysis

The equatorial background environment was influenced by an active MJO in phases 8 and 1 as defined by the RMM phase space leading up to the EPE (Fig. 5.3). An active MJO in phases 1 and 8 is manifested by as eastward propagating areas of anomalous 850-hPa westerlies across the North Pacific and negative velocity potential anomalies at 200-hPa, which are indicative of divergence aloft (Figs. 5.4 and 5.5). As suggested by previous studies discussed in section 1, heavy rainfall and TC development have been notably coincident with phases 1 and 8 of the MJO. In this case study, an EPE characterized by a “Scenario 1” evolution featuring a CAG circulation and within an active MJO is consistent with Papin et al. (2017) in which they showed that CAGs often form coincident with MJO phases 1, 2, and 8.

Beginning at 0000 UTC 26 September, the upper-tropospheric pattern was characterized by a “Rex” blocking pattern (Rex 1950) over the eastern North Pacific, which is depicted as an upper-tropospheric ridge located poleward of a closed, upper-tropospheric trough (Fig. 5.6a). Further downstream, a trough centered over the north central U.S. and a ridge over the subtropical western Atlantic was linked to the development of a downstream surface low that formed over the Labrador Peninsula (Fig. 5.6b). By 1200 UTC 28 September, anticyclonic wave breaking centered offshore of the eastern U.S. near 40°N formed a PV streamer that led to an elongation of 300–200-hPa PV that stretched from Cuba to the central Atlantic. The PV streamer contained westerlies (> 50 kt) along its southern flank over the Caribbean Sea (Fig. 5.7b), which
was centered over an area that exhibited lower-tropospheric easterlies (> 15 kt) (Fig 5.7a). The
aforementioned configuration led to an increase in vertical wind shear which inhibited further
development of TC Kirk that moved into the western Caribbean by 1200 UTC 28 Sep.

Leading up to the onset of the EPE, the aforementioned Rex block pattern over the EPAC
transitioned into a deep upper-tropospheric trough centered offshore of California and a previous
central U.S. trough beginning at 0000 UTC 26 September became replaced by a persistent upper-
tropospheric ridge over the eastern U.S. by 1200 UTC 1 October. The building eastern U.S. ridge
was associated with anticyclonic wave breaking that led to an injection of higher 300–200-hPa
PV beginning at 1200 UTC 3 October. The high PV became centered over the Gulf of Mexico
and contributed to upper-tropospheric westerlies (> 30 kt) along its equatorward flank over the
Gulf of Honduras by 0000 UTC 6 October (Fig. 5.8b) in proximity to an area of observed above
normal PWAT values (Fig. 5.8a). Thus, vertical wind shear increased to 60 kt over the Gulf of
Honduras providing a less favorable environment for TC development during the EPE valid 4–6
October (Fig. 5.8b). The vertical wind shear over the Gulf of Honduras gradually lowered in
value beginning 0000 UTC 7 October that contributed to an environment more favorable for
tropical cyclogenesis. By 0600 UTC 7 October, a tropical depression (TD) formed in the Gulf of
Honduras and moved poleward into the southeastern Gulf of Mexico. This TD was upgraded to
Tropical Storm (TS) Michael by 1200 UTC 8 Oct. The preceding evolution of the environment
in proximity to Central America was notably influenced by upper-tropospheric PV intrusions that
initially hindered the development for both TCs Kirk and Michael. Nevertheless, both PV
intrusions were not able to shut off TC development completely and only appeared to delay
organization as observed throughout the EPE.
Two days prior to the three-day EPE beginning on 4 October, an area of surface low pressure anomalies and above normal PWAT anomalies were observed over the western Caribbean and EPAC (Fig. 5.9a). In the Gulf of Mexico and western Caribbean, strong 850-hPa easterlies (> 20 kt) were observed within a geopotential height gradient of ~10 dm from 10–30°N (Fig. 5.9b). After the passing of Kirk’s remnants valid 0000 UTC 2 October into Nicaragua (Fig. 5.1), the aforementioned development of a low-pressure system appeared to occur by 1200 UTC 3 October as indicated by a −2σ contour over the Gulf of Papagayo (Fig. 5.9c,d). Further east, a broad area of below normal surface pressure in the western Caribbean and above normal PWAT were observed by 1200 UTC 3 October, thereby making up an envelope of two distinct low-pressure systems embedded within a broader cyclonic circulation across Central America (Fig. 5.9c,d). The evolution of the low-pressure system in the Gulf of Papagayo favored strong southerlies (>15 kt) on the eastern flank of the surface low pressure minima, which was critical for enhancing the aforementioned broad area of below normal surface pressure over the western Caribbean as depicted by multiple cyclonic relative vorticity maxima. The aforementioned cyclonic relative vorticity maxima embedded within the broad area of below normal surface pressure over the western Caribbean was enhanced and can be traced to a previous westward-propagating TC Kirk that degenerated by 0000 UTC 29 September, a few hundred miles south of the Virgin Islands (Fig. 5.1).

Further south over the Panama Bight, a large area of below normal PWAT anomalies (< 4σ) originating offshore of Peru near 10°S propagated poleward from 1200 UTC 2 October – 0000 UTC 5 October (Fig. 5.9a,c,e). The aforementioned air mass characterized by below normal PWAT anomalies contained dry air in the mid-tropospheric layer (~800–500-hPa) as depicted in the dewpoint depressions throughout this layer valid 1200 UTC 5 October (Fig. 5.10). An
An important artifact of the aforementioned dry air surge is the enhanced moisture and surface pressure gradient observed over Costa Rica beginning at 1200 UTC 4 October (Fig. 5.9e,f). As suggested by the 850-hPa wind field, the aforementioned moisture and surface pressure gradients were associated with strong 850-hPa southerlies (> 10 kt) east of 84°W over the EPAC. In conjunction with 850-hPa southerlies, IVT and moisture flux convergence (MFC) became enhanced over Costa Rica in a region characterized by K-index values (> 30), suggestive of a conducive environment for orographically induced precipitation (Fig. 5.13a,b). Downwind of the Panama dry air mass over the western Caribbean, an area of cyclonic relative vorticity increased where southerly flow at 850 hPa intersected easterly flow farther north valid at 1200 UTC 4 October (Fig. 5.9e,f). Similarly, relative vorticity over the Gulf of Papagayo became enhanced on the cyclonic shear side of strong EPAC 850-hPa southerlies (> 10 kt) and further enhanced by northeasterly 850-hPa winds (> 10 kt) through the Papagayo Gap (Fig. 5.9f).

By 1200 UTC 5 Oct, the 850–600-hPa layered-averaged relative vorticity exhibited two distinct circulations over the EPAC and western Caribbean within an envelope of negative
MSLP anomalies (< −1σ) and positive PWAT values (> 1) (Fig. 5.9i,j). As suggested by infrared satellite imagery (Fig. 5.10), deep convection was observed along the eastern flanks of the cyclonic 850–600-hPa layered-averaged relative vorticity circulations within areas characterized by enhanced MFC and IVT. Over the next 24 h, the aforementioned cyclonic circulations in the EPAC and western Caribbean moved northwest and were associated with a changed axis of enhanced precipitation from Costa Rica to the Pacific coastlines of Nicaragua and El Salvador. The northwestward transition of regional heavy rainfall was accompanied by a change in location of the most enhanced southwesterly 850-hPa flow (> 30 kt) in the EPAC valid 0000 UTC 6 October (Figs. 5.2d and 5.9k,l). Offshore of Nicaragua in the EPAC, the enhancement of 850-hPa southerlies was associated with enhanced values of IVT (> 700 kg m⁻¹ s⁻¹) through the Papagayo gap (Fig. 5.13c,d). Over the next 12 h, enhanced IVT across the Papagayo gap shifted northeast into the western Caribbean, suggestive of an additional source of moisture for the nearby closed cyclonic circulation centered over the Gulf of Honduras (Fig. 5.13e,f). By 0000 UTC 7 Oct, the cyclonic circulation over the western Caribbean strengthened over the Gulf of Honduras while the cyclonic circulation over the EPAC decayed and dissipated over the border of El Salvador and Nicaragua (Figs. 5.9m,n and 5.13g,h). Similarly, widespread rainfall along the Pacific coastlines of Central America rapidly decreased once the cyclonic circulation over the Gulf of Honduras became dominant and was subsequently classified as TC Michael.

5.3 Representative Case Study of a “Scenario 2” EPE

5.3.1 Case Overview

During 18–19 November 2014, a widespread two-day EPE was linked to a westward-propagating PWAT anomaly in the Caribbean Sea and an area of anomalous high surface
pressure over the western Caribbean and Gulf of Mexico. The aforementioned flow evolution led to widespread rainfall exceeding 150 mm observed predominantly along the Caribbean coastlines of Central America (Fig. 5.14). This EPE was only classified to Node 2 from 18–19 November 2014 as suggested by the presence of both a westward-propagating PWAT anomaly in the Caribbean Sea and above normal MSLP standardized anomalies throughout the domain. However, the EPE’s association with relatively high surface pressure anomalies in the Gulf of Mexico as depicted throughout the evolution of Node 4 signifies a qualitative “intersection” of the depicted features observed in both Nodes 2 and 4. Given that there are no observed EPEs exceeding one day that are attributed to both Nodes 2 and 4 (“Scenario 2”, Fig. 4.6b,d), this EPE serves as a suitable candidate for understanding a Scenario 2 evolution.

5.3.2 Case Analysis

Beginning on 0000 UTC November 16, the 1000–500-hPa thicknesses and 850-hPa geopotential heights over the subsequent 24 h depicted ridge building near the Gulf of Alaska and downstream trough formation over the central U.S.. Thermal ridge building over the Gulf of Alaska accompanied a 1038-hPa mean sea-level high-pressure system and below normal 850-hPa temperatures (< −2σ) over the Pacific Northwest (Fig. 5.15a–f). The anomalously cold air over the Pacific Northwest was advected equatorward and became entrenched against the eastern slopes of the Rocky Mountains, suggestive of cold-air damming adjacent to higher terrain. Further downstream, a 1032-hPa mean sea-level high-pressure system moved offshore of the northeast U.S. and 850-hPa geopotential heights increased over the western Atlantic. The consequential change in geopotential heights across the U.S. was linked to an enhancement of 850-hPa easterlies and southerlies over the western Caribbean and Gulf of Mexico, respectively.
The equatorward advection of cold air originating from the Pacific Northwest reached the Gulf of Mexico by 0000 UTC 18 November as thermal ridge building continued over the 48-h period preceding the EPE (Fig. 5.15g,h). Further downstream, above normal 850-hPa temperatures (> 1.5 σ) were observed over the western Caribbean and along the leading edge of the 15°C 850-hPa isotherm near the Bay of Campeche in association with the equatorward migrating surface high. Subsequently, a surface high associated with the advected cold air mass further extended into the Gulf of Mexico and began translating eastward and weakening in magnitude by 4 hPa between 0000 UTC 19 November and 0000 UTC 20 November (Fig. 5.15i–l). The evolution depicted during each 24-h period on 18 November and 19 November, respectively, suggest two primary transitions. On Day 1 of the EPE, cold air damming along the Rocky Mountains led to anomalously low 850-hPa temperatures along the Sierra Madre Oriental and western Gulf of Mexico upstream of above normal 850-hPa temperatures and easterly winds in the western Caribbean and Atlantic. During Day 2, enhanced gradients of MSLP and 850-hPa temperature both moved westward over the central Gulf of Mexico.

Nodes 2 and 4 featured a thermal ridge building centered over the western U.S. during the 48-h period preceding the EPE onset as also suggested by the Scenario 2 large-scale composites discussed in section 4. The evolution of the EPE case study in comparison to Nodes 2 and 4 depicts a similar but more enhanced ridge and warm air anomaly along the western U.S. and over Alaska, respectively, as suggested by the 850-hPa geopotential heights and temperatures (Figs. 4.12 and 5.15). The aforementioned configuration led to a widespread cold air outbreak across the entire U.S. and into the Gulf of Mexico during the evolution of the EPE, a characteristic featured in both Nodes 2 and 4 at lesser magnitudes both spatially and in intensity (Fig. 4.12e,f, 5.15h,j).
As depicted by the large-scale evolution, MSLP and 850-hPa geopotential heights increase over the western Atlantic between 0000 and 1200 UTC 16 November (Fig. 5.15a–d). The aforementioned increase in pressure across the western Atlantic corresponded to an increase of ~10 kt in 850-hPa easterly winds throughout the western Caribbean that become more zonally oriented. The enhancement of the western Caribbean easterlies is also accompanied by an increase of ~200 kg m\(^{-1}\) s\(^{-1}\) in IVT and ~15 in K-index values, corresponding to the observed westward-propagating positive PWAT anomaly (Fig. 5.17a–d). By 1200 UTC 17 Nov, the aforementioned positive PWAT anomaly increases spatially from the western Caribbean to the EPAC in an area characterized by K-index values > 27 and IVT > 300 kg m\(^{-1}\) s\(^{-1}\) (Figs. 5.16e,f and 5.17e,f). As suggested by the above normal 850-hPa temperatures and increased IVT in the western Caribbean, the corresponding increases in K-index suggest a moistening of the mid-troposphere (i.e., 700–850-hPa) and/or an increase in the vertical temperature lapse rate between 850 and 500 hPa.

Converging 850-hPa northerlies that are associated with increasing MSLP over the Gulf of Mexico and enhanced easterlies over the Caribbean Sea are observed in proximity to the Gulf of Honduras on 1200 UTC 18 November (Fig. 5.16g,h). Between 10°N and 15°N, a 10-kt increase in 850-hPa easterlies from 1200 UTC 17 November and 1200 UTC 18 November corresponds to an area of MFC and mid-tropospheric (i.e., 700–500-mb) ascent along the Caribbean slopes of Nicaragua and Costa Rica (Fig. 5.16g–j and 5.17g–j). By 1200 UTC 19 Nov, a shifted convergence zone of 850-hPa northerlies and easterlies becomes enhanced over the Gulf of Honduras within a broad area of above normal PWAT anomalies that extend along the leading edge of the 1σ MSLP anomaly contour in the western Atlantic (5.16i,j). Furthermore, enhanced MFC and mid-tropospheric ascent are concurrently observed along Caribbean
coastlines of Honduras and Costa Rica where upslope is favored within a convectively unstable environment (5.17i,j). The aforementioned MFC also coincides within an area of northerly IVT vectors observed along the Caribbean slopes of Belize and Honduras, suggestive of a potential importance of moisture transport from the Gulf of Mexico ahead of the equatorward and eastward moving cold air mass boundary. Thus, the aforementioned transition of MFC and PWAT depicted between Days 1 and 2 is largely governed by the relative locations of increased high pressure poleward of 15°N, which appears to govern not only the locations of enhanced moisture transport needed for widespread heavy rainfall but the preferential areas of converging anomalous northerlies in the Gulf of Mexico and easterlies in the western Caribbean.

As depicted in SOM Nodes 2 and 4, the initiation of the two-day EPE valid 18–19 November 2014 was characterized by a westward-propagating PWAT anomaly and above normal MSLP in the Gulf of Mexico, respectively. However, the westward-propagating PWAT anomaly is not accompanied by below normal MSLP in the western Caribbean. Rather, the EPE depicts increases in surface high pressure throughout the entire SOM domain, which likely made this two-day EPE purely assigned to Node 2 as opposed to both Nodes 2 and 4. Nevertheless, classification between Nodes 2 and 4 are sensitive to the magnitude and spatial extent of the surface pressure anomaly associated with the NH extratropical originating cold surge and the presence of a westward-propagating surface pressure anomaly in the western Caribbean.

5.4 Summary

The case study analyses provide a detailed evolution of the important features represented within two general patterns of EPEs in the autumn. Furthermore, the chosen representative case studies depict large variability in the context of both extratropical and tropical originating
features that influence Central American heavy rainfall during the autumn (Figs. 5.18 and 5.19). The representative cases also demonstrate and reflect the differences in rainfall distribution along the Pacific and Caribbean coastlines when comparing Scenarios 1 and 2, respectively.

The representative Scenario 1 EPE was generally characterized by the formation of a CAG and two tropical cyclonic circulations that indirectly enhanced the rainfall primarily the Pacific facing slopes of Central America. Preceding the EPE, the cyclonic circulation associated with the remnants of TC Kirk over the western Caribbean underwent two periods of weakening prior to, and at the onset of, the EPE due to the vertical wind shear induced by two nearby PV streamers. It is hypothesized that the cyclonic circulation in the Caribbean that interacted with high vertical wind shear prevented an earlier formation of a TC that would have likely overtaken the larger gyre circulation that formed earlier at the beginning of the EPE. Additionally, a distinguishing feature not found within the SOMs as discussed in section 4 was the presence of a dry air surge originating from the SH that was accompanied by enhanced lower-tropospheric southerly flow. The aforementioned southerlies associated with the SH dry air surge converged with easterlies over the western Caribbean, thereby leading to a lower-tropospheric convergence and subsequent cyclonic relative vorticity growth. Without the presence of a SH dry air surge, the formation of a CAG circulation and subsequent tropical cyclogenesis in the Gulf of Honduras would have been less likely to occur.

In contrast to the representative Scenario 1 EPE that was governed by the formation of cyclonic disturbances in the EPAC and western Caribbean, the evolution of the representative Scenario 2 EPE was largely governed by the evolution of the extratropical wave pattern. More specifically, the advection of a cold air mass traced temporally back to the Pacific Northwest appeared to reach the entire eastern U.S. and Gulf of Mexico during the EPE period. The
advection of this cold air mass was linked to continuous thermal ridge building observed near Alaska and the western U.S. between 1200 UTC 15 November and 0000 UTC 20 November 2014. Additionally, an important aspect of the representative Scenario 2 EPE is the relative change of the lower-tropospheric pressure over the western Atlantic as indicated by its relative increase in MSLP and 850-hPa geopotential heights throughout the 48-h period prior to the EPE onset. The lower-tropospheric pressure increased in magnitude within the equatorward exit region of a 250-hPa jet that formed in the Northeast U.S. in response to downstream baroclinic development that followed 1000–500-hPa thermal ridge building over western North America. Thus, this case study illustrates a unique opportunity during the latter end of autumn in which the combined influences of NH extratropical influences manifested in the form of a cold air surge and convective favorability in the tropics supported widespread heavy rainfall across Central America.
FIG. 5.1. The 6-hourly tracks of TCs Kirk and Michael as defined by HURDAT (circles and lines) and 850-hPa relative vorticity (contours, beginning at $4 \times 10^{-5}$ s$^{-1}$). The shading of the contours correspond to the dates shown in the colorbar.
FIG. 5.2. The cumulative EPE daily rainfall (mm) observed with PERSIANN-CCS-CDR valid (a) 4–6 October 2018, (b) 4 October 2018, (c) 5 October 2018, and (d) 6 October 2018.

FIG. 5.3. Phase diagrams of the Madden Julian Oscillation (MJO) valid 1 October 2018 – 31 December 2018. The axes (RMM1 and RMM2) represent daily values of the principal components from the two leading modes. Distance from the origin is proportional to MJO strength. Adapted from the Australia Bureau of Meteorology and the NOAA/OAR/ESRL PSD (http://www.bom.gov.au/climate/mjo/).
FIG. 5.4. (left) Anomalous 200-hPa velocity potential ($\times 10^6$ m$^2$ s$^{-1}$) and (right) 850-hPa zonal winds (m s$^{-1}$) averaged from 5$^\circ$N–15$^\circ$N using CFS analyses. Contours identify Kelvin wave (blue), equatorial Rossby wave (red), MJO (black), and a low frequency (purple) filtered anomalies. Contours are drawn at $\pm 3 \times 10^6$ m$^2$ s$^{-1}$ with the enhanced (suppressed) convective phase of these phenomena indicated by solid (dashed) contours. TCs are marked in red symbols. Adapted from Carl Schreck (https://ncics.org/pub/mjo/archive/).

FIG. 5.5. Anomalous 3-day averaged 850-hPa zonal winds (m s$^{-1}$) using CFS analyses. Black contours identify MJO filtered anomalies. Contours are drawn at $\pm 2 \times 10^6$ m$^2$ s$^{-1}$ with the enhanced (suppressed) convective phase of MJO indicated by solid (dashed) contours. TCs are marked in red symbols. Adapted from Carl Schreck (https://ncics.org/pub/mjo/archive/).
FIG. 5.6. (a) 500-hPa geopotential height (black contours, dam), temperature (red dashed contours, °C), wind (barbs, kt), and cyclonic relative vorticity. (b) 250-hPa wind speed (shaded, m s⁻¹), mean sea-level pressure (black contours, hPa), and 1000–500 hPa thickness (red/blue dashed contours, dam) valid 0000 UTC 26 Sep 2018. Adapted from Dr. Alicia Bentley (https://www.atmos.albany.edu/student/abentley/realtimes.html).

FIG. 5.7. (a) 350-K surface Potential Vorticity (shaded, PVU), pressure (black contours, hPa), and winds (barbs, kt). (b) 300–200-hPa layer averaged PV (gray contours, PVU), coupling Index (shaded, °C), 850–200-hPa vertical wind shear (barbs, kt), and low-pressure system minima (red text, hPa) valid 1200 UTC 30 Sep 2018. The green circles indicate the location of TC Kirk’s remnants and its proximity to an area of enhanced vertical wind shear. Adapted from Dr. Alicia Bentley (https://www.atmos.albany.edu/student/abentley/realtimes.html).
FIG. 5.8. As in Fig. 5.7, except the green circles indicate the location of TC Michael and its proximity to an area of enhanced vertical wind shear valid for 1200 UTC 6 Oct 2018. Adapted from Dr. Alicia Bentley (https://www.atmos.albany.edu/student/abentley/realtime.html).
FIG. 5.9. (left) Standardized MSLP (contours) and PW anomalies (shaded) valid 1200 UTC 2 Oct 2018. Dashed (solid) contours represent negative (positive) anomaly values. (right) Mean sea-level pressure (contours, hPa), 850-hPa relative vorticity (shaded, $x 10^5$ s$^{-1}$) and 850-hPa winds (barbs, kt) for (a,b) 1200 UTC 2 Oct 2018, (c,d) 1200 UTC 3 Oct 2018, (e,f) 1200 UTC 4 Oct 2018, (g,h) 0000 UTC 5 Oct 2018, (i,j) 1200 UTC 5 Oct 2018, (k,l) 0000 UTC 6 Oct 2018, and (m,n) 0000 UTC 7 Oct 2018. The surface elevation exceeding 500 m is depicted in gray shading.

Panama Sounding valid 1200 UTC 5 Oct

12Z 05 Oct 2018

University of Wyoming
FIG. 5.10. (top) An observed sounding from MPCZ Corozal site (location labeled as pink star). Adapted from University of Wyoming NWS Sounding Archive (https://weather.uwyo.edu/upperair/sounding.html). (bottom) GOES-16 Channel 13 (IR) Satellite Imagery valid 1235 UTC 5 Oct 2018 depicting convection in proximity to Central America. Adapted from TropicalTidbits.com. (https://www.tropicaltidbits.com)
FIG. 5.11. 144-h backwards trajectories beginning in the area confined within the green outlined box on 1200 UTC 5 Oct using CDC1 Reanalysis. Images from NOAA Hysplit Model.

FIG. 5.12. An area-averaged sounding using CFSR reanalysis valid 1200 UTC 5 Oct. The areal domain of the derived sounding is referenced in the green outlined box and specified in the image title.
FIG. 5.13. (left) Reanalysis of 850–600-hPa layer-averaged cyclonic relative vorticity (blue contours, $\times 10^{-5}$ s$^{-1}$) and K-index (shaded). (right) 700-hPa geopotential heights (contours, dm) and IVT (shaded, kg m$^{-1}$ s$^{-1}$) (vectors, kg m$^{-1}$ s$^{-1}$) for (a,b) 1200 UTC 4 Oct 2018, (c,d) 0000 UTC 6 Oct 2018, (e,f) 1200 UTC 6 Oct 2018, (g,h) 0000 UTC 7 Oct 2018, and (i,j) 1200 UTC 7 Oct 2018.

FIG. 5.14. As in Fig. 5.2, but valid 18–19 Nov 2014.
FIG. 5.15. (left) Analysis of mean sea level pressure (black contours, hPa), 1000–500-hPa thickness (blue/red dashed contours, dam), and 250-hPa wind speed (shaded, m s$^{-1}$). (right) 850-hPa temperature (contours, °C), wind speed anomalies (vectors, m s$^{-1}$), and standardized temperature anomalies (shaded) for (a,b) 0000 UTC 16 Nov 2014, (c,d) 1200 UTC 16 Nov 2014, (e,f) 0000 UTC 17 Nov 2014, (g,h) 0000 UTC 18 Nov 2014, (i,j) 0000 UTC 19 Nov 2014, and (k,l) 0000 UTC 20 Nov 2014.
FIG. 5.16. As in Fig. 5.9, except for (a,b) 0000 UTC 16 Nov 2014, (c,d) 1200 UTC 16 Nov 2014, (e,f) 1200 UTC 17 Nov 2014, (g,h) 1200 UTC 18 Nov 2014, and (i,j) 1200 UTC 19 Nov 2014.
FIG. 5.17. As in Fig. 5.13, except for (a,b) 0000 UTC 16 Nov 2014, (c,d) 1200 UTC 16 Nov 2014, (e,f) 1200 UTC 17 Nov 2014, (g,h) 1200 UTC 18 Nov 2014, and (i,j) 1200 UTC 19 Nov 2014.

FIG. 5.18. Multivariate SOMs of standardized MSLP (contours) and PW anomalies (shaded) centered at 1200 UTC at EPE onset composited relative to (a) Node 1 and (b) Node 3 that correspond to the EPE case study. Dashed (solid) contours represent negative (positive) anomaly values. (c) Temporally averaged MSLP (contours, hPa), PWAT (shaded) standardized anomalies, and 850-hPa winds that exceed 1σ (barbs, kts) from 1200 UTC 4–6 Oct 2018. Features of interest are depicted in schematic form.
FIG. 5.19. As in Fig. 5.18, except for (a) Node 2 and (b) temporally averaged from 1200 UTC 18–19 Nov 2014.
6. Discussion, Conclusions, and Suggestions for Future Work

The primary goals of this thesis were to: 1) capture and investigate the frequency, magnitude, and intensity of EPEs in Central America by constructing a climatology of all EPEs that occur in the autumn; 2) improve the understanding of extratropical and tropical interactions that produce EPEs in Central America through representative case study analyses of EPEs; and, 3) investigate the frequency and magnitude of the aforementioned interactions and dominant large-scale flow patterns that are linked to EPEs. Although numerous studies have examined the climate dynamics and teleconnections associated with above-normal precipitation during the wet season and the variability of specific phenomena that influence Central American rainfall, there have been very few studies that have examined the synoptic precursors and local flow patterns objectively that induce EPEs. While summertime variability has been the focus of considerable analysis, there has been much less attention on EPEs that occur during the autumn, a season characterized by the combined variability and interactions of both “cool” and “warm” season phenomena. Thus, this study takes a novel approach for objectively examining extreme rainfall in Central America during autumn using SOMs. Furthermore, this thesis aimed to better understand the underlying dynamic processes and features that may contribute to Central American EPEs from both a climatological and case-study perspective.

6.1 Discussion and Conclusions

6.1.1 EPE Climatology

To capture the intraseasonal variability of EPEs and their associative environments during SON, a criterion to capture extreme widespread daily rainfall across Central America was first formulated using the PERSIANN-CDR gridded dataset for the September–November 1983–
2018 time period. The EPE criterion was first defined by the exceedance of the 95th percentile for daily rainfall at each grid point located over Central America to capture a daily extreme. For observed daily rainfall amounts that exceeded the 95th percentile, an EPE was further classified by the exceedance of the 90th percentile of total grid points among all observed days that exceed the 95th percentile within the domain. The aforementioned criteria allowed us to objectively extract extreme rainfall days that exhibited widespread spatial extents.

The EPE extraction criteria identified a total of 265 EPEs throughout the climatology, which equates to approximately 8 EPEs on average observed in any given autumn. The total number of EPEs observed within each month are 57, 133, and 75 for September, October, and November, respectively. For any given month in autumn, EPEs are observed to most frequently occur during a one-day time period. When comparing among all EPEs, one- and two-day EPEs make up 49.8% and 14.3% of the total number of events identified in the climatology, respectively. October, on average, exhibited the largest number, areal spread, and frequency of EPEs across the entire Central American region by examining the spatial extent and variability among all EPEs relative to each month.

6.1.2 SOM Analyses

In order to better understand the synoptic precursors and environments conducive for EPEs, this thesis utilized SOMs, an unsupervised neural network (see section 2 for details) based on competitive learning used to project high-dimensional input data onto a lower dimensional space (i.e., a two-dimensional space in this thesis). The input data was derived from combined standardized PWAT and MSLP anomalies using the NCEP CFSR during EPE days centered at 1200 UTC over a Central American domain. Thus, the aforementioned combined input produced
a bivariate analysis that captured synoptic patterns using a 2 x 2 (i.e., 2 columns x 2 rows) SOM size. The 2 x 2 configuration was deemed sufficient for capturing enough detail to distinguish among different variations of the same regime while being manageable for physical interpretation.

Two primary patterns or “scenarios” emerged from SOMs when using a combined input variable to identify the intraseasonal variability of autumn. Nodes 1 and 3 were described as a “Scenario 1” pattern, which depicted negative MSLP and positive PWAT standardized anomalies over Central America. In contrast to “Scenario 1”, Nodes 2 and 4 were categorized as a “Scenario 2” pattern, which generally featured the presence of positive MSLP and PWAT standardized anomalies across and poleward of Central America. While Scenario 2 depicted a relatively larger variability of MSLP between Nodes 2 and 4 across Central America, the average daily EPE precipitation observed within each node depicted distributions that were nearly identical and provided further evidence of similar dynamic and thermodynamic influences. The variance of the MSLP was largely attributed to changes in the intensity or propagation of an extratropical-originating cold surge and the presence of a westward-moving developing low-pressure system in the western Caribbean. Thus, Scenarios 1 and 2 were intercompared and holistically described in context to their relative features and mechanisms associated with all autumn EPEs.

Daily time-lagged composite analyses were subsequently constructed for Scenarios 1 and 2 to better understand the EPE classification within all nodes of the 2 x 2 SOM configuration. The composites were first used to examine the associative large-scale features in North America and its vicinity that were linked to EPEs in Central America. As discussed in section 4.2, Scenarios 1 and 2 both depicted anomalous 850-hPa easterlies along the Caribbean Sea.
throughout the EPE event. The aforementioned easterly winds are consistent with previous studies that examined the local variability of above-normal precipitation wet seasons and local extremes identified with precipitation gauge data (Amador 1998; Amador et al. 2010; Cook and Vizy 2010; Maldonado et al. 2013). More specifically, lower-tropospheric (i.e., below 850 hPa) easterlies in the Caribbean Sea were shown to be a primary source of moisture transport for Central American rainfall during the autumn and linked to the variability of the Bermuda High. Furthermore, the strength and spatial extent of the Caribbean Sea easterlies is sensitive to the meridional MSLP gradient over the Caribbean, which is linked to the variability of higher lower-tropospheric surface pressure observed over the western Atlantic.

The geopotential height gradient near the Caribbean Sea is also sensitive to features or other air masses observed in proximity to Central America, such westward-propagating negative MSLP anomalies in the western Caribbean. Scenario 1 suggests a sensitivity to the local geopotential height gradient as it pertains to the presence of a westward-propagating negative MSLP anomaly in the western Caribbean. The westward-propagating negative MSLP anomaly is associated with anomalous 850-hPa easterlies near 20°N that act to promote a CAG circulation by EPE onset. The symmetry and strength of the initial CAG circulation prior to EPE onset also governs the steering direction of the westward-propagating disturbance that aids in the production of heavy rainfall. Under the influences of a CAG, a discriminating feature of Scenario 1 is the presence of lower-tropospheric (~850-hPa) westerlies along 10°N in the EPAC leading up to the onset of an EPE event. It is hypothesized that the low-level westerlies can act as a mechanism for enhancing the CAG circulation before westward-propagating disturbances originating from the Caribbean Sea can further enhance the CAG circulation. Additionally, the presence of westerlies in the EPAC led to the contribution of enhanced rainfall along the Pacific
coastline of Central America, a particularly discriminating precipitation pattern when compared to Scenario 2.

Scenario 2 generally depicts the combined presence of higher MSLP anomalies and negative 850-hPa temperature anomalies in the Gulf of Mexico. The magnitude and spatial extent of negative 850-hPa temperature anomalies in the Gulf of Mexico and the presence of negative MSLP anomalies in the western Caribbean near 10°N (i.e., contained in Node 4) are the leading discriminating features when examining the variability of Scenario 2. The magnitude and spatial extent of the negative 850-hPa temperature anomalies in the Gulf of Mexico are linked to the differences in the magnitude, location, and evolution of an upper-level ridge over the western U.S. and the EPAC and their associative negative 850-hPa temperature anomalies observed over the Pacific Northwest leading up to the EPE. The magnitude and spatial extent of the aforementioned 850-hPa temperature anomalies are linked to both the evolution of the upstream upper-level ridge and of subsequent cold-air damming, which is consistent with previous studies that investigated the impacts of varying cold air surges during the cool season in relation to precipitation over Central America (e.g., Reding 1992; Konrad 1996; Schultz et al. 1998).

6.2 Case Study Analyses

6.2.1 Overview

The 4–6 October 2018 and 18–19 November 2014 EPEs were chosen as representative cases to better define a standard evolution of both “Scenario 1” and “Scenario 2”. Recall that “Scenario 1” and “Scenario 2” are generally illustrative of CAG and North American cold surge patterns respectively. Representative case studies enable us to better understand and identify key weather features and dynamic processes that can be potentially aliased within the SOM.
composites. The two representative case analyses, manifested in the form of Scenarios 1 and 2, suggest an important linkage to the following aliased features: 1) mid-tropospheric tropospheric dry surges originating from the Southern Hemisphere (SH); 2) PV streamers induced by Rossby wave breaking that can inhibit or influence convection over Central America; and, 3) and “weak” cold surges originating from the Northern Hemisphere (NH) that are less revealing in Node 2 likely due to averaging over a larger sample size. The representative case studies additionally add context to the primary roles of the features identified within the SOM composites.

6.2.2 “Scenario 1” Case Study

The 4–6 October 2018 EPE was unique in that it was characterized as a three-day event made up of two separate SOM nodes (Nodes 1 and 3). The transition between Node 3 to Node 1 of the SOM extracted patterns during the 4–6 October 2018 EPE illustrated a scenario is which a broad cyclonic circulation centered over Central America was comprised of low-level cyclonic circulations centered in the EPAC and over the Gulf of Honduras. The EPE was followed and preceded by TCs Kirk and Michael, respectively, with an observed CAG circulation being the intermediate feature that was depicted within Scenario 1 of the SOM composites. Furthermore, the aforementioned low-level cyclonic circulation centered in the EPAC formed in response to a westward-propagating remnant of TC Kirk into the Gulf of Papagayo. As MSLP lowered over the Gulf of Papagayo, 850-hPa easterly gap winds were observed through Nicaragua that induced and promoted cyclonic vorticity growth on the cyclonic shear side of the gap winds. The development of the Papagayo cyclonic circulation was not only conducive for enhancing the southwesterly flow into Costa Rica that favored orographically driven rainfall, but subsequently
enhanced the integrated vapor transport from the EPAC to the western Caribbean prior to TC Michael’s formation.

6.2.3 “Scenario 2” Case Study

While the contribution of precipitation and temperature changes induced by cold surges in the region have been well explored during the NH cool season, the representative Scenario 2 EPE valid 18–19 November 2014 demonstrates an opportunistic period in which lower-tropospheric cold surges can promote widespread heavy rainfall when the mid-troposphere is characterized by higher moisture during the warm season. The widespread extreme rainfall observed in the Scenario 2 EPE was preceded by a moistening of the mid-troposphere over the western Caribbean, which was initially indicated by increased values of the K-index over Central America following an enhancement of IVT and MFC over the western Caribbean and Nicaragua respectively. Subsequently, moistening ahead of the cold surge boundary where 850-hPa easterly winds converged with northerlies originating from the Gulf of Mexico enabled a preferential axis of enhanced precipitation along the Central American coastlines bordering the Gulf of Honduras. As a result, the combined effects of enhanced mid-tropospheric moistening in the Caribbean, converging lower-tropospheric northerlies and easterlies, and orographic induced rainfall led to widespread heavy rainfall. Thus, this case study illustrates a unique opportunity during the latter end of autumn in which the combined influences of NH extratropical influences manifested in the form of a cold air surge and convective favorability in the tropics supported widespread heavy rainfall across Central America.

6.3 Suggestions for Future Work
EPEs in Central America were characterized by anomalous 850-hPa easterlies in the Caribbean Sea and a downwind CAG or cold surge feature as identified from SOMs (i.e., Scenarios 1 and 2). The aforementioned primary modes of variability during the autumn that govern EPEs are characterized by flow patterns that can be difficult to predict on deterministic time scales. More particularly, the location of anticyclonic Rossby wave breaking over the midlatitudes has been linked to the development of upper-tropospheric ridge building over the western North America, which is a common feature depicted in Scenario 2. Further downstream, anticyclonic Rossby wave breaking over the central U.S. as indicated in the representative Scenario 1 EPE case study can lead to PV streamers that extend into the Caribbean and Gulf of Mexico and increase the vertical wind shear over developing TCs as suggested by previous studies (e.g., Papin et al. 2020). Thus, future studies could further explore the linkage and nature of Rossby wave breaking over the extratropics as it potentially links to EPEs in Central America during the warm season.

The deterministic forecasts associated with widespread EPEs have not been well explored in Central America. Given the lack of abundant surface observations, an evaluation of EPEs can be relatively difficult from a predictability standpoint. However, the probabilistic occurrence of EPEs across Central America can likely be extracted and better predicted when considering the leading SOM patterns shown in Figure 4.3. For example, are the individual SOM nodes analyzed in this thesis less difficult to predict at longer lead times compared to other SOM nodes? In the context of synoptic features, it may be hypothesized that Scenario 1 will likely exhibit a higher forecast error due to the presence of TCs and other unorganized cyclonic circulations that are intrinsically more stochastic and have shorter predictability horizons when their associative cyclonic circulations can interact with one another or with the enhanced topography depicted
over Central America. Thus, additional analyses of the physical and forecast sensitivities to prominent features suggested in this thesis are needed to further explore the seasonality of the synoptic-scale flow evolution of EPEs.
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