Moisture Sources for Precipitation Associated With Major Hurricanes During 2017 in the North Atlantic Basin

Albenis Pérez-Alarcón1,2, Patricia Coll-Hidalgo1,3, José C. Fernández-Alvarez1,2, Rogert Sorí1,4, Raquel Nieto1, and Luis Gimeno1,2

1Centro de Investigación Maríta, Universidade de Vigo, Environmental Physics Laboratory (EPhysLab), Ourense, Spain, 2Departamento de Meteorología, Instituto Superior de Tecnologías y Ciencias Aplicadas, Universidad de La Habana, La Habana, Cuba, 3Empresa Cubana de Navegación Aérea, La Habana, Cuba, 4Instituto Dom Luiz, Faculdade de Ciências da Universidade de Lisboa, Campo Grande, Portugal

Abstract The 2017 North Atlantic tropical cyclone season was among the most active in the last two decades, with 17 named storms, of which six reached the major hurricane (MH) intensity: Harvey, Irma, Jose, Lee, Maria, and Ophelia. In this study, the water vapor sources for precipitation for these six MHs were examined using a Lagrangian approach. The particle dispersion model, FLEXPART, was used to identify moisture sources. Overall, the North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico were identified as the main moisture sources, supplying ∼75%–85% of the atmospheric humidity gained by tropical cyclones, which resulted in precipitation associated with the MHs. However, the South Atlantic Ocean also contributed considerable humidity (∼14%–20%), and the remaining ∼1%–5% originated from the tropical eastern Pacific Ocean. The accumulated moisture uptake higher than the 90th percentile generally appeared within approximately 3° to 5° of the TC trajectory.

1. Introduction

Tropical cyclones (TCs) can produce intense rainfall, and with storm surges can cause coastal flooding with serious societal impacts. The most significant disasters (Blake & Zelinsky, 2018; Cangialosi et al., 2021; Knabb et al., 2005; Pasch et al., 2006) caused by TCs are produced by major hurricanes (MHs), which are defined as TCs with maximum sustained (1 min) surface winds higher than 178 km/hr at any time during their lifetimes (including hurricanes categories ≥3 on the Saffir-Simpson Wind Scale).

The 2017 North Atlantic TC season was extremely active (Wachnicka et al., 2020), with 17 named storms, 10 hurricanes, and six MHs (the median was 12, 7, and 2, respectively, in 1980–2019). This increased activity occurred during La Niña and the warm phase of the Atlantic Multidecadal Oscillation. Three of these MHs made landfall at least once in their lifetime, causing ecological and human tolls, mainly due to heavy rainfall. Hurricane Harvey affected the coast of Texas in the United States (US; Blake & Zelinsky, 2018). Hurricane Irma affected the northern coast of Cuba and the southeastern US (Cangialosi et al., 2021). Hurricane Maria impacted several Caribbean islands, such as the US Virgin Islands and Puerto Rico (Pasch et al., 2019).

Dynamics and thermodynamics are factors that play an essential role in TC genesis and development (Emanuel et al., 2004). Among other factors, TC formation requires moist layers in the mid-troposphere to enhance thunderstorm formation (Emanuel, 1987; Gray, 1968). Several studies (Braun et al., 2012; Emanuel et al., 2004; Ge et al., 2013; Kimball, 2006; Tao & Zhang, 2014; Wang et al., 2009) have investigated the role of atmospheric humidity in TC development. Theoretical and modeling studies (Emanuel et al., 2004; Ge et al., 2013; Kimball, 2006) have suggested that high environmental moisture may favor TC intensification, and Hill and Lackmann (2009) highlighted that environmental moisture is a key factor contributing to TC size. However, substantial moisture may also negatively affect TC strength by facilitating the formation of TC outer rain bands, which reduces the horizontal pressure gradient in a TC (Tao & Zhang, 2014; Wang et al., 2009; Ying & Zhang, 2012).

Studies (e.g., Braun, 2006) have revealed that a majority of condensation occurs in convective hot towers in the eyewall, whereas vapor deposition and aggregation are dominant outside the eyewall. In addition, the ocean source for water vapor in the inner core of TCs is a small portion of the horizontal vapor import, as shown by Yang et al. (2011) using Typhoon Nari (2001) simulations, with a 2 km horizontal fine grid resolution. Additionally, dry air intrusions weaken TCs by favoring convection-driven downdrafts and associated boundary layer...
cooling (Dunion & Velden, 2004; Ge et al., 2013), and idealized simulations (Braun et al., 2012) show that only dry air near the vortex center leads to asymmetric convection and delays the development of the storm. In a 6-km grid simulation of Hurricane Andrew (1992), Zhang et al. (2002) demonstrated that horizontal advection tended to transport drier air from the outer region into the core in the marine boundary air. Moreover, some studies have investigated other components of the water budget linked with TC genesis and intensification, such as precipitation (Alvey et al., 2015; Tao et al., 2017; Wu & Chen, 2012), surface evaporation (Gao et al., 2016, 2017; Jaimes et al., 2015), and moisture flux convergence (Gao et al., 2017; Makarieva et al., 2017; Yin et al., 2015).

Precipitation associated with TC extends far from their core, with a large amount of precipitation in the spiral bands. Wu and Chen (2012) conducted sensitivity experiments to investigate the impact of ambient moisture content on TC related precipitations. Their findings revealed that the decrease in precipitation was controlled by a decrease in available moisture and a reduction in TC size. Makarieva et al. (2017) studied how the water vapor budget of a TC is dependent on its motion and showed that TC precipitation could not be fully explained by local evaporation. Furthermore, Montgomery and Smith (2017) stated that TC precipitation is mainly a product of the secondary circulation transporting moisture inward; thus, most of the precipitation is expected to occur as the TC intensifies. Notably, surface evaporation is proportional to the 10 m wind speed and sea surface temperature (SST; Gao et al., 2016, 2017); therefore, TC precipitation increases with an increase in SST and an increase in atmospheric humidity (Hill & Lackmann, 2009; Lin et al., 2015; Matyas, 2010). Kim et al. (2021) used satellite precipitation and reanalysis data and confirmed that environmental flows, SST, and humidity influence the inner-core rainfall and rainfall area along the TC trajectory.

Several studies have used Eulerian approaches to compute the water budget associated with TCs (e.g., Chauvin et al., 2017; Fritz & Wang, 2013, 2014; Gao et al., 2017; Makarieva et al., 2017; Vannière et al., 2020; Wu et al., 2013); however, several methods can be applied to investigate the origin of atmospheric moisture (comparative review by Gimeno et al. (2012)). Lagrangian approaches have proven powerful tools for identifying moisture sources and studying anomalous atmospheric moisture transport in global and regional studies (Knippertz et al., 2013; Miralles et al., 2016; Nieto et al., 2014; Stohl & James, 2004, 2005; Vázquez et al., 2020), meteorological systems such as extra TCs (Cloux et al., 2021; Liberato et al., 2012), or low-level jets and atmospheric rivers (Algarra et al., 2019, 2020; Braz et al., 2021; Ramos et al., 2016, 2019). However, these techniques have rarely been used for TCs. For example, they were to analyze two individual TCs in the Pacific. Xu et al. (2017) used a Lagrangian flexible particle dispersion model (FLEXPART, Stohl et al., 2005, 2016) to investigate the physical processes responsible for the torrential rainfall that occurred along the northernwestern Pacific coast of Japan during the landfall of Typhoon Nina in 2013. Similarly, Yang et al. (2017) analyzed the moisture sources for Typhoon Nina (in 1975) by using the Lagrangian analysis tool LAGRANTO developed by Sprenger and Wernli (2015) fed by downscaled Weather Research and Forecasting (WRF) model simulations. Pazos and Gimeno (2017) and Pérez-Alarcón et al. (2021a), also using the FLEXPART model, accounted for the water budget associated with all the TCs whose origin is over the eastern part of the North Atlantic Ocean basin (near the West African coast); both studies differ in the period analyzed (1979–2012 and 1980–2018, respectively), and in the definition of the target regions. Pazos and Gimeno (2017) defined the target region as a fixed box between 8°–20°N and 15°–45°W, and the whole area was analyzed when a TC occurred. Pérez-Alarcón et al. (2021a) used only the area enclosed by each TC outer radius at the moment of genesis. However, both studies analyze the search for moisture sources associated with TCs, but not for the moisture that finally generates precipitation. Regarding this last goal, Sodemann et al. (2008) proposed an approach to identify the moisture sources by discounting proportionally to all previous moisture uptakes (MUs) the precipitation in route. This methodology was applied to identify sources and transport pathways of precipitating waters of weather systems at a synoptic scale, such as extratropical cyclones (e.g., Papritz et al., 2021), but never for TCs.

Climate modeling studies (Knutson et al., 2015; Patricola & Wehner, 2018; Scoccimarro et al., 2014; Yoshida et al., 2017) have reported increased TC rainfall due to global warming. A relevant common factor in these studies is the projected increase in atmospheric humidity, which leads to enhanced moisture convergence and thus increases the rainfall rate. In addition, Kossin et al. (2020) suggested a positive trend in TC intensity with a warming climate. Therefore, based on climate projections, studying the water budgets of MHs is necessary to improve the knowledge of the influence of atmospheric humidity on the development of intense TCs.

Despite the observational and modeling studies of TCs, deepening the understanding of the moisture transported to TCs that finally produces precipitation is necessary. Thus, in this study, by applying the Lagrangian

Funding acquisition: Raquel Nieto, Luis Gimeno
Investigation: Albenis Pérez-Alarcón, Patricia Coll-Hidalgo, Rogert Sorí, Raquel Nieto, Luis Gimeno
Methodology: Albenis Pérez-Alarcón, José C. Fernández-Alvarez, Rogert Sorí, Raquel Nieto, Luis Gimeno
Project Administration: Raquel Nieto, Luis Gimeno
Software: Albenis Pérez-Alarcón, José C. Fernández-Alvarez
Writing – review & editing: Albenis Pérez-Alarcón, Patricia Coll-Hidalgo, José C. Fernández-Alvarez, Rogert Sorí, Raquel Nieto, Luis Gimeno

PÉREZ-ALARCÓN ET AL.
moisture source diagnostic method proposed by Sodemann et al. (2008), we investigated the moisture transport and sources that produced precipitation during the entire trajectories along their complete lifecycle of the six TCs that reached the MH category in the North Atlantic basin in 2017. In addition to improving the previous studies (e.g., Pazos & Gimeno, 2017; Pérez-Alarcón et al., 2021a), we assumed variable target regions defined by the outer radius of TCs in each position of each TC trajectory.

The remainder of this paper proceeds as follows. Section 2 describes the data set and the methodology used, namely the Lagrangian approach to computing the sources of moisture for TC. The results and discussion are presented in Section 3, and the conclusions are presented in Section 4.

### 2. Materials and Methods

#### 2.1. Data

Data on MHs in 2017 were obtained from the Atlantic hurricane database (HURDAT2; Landsea & Franklin, 2013) available online at the US Hurricane Center (NHC) web page (https://www.nhc.noaa.gov/data/#hurdat). This data set is a reanalysis effort to extend and revise the NHC’s North Atlantic hurricane database. Table 1 shows the features of the six MHs in the 2017 North Atlantic TC season. A brief description of the synoptic history of each MH is presented in Text S1 of Supporting Information.

Daily SST anomalies were extracted from the NOAA Daily Optimum Interpolation Sea Surface Temperature (OISST) data set v2.1 (Banzon et al., 2020), constructed by combining observations from different platforms (satellites, ships, and buoys) on a grid with 0.25° × 0.25° horizontal resolution.

The precipitation rate from the Global Precipitation Measurement (GPM; Huffman et al., 2019) was used. In this data set, the precipitation was estimated from the relevant satellite passive microwave sensors comprising the GPM constellation, computed using the Goddard profiling algorithm (Kummerow et al., 2015; Randel et al., 2020), and merged into a grid of half-hourly 0.1° × 0.1° horizontal resolution. Because the GPM precipitation data set has a higher horizontal resolution (0.1° × 0.1°) than the other data sets used, we regridded the GPM data using the nearest neighbor method (Chen et al., 2010) to the MU grid resolution (1° × 1°). In this study, we only considered the precipitation rate (R) related to TCs, which was defined as the R within the outer radius of the TC. The R calculation has been used in several studies (Guo et al., 2017; Jiang & Zipser, 2010; Larson et al., 2005; Prat & Nelson, 2013). The precipitation was computed for every 6 hr time step along the TC trajectories.

Furthermore, the integrated eastward and northward moisture fluxes, which were extracted from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-5 reanalysis data set, were used to compute the vertically integrated moisture flux (VIMF). In addition, surface evaporation data used to calculate the local evaporation within the TC outer radius along the trajectory were derived from the ERA-5 reanalysis. ERA-5 combines model data and worldwide observations into a global consistent data set using the laws of physics. Data are available on a latitude-longitude grid with a 0.25° horizontal resolution (Hersbach et al., 2020).

### 2.2. Methodology

#### 2.2.1. Lagrangian Identification of Moisture Sources for Precipitation

By neglecting the impact of mixing with adjacent air parcels and ignoring the presence of liquid water and ice in the atmosphere, moisture changes in an air parcel during a certain time interval (\(dt = 6\) hr) are controlled by evaporation (\(e\)) and precipitation (\(p\)) along the atmospheric particle trajectory (Stohl & James, 2004, 2005) throughout its changes in the specific humidity (\(q\)):

\[
\frac{dm}{dt} \approx m \left( \frac{\Delta q}{\Delta t} \right) = (e - p)
\]

**Table 1**

| TC name | Lifetime          | \(V_{max}\) (km/hr) | \(P_{min}\) (hPa) |
|---------|-------------------|----------------------|-------------------|
| Harvey  | 17 August to 1 September | 200                  | 937               |
| Irma    | 30 August to 12 September | 290                  | 914               |
| Jose    | 4 to 25 September   | 250                  | 938               |
| Lee     | 14 to 30 September  | 190                  | 962               |
| Maria   | 16 September to 2 October | 280                  | 908               |
| Ophelia | 6 to 17 October     | 190                  | 959               |

*Note. \(V_{max}\), maximum wind speed; \(P_{min}\), minimum central pressure.*
where \( m \) represents the mass of the air parcel (a particle).

For identifying the source of the parcels that produce precipitation in TCs, parcels were individually followed backward in time up to 10 days, which is considered the mean residence time of water vapor in the atmosphere (Numaguti, 1999; van der Ent & Tuinenburg, 2017). According to Läderach and Sodemann (2016), we only considered those parcels in which the specific humidity decreased more than 0.1 g/kg in the 6 hr before arrival at our target regions.

Backward trajectories of precipitant parcels were extracted from the global outputs of the FLEXPART v9.0 model (Stohl et al., 2005, 2016). The model was forced with the ERA-Interim reanalysis data set (Dee et al., 2011) at a resolution of 1° × 1° on the native ECMWF model levels. FLEXPART considers the atmosphere homogeneously divided into approximately 2 million uniformly distributed parcels, which are moved with 3D wind fields. Outputs are available every 6 hr at the initial grid resolution. According to Läderach and Sodemann (2016), the 6 hr-diagnostics preserve better than the 3 hr-diagnostic the consistency of the meteorological fields. Additionally, cycles of evaporation and precipitation within the TC occur quickly. However, outside TC circulation, evaporation and precipitation cycles occur at the time scale of typical tropical processes. Therefore, the 6 hr-diagnostics is suitable for our study because we are interested in the moisture changes of atmospheric parcels along their trajectories before reaching the TC circulation.

Our target regions were defined as the area enclosed by the outer radius of the best track position for each TC. Several authors (e.g., Kilroy & Smith, 2017; Lu et al., 2011; Wu et al., 2015) have used a radius of 34 kt (~17 m/s, R_{34kt}) as a metric for the TC size. However, by definition, R_{34kt} is available for TCs that reach the tropical storm wind force or higher. Likewise, the radius of the outermost closed isobar (ROCI) has been used as an estimation of the TC outer radius (e.g., Dean et al., 2009; Kimball & Mulekar, 2004; Wu et al., 2015). Nevertheless, as expected, values are missing for R_{34kt} and ROCI in the first and latest TC records. Recently, Pérez-Alarcón et al. (2021b) developed a new approach to estimate the TC outer radius by using the TC radial wind profile developed by Willoughby et al. (2006), which requires the maximum wind speed and TC position as input parameters. The outer radius was then defined as the radius at which the tangential wind speed estimated from the Willoughby et al. (2006) radial wind profile was equal to or less than 2 m/s Pérez-Alarcón et al. (2021b) also demonstrated that this estimated outer radius fits well with the outer radius estimated from the ERA-5 reanalysis. Therefore, because we were interested in analyzing the moisture source for all TC positions along its trajectory, we computed the TC size by applying the method of Pérez-Alarcón et al. (2021b). Notably, the cloud pattern of TCs provides a large amount of precipitation in the spiral bands of the system once they appear; thus, reducing the radius of the system would induce the possible loss of areas with convection and intense precipitation that largely depend on the adveded water vapor flux that feeds the TC. This fact would lead to underestimation and a less realistic identification of the sources of moisture associated with precipitation.

Although several studies (see Gimeno et al. (2020) and references therein) have used the water budget approach of Stohl and James (2004, 2005) to identify the origin of precipitation, one of the possible limitations of this method is that the precipitation in route between the sources and the target regions leads to a distorted picture of the source locations. Therefore, we followed the moisture source diagnostic method of Sodemann et al. (2008); see complete details in the cited paper. The moisture changes, based on the specific humidity \( q \) along each forward trajectory in time (from the end to the starting point of the backward trajectory), were assessed, and at a moisture loss location, all prior moisture contributions \( \Delta q > 0 \) to the air parcel were discounted in proportion to the moisture loss amount. Hence, the precipitation of the target area is the weighted sum of the prior uptakes (Sodemann et al., 2008). Therefore, the MU of all particles resulting in precipitation along their trajectories was computed as the sum of the moisture contributions over a specific grid cell \((1° × 1°), \text{in our study})\):

\[
MU = \frac{m \sum_{i=1}^{N} \Delta q'_i}{A}
\]

where \( m \) is the mass of the air parcel (assumed constant), \( N \) is the number of air parcels that crossed over a grid cell \((1° × 1°)\) of area \( A \) before arriving at the target region, and \( \Delta q' \) is the final moisture change (see Equation (7) of Sodemann et al. (2008)) of each parcel over \( A \).

In addition, over several days, an air parcel may undergo multiple cycles of evaporation and precipitation. Therefore, by applying the moisture source diagnostic method of Sodemann et al. (2008), we computed the moisture...
contributions of each evaporation location to the final moisture content of each parcel before it precipitates over the target region. Next, to estimate the moisture contributions for the precipitation related to the TC at each position, we averaged all moisture contributions over each grid cell of 1° × 1°. Finally, to gain a total point of view of the relative contribution of moisture sources to the TC precipitation along its trajectory, the moisture contributions for all TC positions were summed and then relativized concerning the maximum of that sum. A detailed example of how moisture source contribution was computed is provided in Text S2 of Supporting Information.

It is worth noting that the moisture contributions from the moisture sources were first calculated every 6 hr for each position of the TC trajectory according to the HURDAT2 database, and then, the accumulated MU as the sum of all MUs along the TC trajectory. As a moisture source can supply atmospheric humidity for the precipitation associated with the TC at several TC positions, we focused our attention on the moisture contributions for the total precipitation of the TC during its lifetime by estimating the accumulated MU.

3. Results and Discussion

The 2017 North Atlantic TC season was very active in terms of TC recorded, it was characterized by a developing moderate La Niña and its associated conditions, and by positive SST anomalies over the North Atlantic Ocean (Murakami et al., 2018). The SST anomaly composite during the 2017 TC season was 1.5 standard deviations above normal in the Main Development Region of Atlantic tropical cyclones, a 10°–20°N latitude belt stretching from North Africa to Central America (Gray et al., 1993). These factors were essential for TC intensification.

Murakami et al. (2018) also pointed out that five of the six TCs studied here (Harvey, Irma, Jose, Lee, and Maria) reached the MH intensity (green line over tracks in Figure 1) over warmer regions during their westward movement. Moreover, according to Stewart (2018), the rare and unusual strength of Ophelia (Figure 1f) was controlled by suitable environmental conditions for TC development. Positive SST anomalies along the trajectory of Ophelia contributed to the pronounced tropospheric lapse rates, supporting the development of vigorous deep convection (Stewart, 2018).

3.1. Spatial Distribution of Precipitation Rate

Precipitation within the outer radius of Hurricane Harvey (Figure 2a) during the first 6–7 days after genesis was small, with precipitation totals less than 45–80 mm. This may have been related to the weakening of Harvey into a tropical wave due to northerly wind shear during its movement through the Caribbean Sea (Blake & Zelinsky, 2018). Harvey reintensified over the Gulf of Mexico, and the accumulated precipitation ranged between 125 and 370 mm near the center (Figure 2a). After making landfall in Texas, the accumulated precipitation reached values higher than 620 mm. Previous studies (Emanuel, 2017) have reported that Harvey produced record levels of rainfall (~1219 mm) in the Houston metropolitan area.

Figure 2b shows the accumulated precipitation along the Irma trajectory. Although Irma was already an MH 48 hr after genesis, the accumulated precipitation was less than 80 mm close to the TC center during that period. After the hurricane reached its maximum intensity near the northern islands of the Lesser Antilles Arc, the precipitation totals reached values higher than 200 mm along the northern coast of Cuba, the Straits of Florida, and the Florida Peninsula. The Institute of Meteorology of Cuba reported an accumulated rainfall of over 250 mm, with the maximum (585 mm) observed in Topes de Collantes, followed by a second record in Sancti Spiritus (490 mm). Over the Florida Peninsula, the accumulated rainfall ranged from 250 to 380 mm, and the storm-total rainfall was ~560 mm, measured from September 9 to 12 (Cangialosi et al., 2021).

Hurricanes Jose (Figure 2c) and Maria (Figure 2d) exhibited similar patterns in terms of accumulated precipitation. Heavy rainfall over land from Jose was limited to portions of extreme southeastern Massachusetts, which reported a storm-total rainfall of ~172 mm at Nantucket Memorial Airport (Berg, 2018). In the case of Maria, according to Pasch et al. (2019), Dominica experienced torrential rains with a maximum total rainfall of 580 mm, and Puerto Rico recorded values close to 965 mm. Maria also produced heavy rains in Guadeloupe and parts of the Dominican Republic, with a total rainfall of ~250–330 mm.

Hurricane Lee (Figure 2e) traveled over the North Atlantic Ocean without making landfall. Accumulated precipitation during most of its trajectory was less than 120 mm. However, some cores ranging from 175 to 290 mm were observed. The accumulated precipitation of Ophelia (Figure 2f) was less than 125 mm during its movement...
to the northeast, although slightly higher precipitation totals were observed (150–200 mm), especially in the first days after its genesis. According to Stewart (2018), the remnants of Ophelia produced a total rainfall of less than 50 mm across Ireland and the United Kingdom.

#### 3.2. Identification of the Moisture Sources for Major Hurricanes in 2017

The accumulated MU along the trajectory of each MH reveals the main global moisture sources that result in precipitation (Figure 3). Except for Ophelia, the moisture sources were located over a wide band along the North Atlantic from 10°N to 30°N and longitudinally across the entire basin, extending westward over continental areas into the Sahel. Two marked additional branches completed this field, one from the north along the European and African coasts and another from the South Atlantic Ocean. In addition, the pattern over the southeastern US suggested that a recycling process within the outer radius contributed moisture to maintain the MH over the continent in the case of Harvey and Irma (Figures 1a and 1b).
Figure 3 also reveals that the maximum MU was detected near their trajectories when the TCs reached maximum intensity, unlike the regions close to the TC genesis where the contribution from moisture sources is lower. Again, Ophelia did not match this behavior, with maximum MU during the initial days after genesis. Notably, Ophelia also differs from the other MHs in its non-tropical origin (Text S1 of Supporting Information and Stewart, 2018).

According to Stewart (2018), Ophelia developed over marginal SSTs to TC intensification, but the mid-level temperatures being cooler than average favored deep convection.

Additionally, the VIMF fields plotted in Figure 3, accompanying the accumulated MU pattern, show that the moisture contribution from the North Atlantic basin was mainly due to the wind around the Bermuda-Azores High, and particularly intensified from the easterly winds along its southern branch and around it. The contribution
from the South Atlantic Ocean occurred through the northwestward branch of the South Atlantic high-pressure system (SAHS).

Furthermore, of all the TCs studied, Jose exhibited the most intense MU throughout its lifetime, reaching 32,086 mm, which computes to the 90th percentile of the accumulated MU. Maria and Harvey totaled 24,760 and 20,706 mm, respectively, and Irma (12,902 mm) showed a lower uptake. The accumulated MU higher than the

Figure 3. Accumulated moisture uptake (green colors, in mm) along the trajectory of each 2017 North Atlantic major hurricane (MH): (a) Harvey, (b) Irma, (c) Jose, (d) Lee, (e) Maria, and (f) Ophelia. The mean vertical integrated moisture flux (VIMF, kg/ms) from the ERA-5 reanalysis during the tropical cyclones (TCs) lifetime is represented as arrows. The red marker represents the tropical cyclone (TC) genesis location, the gray dashed line shows the trajectory, and the lifetime intensity of each TC is represented in shades of purples (data from HURDAT2 database). The blue line denoted the 90th percentile of the accumulated moisture.
90th percentile (blue contour in Figure 3) generally appeared within approximately 3° to 5° of the TC trajectory, but mostly occurred on the right side of the trajectory (which may be related to the anticlockwise circulation of TCs in the Northern Hemisphere). Previous research (Gao et al., 2017; Trenberth et al., 2007; Wang et al., 2015; Yang et al., 2011) has suggested that the ocean source for water vapor in the inner core is a small portion of the horizontal vapor input.

According to Makarieva et al. (2017), a TC first depletes available atmospheric moisture as it moves controlled by the large-scale flow in which it is embedded, while a moist flow proportional to the TC translation speed converges toward the TC position. This behavior could explain why along the trajectory of each TC, the areas of higher accumulated precipitation mostly coincide with areas of higher accumulated MU (Figures 2 and 3). Moreover, by comparing these patterns with the spatial distribution of accumulated evaporation from the ERA-5 reanalysis within the outer radius along the trajectory of each TC (Figure 4), the higher evaporation regions agree with the higher precipitation and MU areas. Nevertheless, as in the literature was suggested (e.g., Fritz & Wang, 2014; Huang et al., 2014; Makarieva et al., 2017; Yang et al., 2011), evaporation from local sources cannot fully explain TC precipitation. Indeed, the mean ratio between evaporation and precipitation within the outer radius along TC trajectory ranged from 0.43 (Maria) to 0.87 (Ophelia). We also found that this ratio decreased as the TCs intensified (not shown), which can be linked to the strengthening of the low-level convergence associated with the secondary circulation (Fritz & Wang, 2014). In other words, moisture was imported from the outer region (Figure 3).

As aforementioned, the tropical North Atlantic was the main moisture source for MHs that moved westward, but remarkable individual differences existed. The Gulf of Mexico is the most important moisture source for Harvey. The western North Atlantic contributed significantly to the moisture supply for Jose and Maria, and the central North Atlantic provided most of the moisture for Lee and Ophelia.

From Figure 5, the major part of moisture that originated the precipitation after the landfalling event of Harvey and Irma on Texas and Florida Peninsula, respectively, was of ocean origin. For Harvey (Figure 5a), the Gulf of Mexico and the Western Caribbean Sea were the main moisture sources. Nevertheless, the contribution of atmospheric humidity from the southern coast of the US suggested an important recycling process, while the contributions from distant sources were lesser extent. Similarly, for Irma (Figure 5b), the Caribbean Sea south of Cuba, the Straits of Florida, the seas at eastern Bahamas Archipelago, and the western North Atlantic Ocean close to the southeastern coast of US contributed more moisture to Irma's rainfall after landfalling on the Florida Peninsula than further away sources. Note that the MU of Harvey after landfalling was higher than Irma, which is in agreement with the highest accumulated precipitation generated by the former (see Figure 2).

3.3. Moisture Sources Contribution

The moisture contribution from each source region at each time step along the MH trajectories was quantitatively computed using the methodology of Sodemann et al. (2008). These values were added to each MH throughout its lifetime (Text S2 of Supporting Information). Figure 6 shows the percentage of the total SC. Our findings showed that the highest SC close to the trajectory occurred during the maximum intensification phase for the TCs, reaching values over 70% (blues). Based on Lagrangian analysis, for most TCs, the area within the outer radius contributed 35%–45% of the total moisture, while contributions from farther away were less than 30%. Figure 6 also reveals that the eastern tropical Pacific Ocean supplied 10%–20% of the moisture for Harvey. The moisture contribution from the South Atlantic Ocean (SATL) for all MHs accounted for 20%–30% of the total (except for Ophelia, which received no contribution). This result supports the findings of Pazos and Gimeno (2017) and Pérez-Alarcón et al. (2021a), who have identified the SATL as a moisture source during the TC genesis phase near the West African coast but did not quantify this value.

Furthermore, water vapor uptake from continental areas was not negligible. Moisture from the Sahel region accounted for 15%–30% for Irma and Lee but was lower for the remaining MHs (less than ~10%). The moisture supplied from continental North America was notable for Harvey (40%–65%) and Irma (~30%) during landfall, and for Jose (~25%) and Maria (~25%) during their parallel movement along the coast. Because Lee occurred far from the eastern coast of North America, land moisture contribution was less than 10%.
3.4. Assessment of the Lagrangian Moisture Source Uptake Diagnostic

The temporal evolution of MU and precipitation rate (R) during the lifetime of each MH indicates a close relationship between both quantities (Figure 7), as discussed. Both values were obtained using different methods. R was obtained from the GPM, and MU was obtained from the global outputs of the FLEXPART model.
However, these values had a statistically significant Pearson correlation ($p < 0.05$) for all MH except for Maria. The highest Pearson correlation coefficients were found for Irma (0.83) and Harvey (0.66), followed by Ophelia (0.59). For Lee and Jose, the correlations were lower but similar (0.43 and 0.40, respectively). Wu and Chen (2012) demonstrated that the decrease in precipitation of TCs could be explained by a reduction in the ambient water vapor content. As expected, a simple inspection of Figure 7 confirms that the precipitation of these TCs was mainly driven by the moisture supply. These relationships confirm the ability of the moisture source diagnostic method (Sodemann et al., 2008) to quantify and identify the origins of the atmospheric humidity that caused precipitation along the trajectory of TCs, independent of the complex thermodynamic and dynamic processes involved in TCs.

Additionally, no consistent relationships were found between MU and total precipitation before and after maximum intensity. Differences observed between the temporal evolution of the precipitation rate ($R$) and the MU that originated the precipitation can be attributed to neglecting the Lagrangian approach for the complex processes that cause moisture changes, such as convection, turbulence, numerical diffusion, and rainwater evaporation (Sodemann et al., 2008).

4. Summary and Conclusions

The 2017 North Atlantic TC season was one of the most active in the last two decades since 2000, with 17 named storms and 10 hurricanes, six of which reached the category of a MH. The six MHs followed three pathways: two (MHs Harvey and Irma) moved straightforwardly from the African coast to the Gulf of Mexico before recurving northward across the US coast, two (MHs Jose and Maria) recurved and bordered the US East Coast, and two (MHs Lee and Ophelia) recurved northward over the middle of the ocean and did not make landfall.

We analyzed the moisture sources that resulted in precipitation for the six 2017 MHs by using a Lagrangian approach. The particle dispersion model FLEXPART, along with the ERA-Interim reanalysis, was used to determine the moisture sources for each position of the best track of the MHs.
The main moisture sources for Harvey and Irma were the tropical North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico, providing approximately 85% of the total moisture. The western North Atlantic Ocean provided approximately 75%–80% for Jose and Maria. The central North Atlantic Ocean supplied similar amounts to Lee and Ophelia. In general, a higher MU was observed on the right side of the trajectory and during the maximum intensity phase of each TC. Additionally, on average, as a moisture source, the South Atlantic Ocean contributed ~14%–20%, and the tropical eastern Pacific Ocean contributed ~1%–5%. On average, higher MU occurred within approximately 3° to 5° of the TC trajectories.

Figure 6. Moisture sources’ contribution (in percent) during each 2017 major hurricane (MH) lifetime: (a) Harvey, (b) Irma, (c) Jose, (d) Maria, (e) Lee, and (f) Ophelia. The MH lifetime intensity is represented in blue-greens along the trajectory; the red marker represents the genesis location. All plots are from the first to last record of each MH in the HURDAT2 database.
Our results also reveal that the Lagrangian moisture precipitation source diagnostic method applied in this study is a suitable tool to provide useful information on the geographical position of these moisture sources and quantify precipitation from TCs. Nevertheless, this work analyzed six TCs and therefore does not provide a climatological view of the moisture sources of TC-related precipitation in this basin. In further research, a similar analysis should consider the total number of systems with different intensities over the Atlantic Ocean basin and focus on the contribution of TCs to the hydrological cycle over continents.
Data Availability Statement

The data sets used in this study are freely available on the internet. The Optimum Interpolation Sea Surface Temperature (OISST) data provided by the NOAA/NCDC were obtained from https://www.ncdc.noaa.gov/oisst, HURDAT2 database is accessible from https://www.nhc.noaa.gov/data/#hurdat, the ERA-5 reanalysis dataset was extracted from https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5, and the GPM data set is available at https://gpm.nasa.gov/data/directory. The FLEXPART model can be downloaded from https://www.flexpart.eu/wiki/FpRoadmap.

Acknowledgments

A.P.-A. acknowledges support from the UVigo PhD grants. J.C.F.-A. and R.S. acknowledge support from the Xunta de Galicia (Galician Regional Government) under grants No. ED481A2020/193 and ED481B2019/070, respectively. We acknowledge the funding for open access from the Universidade de Vigo/Consorcio Interuniversitario do Sistema Universitario de Galicia. This study received support from the LAGRIMA project (grant no. RTI2018-095772-B-I00) funded by the Ministerio de Ciencia, Innovación y Universidades, Spain and partial support from the Xunta de Galicia under the Project ED431C2021/44 (Programa de Consolidación e Estructuración de Unidades de Investigación Competitivas (Grupos de Referencia Competitiva) and Consellería de Cultura, Educación e Universidade). This work has also been supported by the computing resources and technical support provided by the Centro de Supercomputación de Galicia (CESGA). The authors also thank to Christopher W. Landsea and two anonymous reviewers for their comments and suggestions to improve the manuscript.

References

Algarra, I., Eiras-Barca, J., Nieto, R., & Gimenos, L. (2019). Global climatology of nocturnal low-level jets and associated moisture sources and sinks. Atmospheric Research, 229, 39–59. https://doi.org/10.1016/j.atmosres.2019.06.016

Algarra, I., Nieto, R., Ramos, A. M., Eiras-Barca, J., Trigo, R. M., & Gimenos, L. (2020). Significant increase of global anomalous moisture uptake feeding landfalling Atmospheric Rivers. Nature Communications, 11, 5082. https://doi.org/10.1038/s41467-020-18870-w

Alvey, G. R., Zawadzki, J., & Zipser, E. (2015). Precipitation properties observed during tropical cyclone intensity change. Monthly Weather Review, 143, 4476–4492. https://doi.org/10.1175/MWR-D-15-0065.1

Banzon, V., Smith, T., Steele, M., Huang, B., & Zhang, H.-M. (2020). Improved estimation of proxy sea surface temperature in the Arctic. Journal of Atmospheric and Oceanic Technology, 37(2), 341–349. https://doi.org/10.1175/JTECH-D-19-0177.1

Berg, R. (2018). National hurricane center tropical cyclone report: Hurricane Jose. National Weather Service: National Oceanic and Atmospheric Administration. Retrieved from https://www.nhc.noaa.gov/data/AL122017_Jose.pdf

Blake, E. S., & Zelenyuk, D. A. (2018). National hurricane center tropical cyclone report: Hurricane Harvey. National Weather Service: National Oceanic and Atmospheric Administration. Retrieved from https://www.nhc.noaa.gov/data/AL092017_Harvey.pdf

Braun, S. A. (2006). High-resolution simulation of Hurricane Bonnie (1998). Part II: Water budget. Journal of the Atmospheric Sciences, 63, 43–64. https://doi.org/10.1175/1520-0469(2006)063<0043:HRSOHB>2.0.CO;2

Braun, S. A., Sippel, J. A., & Nolan, D. S. (2012). The impact of dry mid-level air on hurricane intensity in idealized simulations with no mean flow. Journal of the Atmospheric Sciences, 69, 236–257. https://doi.org/10.1175/JAS-D-10-05007.1

Braz, D. F., Ambrizzi, T., Porfírio da Rocha, R., Algarra, I., Nieto, R., & Gimenos, L. (2021). Assessing the moisture transports associated with nocturnal low-level jets in continental south America. Frontiers in Environmental Science, 9, 108. https://doi.org/10.3389/fenvs.2021.657764

Cangialosi, J. P., Latto, A. S., & Berg, R. (2021). National hurricane center tropical cyclone report: Hurricane Irmia. National Oceanic and Atmospheric Administration. Retrieved from https://www.nhc.noaa.gov/data/AL12112017_Irmia.pdf

Chauvin, F., Douville, H., & Ribes, A. (2017). Atlantic tropical cyclones water budget in observations and CNRM-CM5 model. Climate Dynamics, 49, 4009–4021. https://doi.org/10.1007/s00382-017-3559-3

Chen, D.-L., Ou, T.-H., Gong, L., Xu, C.-Y., Li, W.-J., Ho, C.-H., & Qian, W. H. (2010). Spatial interpolation of daily precipitation in China: 1951–2005. Advances in Atmospheric Sciences, 27, 1221–1232. https://doi.org/10.1007/s00376-010-9151-y

Cloux, S., Garaboa-Paz, D., Insua-Costa, D., Miguez-Macho, G., & Pérez-Muñuzuri, V. (2021). Extreme precipitation events in the Mediterranean area: Contrasting Lagrangian and Eulerian models for moisture sources identification. Hydrology and Earth System Sciences, 25, 6447–6457. https://doi.org/10.5194/hess-25-6447-2021

Dean, L., Emanuel, K. A., & Chavas, D. R. (2009). On the size distribution of Atlantic tropical cyclones. Geophysical Research Letters, 36, L14803. https://doi.org/10.1029/2009GL040590

Dec, P. P., Uppala, S. M., Simmons, S. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society, 137, 553–597. https://doi.org/10.1002/qj.828

Dunion, J. P., & Velden, C. S. (2004). The impact of the Saharan air layer on Atlantic tropical cyclone activity. Bulletin of the American Meteorological Society, 85, 353–356. https://doi.org/10.1175/BAMS-85-3-353

Emanuel, K., DesAutels, C., Holloway, C., & Korty, R. (2004). Environmental control of tropical cyclone intensity. Journal of the Atmospheric Sciences, 61, 843–858. https://doi.org/10.1175/1520-0469(2004)061<0843:ECONAC>2.0.CO;2

Emanuel, K. A. (1987). The dependence of hurricane intensity on climate. Nature, 326, 483–485.

Emanuel, K. A. (2017). Assessing the present and future probability of Hurricane Harvey’s rainfall. Proceedings of the National Academy of Sciences, 114(48), 12681–12684. https://doi.org/10.1073/pnas.1716222114

Fritz, C., & Wang, Z. (2013). A numerical study of the impacts of dry air on tropical cyclone formation: A development case and a nondevelopment case. Journal of the Atmospheric Sciences, 70(1), 91–111. https://doi.org/10.1175/JAS-D-12-0181.1

Fritz, C., & Wang, Z. (2014). Water vapor budget in a developing tropical cyclone and its implication for tropical cyclone formation. Journal of the Atmospheric Sciences, 71(11), 4321–4332. https://doi.org/10.1175/JAS-D-13-0378.1

Gao, S., Zhai, S., Chen, B., & Li, T. (2017). Water budget and intensity change of tropical cyclones over the western North Pacific. Monthly Weather Review, 145, 3009–3023. https://doi.org/10.1175/MWR-D-17-0031.1

Gao, S., Zhang, W., Liu, J., Lin, L.-I., Chiu, L. S., & Cao, K. (2016). Improvement in typhoon intensity change classification by incorporating an ocean coupling potential intensity index into decision trees. Weather and Forecasting, 31, 95–106. https://doi.org/10.1175/WAF-D-15-0062.1

Ge, A., Li, T., & Peng, M. (2013). Effects of vertical shears and midlevel dry air on tropical cyclone developments. Journal of the Atmospheric Sciences, 70, 3859–3875. https://doi.org/10.1175/JAS-D-13-0608.1

Gimeno, L., Stohl, A., Trigo, R. M., Dominguez, F., Yoshimura, K., Yu, L., et al. (2012). Oceanic and Terrestrial sources of continental precipitation. Reviews of Geophysics, 50, RG4003. https://doi.org/10.1029/2012RG000389

Gray, W. M., Landsea, C. W., Mielke, P. W., Jr., & Berry, K. J. (1993). Predicting Atlantic seasonal tropical cyclone activity by 1 August. Weather and Forecasting, 8, 73–86. https://doi.org/10.1175/1520-0434(1993)008<0073:PASTBC>2.0.CO;2

Guo, L., Klingaman, N. P., Vidale, P. L., Turner, A. G., Demory, M.-E., & Cobb, A. (2017). Contribution of tropical cyclones to atmospheric moisture transport and rainfall over East Asia. Journal of Climate, 30, 3853–3865. https://doi.org/10.1175/jcli-d-16-0308.1
Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146, 1999–2049. https://doi.org/10.1002/qj.3803

Hill, K. A., & Lackmann, G. M. (2009). Influence of environmental humidity on tropical cyclone size. Monthly Weather Review, 137, 3294–3315. https://doi.org/10.1175/2009MWR2679.1

Huang, H., Yang, M., & Sui, C. (2014). Water budget and precipitation efficiency of typhoon Morakot (2009). Journal of the Atmospheric Sciences, 71(7), 112–129. https://doi.org/10.1175/JAS-D-13-053.1

Huffman, G., Stocker, E., Bolvin, D., Nelkin, E. & Tan, J. (2019). GPM IMERG early precipitation L3 half hourly 0.1 degree x 0.1 degree V06, green-belt, MD, Goddard Earth Sciences Data and Information Services Center (GES DISC). https://doi.org/10.5067/GPM/IMERG/3B-HH-E/06

James, B., Shyu, L. K., & Uhlhorn, E. U. (2015). Enthalpy and momentum fluxes during Hurricane Earl relative to underlying ocean features. Monthly Weather Review, 143, 111–131. https://doi.org/10.1175/MWR-D-13-00277.1

Jiang, H., & Zipser, E. J. (2010). Contribution of tropical cyclones to the global precipitation from eight seasons of TRMM data: Regional, seasonal, and interannual variations. Journal of Climate, 23, 1526–1543. https://doi.org/10.1175/2009JCLI3303.1

Kirilov, G., & Smith, R. K. (2017). The effects of initial vortex size on tropical cyclogenesis and intensification. Quarterly Journal of the Royal Meteorological Society, 143, 2832–2845. https://doi.org/10.1002/qj.3134

Kim, D., Ho, C., Murakami, H., & Park, D. R. (2021). Assessing the influence of large-scale environmental conditions on the rainfall structure of Atlantic tropical cyclones: An observational study. Journal of Climate, 34(6), 2093–2106. https://doi.org/10.1175/JCLI-D-20-0376.1

Kimball, S. K. (2006). A modeling study of hurricane landfall in a dry environment. Monthly Weather Review, 134, 1901–1918. https://doi.org/10.1175/MWR3155.1

Kimball, S. K., & Mulekar, M. S. (2004). A 15-year climatology of North Atlantic tropical cyclones. Part I: Size parameters. Journal of Climate, 17, 3555–3575. https://doi.org/10.1175/1520-0442(2004)017<3555:AACNO>2.0.CO;2

Knab, R. D., Rome, J. R., & Brown, D. P. (2005). National hurricane center tropical cyclone report: Hurricane Katrina. National Oceanic and Atmospheric Administration. Retrieved from https://www.nhc.noaa.gov/data/2005/Katrina.pdf

Knappertz, P., Wernli, H., & Glaser, G. (2013). A global climatology of tropical moisture. Journal of Climate, 26, 3031–3045. https://doi.org/10.1175/JCLI-D-12-04030.1

Knutton, T. S., Siriuti, J. J., Zhao, M., Tuleya, R. E., Bender, M., Vecchi, G. A., et al. (2015). Global projections of intense tropical cyclone activity for the late twenty-first century from dynamical downscaling of CMIP5/RCP4.5 scenarios. Journal of Climate, 28(18), 7203–7224. https://doi.org/10.1175/JCLI-D-15-0129.1

Kossin, J. P., Knapp, K. R., Olander, L. T., & Velden, C. S. (2020). Global increase in major tropical cyclone exceedance probability over the past four decades. Proceedings of the National Academy of Sciences, 117(17), 11975–11980. https://doi.org/10.1073/pnas.1902849117

Kumeneff, C. D., Randel, D. L., Kulie, M., Wang, N. Y., Ferraro, R., Munchak, J. S., & Petkovic, V. (2015). The evolution of the goddard atmospheric physics retrieval budget of a hurricane as dependent on its movement. Monthly Weather Review, 143, 216–230. https://doi.org/10.1175/MWR-D-14-00254.1

Lambert, A., & Sodemann, H. (2016). A revised picture of the atmospheric moisture residence time. Geophysical Research Letters, 43, 924–933. https://doi.org/10.1002/2015GL067449

Landsea, C. W., & Franklin, J. L. (2013). Atlantic hurricane database uncertainty and presentation of a new database format. Monthly Weather Review, 141(11), 3576–3592. https://doi.org/10.1175/MWR-D-12-00254.1

Larson, J., Zhou, Y., & Higgins, R. W. (2005). Characteristics of landfalling tropical cyclones in the United States and Mexico: Climatology and interannual variability. Journal of Climate, 18, 1247–1262. https://doi.org/10.1175/JCLI3117.1

Liberato, M. L. R., Ramos, A. M., Trigo, R. M., Trigo, I. F., Durán-Quesada, A. M., Nieto, R., & Gimeno, L. (2012). Moisture sources and large-scale dynamics associated with a flash flood event. In J. Lin, D. Brunner, C. Gerbig, A. Stohl, A. Luhar, & P. Webley (Eds.), Lagrangian modeling of the atmosphere. American Geophysical Union. https://doi.org/10.1029/2012GM001244

Lin, Y., Zhao, M., & Zhang, M. (2015). Tropical cyclone rainfall area controlled by relative sea surface temperature. Nature Communications, 6, 6591. https://doi.org/10.1038/ncomms7591

Lu, X., Yu, H., & Lei, X. (2011). Statistics for size and radial wind profile of tropical cyclones in the western North Pacific. Acta Meteorologica Sinica, 25, 104–112. https://doi.org/10.1007/s13351-011-0008-9

Makarieva, A., Gorschkov, V. G., Nefiodov, A. V., Chikunov, A. V., Sheil, D., Nobre, A. D., & Li, B. L. (2017). Fuel for cyclones: The water vapor budget of a hurricane as dependent on its movement. Atmospheric Research, 193, 216–230. https://doi.org/10.1016/j.atmosres.2017.04.006

Mania, C. J. (2010). Associations between the size of hurricane rain fields at landfall and their surrounding environments. Meteorology and Atmospheric Physics, 106, 135–148. https://doi.org/10.1007/s00757-009-0056-1

Miralles, D. G., Nieto, R., McDowell, N. G., Dorigo, W., Verhoest, N. E. C., Liu, Y. L., et al. (2016). Contribution of water-limited ecoregions to their own supply of rainfall. Environmental Research Letters, 11, 124007. https://doi.org/10.1088/1748-9326/11/12/124007

Montgomery, T. M., & Smith, R. K. (2017). Recent developments in the fluid dynamics of tropical cyclones. Annual Review of Fluid Mechanics, 49, 541–574. https://doi.org/10.1146/annurev-fluid-010816-060022

Murakami, H., Levin, E., Delworth, T. L., Guglert, R., & Hsu, P.-C. (2018). Dominant effect of relative tropical Atlantic warming on major hurricane occurrence. Science, 362, 794–799. https://doi.org/10.1126/science.aat6711

Nieto, R., Castillo, R., Drumond, A., & Gimeno, L. (2014). A catalog of moist sources for continental climatic regions. Water Resources Research, 50, 532532. https://doi.org/10.1002/2013WR013901

Numaguti, A. (1999). Origin and recycling processes of precipitating water over the Eurasian continent: Experiments using an atmospheric general circulation model. Journal of Geophysical Research, 104, 1957–1972. https://doi.org/10.1029/1998JD900026

Papritz, L., Aemisegger, F., & Wernli, H. (2021). Sources and transport pathways of precipitating waters in cold-season deep North Atlantic cyclones. Journal of the Atmospheric Sciences, 78(10), 3349–3368. https://doi.org/10.1175/JAS-D-21-01051.1

Patricola, C. M., & Wehner, M. F. (2018). Anthropogenic influences on major tropical cyclone events. Nature, 563, 339–346. https://doi.org/10.1038/s41586-018-0673-2

Pazos, M., & Gimeno, L. (2017). Identification of moisture sources in the Atlantic Ocean for cyclogenesis processes. Proceedings of the 1st International Electronic Conference on Hydrological Cycle (CogHyCle-2017) (Vol. 1). Sciforum Electronic Conference Series. https://doi.org/10.3390/cyclone-2017-04882
Pérez-Alarcón, A., Sori, R., Fernández-Alvarez, J. C., Nieto, R., & Gimeno, L. (2021a). Moisture sources for tropical cyclones genesis in the coast of West Africa through a Lagrangian approach. *Environmental Sciences Proceeding, 4*, 3. https://doi.org/10.3390/esac2020-08126

Pérez-Alarcón, A., Sori, R., Fernández-Alvarez, J. C., Nieto, R., & Gimeno, L. (2021b). Comparative climatology of outer tropical cyclone size using radial wind profiles. *Weather and Climate Extremes, 33*, 100366. https://doi.org/10.1016/j.wace.2021.100366

Prat, O. F., & Nelson, B. R. (2013). Mapping the world’s tropical cyclone rainfall contribution over land using the TRMM Multi-satellite Precipitation Analysis. *Water Resources Research, 49*, 7236–7254. https://doi.org/10.1002/wrcr.20527

Ramos, A. M., Blamey, R. C., Algara, I., Nieto, R., Gimeno, L., Tomé, R., et al. (2019). From Amazonia to southern Africa: Atmospheric moisture transport through low-level jets and atmospheric rivers. *Annals of the New York Academy of Sciences, 1456*, 217–230. https://doi.org/10.1111/nyas.13960

Ramos, A. M., Nieto, R., Tomé, R., Gimeno, L., Trigo, R. M., Librero, M. L. R., & Lavers, D. A. (2016). Atmospheric rivers moisture sources from a Lagrangian perspective. *Earth System Dynamics, 7*, 371–384. https://doi.org/10.5194/esd-7-371-2016

Randel, D., Kummerow, C., & Ringerud, S. (2020). The Goddard Profiling (GPROF) precipitation retrieval algorithm. In V. Levizzani, C. Kidd, D. Kirschbaum, C. Kummerow, K. Nakamura, & F. Turk (Eds.), *Satellite precipitation measurement* (pp. 141–152). Springer. https://doi.org/10.1007/978-3-030-24568-9_8

Scoccimarro, E., Guidi, S., Villarini, G., Vecchi, G. A., Zhao, M., Walsh, K., & Navarra, A. (2014). Intense precipitation events associated with landfalling tropical cyclones in response to a warmer climate and increased CO2. *Journal of Climate, 27*(12), 4642–4654. https://doi.org/10.1175/JCLI-D-14-00065.1

Sodemann, H., Schwierz, C., & Wernli, H. (2008). Interannual variability of Greenland winter precipitation sources: Lagrangian moisture diagnostic and north Atlantic oscillation influence. *Journal of Geophysical Research, 113*, D03107. https://doi.org/10.1029/2007JD008903

Sprenger, M., & Wernli, H. (2015). The LAGRANTO Lagrangian analysis tool-Version 2.0. *Geoscientific Model Development, 8*, 2569–2586. https://doi.org/10.5194/gmd-8-2569-2015

Stohl, A. (2015). *The Lagrangian analysis of the atmospheric branch of the global water cycle*. Part I: Method description, validation, and demonstration for the August 2002 flooding in central Europe. *Journal of Hydrometeorology, 5*, 6562–6678. https://doi.org/10.1175/JCLI-D-11-00463.1

Stohl, A., & James, P. A. (2004). Lagrangian analysis of the atmospheric branch of the global water cycle. Part I: Method description, validation, and demonstration for the August 2002 flooding in central Europe. *Journal of Hydrometeorology, 5*, 6562–6678. https://doi.org/10.1175/JCLI-D-14-00065.1

Tao, C., Jiang, H., & Zawislak, J. (2017). The relative importance of stratiform and convective rainfall in rapidly intensifying tropical cyclones. *Monthly Weather Review, 145*, 795–809. https://doi.org/10.1175/MWR-D-16-0316.1

Tao, D., & Zhang, F. (2014). Effect of environmental shear, sea-surface temperature, and ambient moisture on the formation and predictability of tropical cyclones: An ensemble-mean perspective. *Journal of Advances in Modeling Earth Systems, 6*, 384–404. https://doi.org/10.1002/2014MS000314

Trenberth, K. E., Davis, C. A., & Fasullo, F. (2007). Water and energy budgets of hurricanes: Case studies of Ivan and Katrina. *Journal of Geophysical Research, 112*, 3106. https://doi.org/10.1029/2006JD008303

van der Ent, R. J., & Tuinenburg, O. (2017). The residence time of water in the atmosphere revisited. *Geoscientific Model Development, 10*, 371–384. https://doi.org/10.5194/gmd-10-371-2017

Wang, Z., Montgomery, M. T., & Dunkerton, T. J. A. (2009). Dynamically-based method for forecasting tropical cyclones using the axis of the Atlantic sector using global model products. *Geophysical Research Letters, 36*, L03801. https://doi.org/10.1029/2008GL035586

Wu, W., & Chen, J., & Huang, R. (2013). Water budgets of tropical cyclones: Three case studies. *Journal of Climate, 28*, 66–85. https://doi.org/10.1175/JCLI-D-14-00044.1

Wang, Z., Montgomery, M. T., & Dunkerton, T. J. A. (2009). Dynamically-based method for forecasting tropical cyclones using the axis of the Atlantic sector using global model products. *Geophysical Research Letters, 36*, L03801. https://doi.org/10.1029/2008GL035586

Wu, W., & Chen, J., & Huang, R. (2013). Water budgets of tropical cyclones: Three case studies. *Journal of Climate, 28*, 66–85. https://doi.org/10.1175/JCLI-D-14-00044.1

Wu, W., & Chen, J., & Huang, R. (2013). Water budgets of tropical cyclones: Three case studies. *Journal of Climate, 28*, 66–85. https://doi.org/10.1175/JCLI-D-14-00044.1

Wu, W., & Chen, J., & Huang, R. (2013). Water budgets of tropical cyclones: Three case studies. *Journal of Climate, 28*, 66–85. https://doi.org/10.1175/JCLI-D-14-00044.1

Wu, W., & Chen, J., & Huang, R. (2013). Water budgets of tropical cyclones: Three case studies. *Journal of Climate, 28*, 66–85. https://doi.org/10.1175/JCLI-D-14-00044.1

Ying, Y., & Zhang, Q. (2012). A modeling study on tropical cyclone structural changes in response to ambient moisture variations. *Journal of the Meteorological Society of Japan, 90*, 755–770. https://doi.org/10.2151/jmsj.2012-512

Ying, Y., & Zhang, Q. (2012). A modeling study on tropical cyclone structural changes in response to ambient moisture variations. *Journal of the Meteorological Society of Japan, 90*, 755–770. https://doi.org/10.2151/jmsj.2012-512
Yoshida, K., Sugi, M., Mizuta, R., Murakami, H., Ishii, M. (2017). Future changes in tropical cyclone activity in high-resolution large-ensemble simulations. *Geophysical Research Letters* 44, 9910–9917. https://doi.org/10.1002/2017GL075058

Zhang, D.-L., Liu, Y., & Yau, M. K. (2002). A multiscale numerical study of Hurricane Andrew Part V: Inner-core thermodynamics. *Monthly Weather Review*, 130, 2745–2763. https://doi.org/10.1175/1520-0493(2002)130<2745:AMNSOH>2.0.CO;2