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Water Budgets of Tropical Cyclones Through a Lagrangian Approach: A Case of Study of Hurricane Irma (2017)

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Abstract: This study examined the water budget of Hurricane Irma (2017) through a Lagrangian approach. To identify the moisture sources for the Hurricane Irma genesis and intensification the particle dispersion model FLEXPART was used. The North Atlantic Ocean between 15° and 30° North latitude and the South Atlantic Ocean were identified as the main moisture sources for Irma development. From the perspective of the water budget, the maximum accumulated precipitation along Irma's trajectory coincides with the maximum water budget efficiency, which suggests that total precipitation depends largely on the water vapour supplied, rather than the storm intensity. Furthermore, the moisture supplies from the surface under the area delimited by hurricane size is small, thus, the water vapour supplies from the environment through the secondary circulation transports more moisture inward.

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1. Introduction

Tropical cyclones (TCs) are one of the natural hazards that annually cause major disasters worldwide, including many human deaths and large economic losses due to the increasing populations in coastal regions and the increasing economic value of infrastructures [1].

Among others factors, TCs formation requires moist layers at mid-troposphere to enhance thunderstorm formation [2,3]. Thus, the cyclone scale circulation provides moisture for cumulus development, and the latent heat release in cumulus clouds drives the cyclone circulation in return. Several author [4-10] have investigate the role of the atmospheric humidity in TC development. There are several methods to investigate the origin of moisture (e.g., Eulerian, and Lagrangian). A further review and comparison of the different approaches used to study moisture transport may be found in Gimeno et al. [11].

Although there have been many observational and modeling studies of TCs, and the Lagrangian diagnostic scheme has proved to be a powerful tool to identified moisture sources and study anomalous atmospheric moisture transports [12,13], the TCs' water budgets through a Lagrangian approach has been poorly studied. Thus, in this study we aim to investigate the water budget of North Atlantic Hurricane Irma (2017) using the Lagrangian analysis

1.1 Hurricane Irma (2017)

The Hurricane Irma (2017) was formed from a tropical wave at 0000 UTC 30 August [32]. While moving westward to the south of a mid-level ridge over the eastern Atlantic, Irma strengthened rapidly in environmental conditions of low vertical wind shear and a fairly moist lower troposphere while it was over marginally warm sea surface temperature (SST). Only 48 h after genesis, Irma reached the major hurricane strength (category +3 hurricane on Saffir – Simpson scale) at 0000 UTC 1st September. The RI process (130 km/h in 48 h) undergo by Irma is a remarkable rate that has only achieved by a small fraction of Atlantic tropical cyclones [14].

The hurricane reached its maximum intensity of 286 km/h around 1800 UTC 5 September. As a category 5 hurricane, Irma made landfall on Barbuda and St. Martin around 0545 UTC and 1115 UTC 6 September, respectively. About 1630 UTC 6 September Hurricane Irma made its third landfall on the island of Virgin Gorda in the British Virgin Islands as category 5 hurricane [14]. Irma again made landfall on Little Inagua Island in the Bahamas at 0500 UTC 8 September category 4 intensity. Irma then turned slightly to the left, due to a building subtropical ridge, and moved toward the northern coast of Cuba and made the fifth landfall near Cayo Romano, Cuba, at 0300 UTC 9 September, with estimated maximum winds of 270 km/h.

The land interaction of the storm circulation in its movement along the northern coast of Cuba led to Irma weakening to a category 2 hurricane, however, the movement over warm waters in the Straits of Florida allowed that the hurricane re-intensified once again before making landfall for the sixth time near Cudjoe Key in the lower Florida Keys around 1300 UTC 10 September [14]. Finally, Irma dissipated at 1200 UTC 13 September.

2. Material and Methods

2.1 Data

The information of the Hurricane Irma was obtained from the Atlantic hurricane database (HURDAT2)[15], available online at the National Hurricane Center (NHC) of the United States of America web page. This dataset is a re-analysis effort to extend and revise the NHC's North Atlantic hurricane dataset (HURDAT).

The rain rate from the Global Precipitation Measurement (GPM) [16] was used. In this dataset, the precipitation is estimated from the various precipitation-relevant satellite passive microwave sensors comprising the GPM constellation, computed using the Goddard Profiling Algorithm. This dataset is merged into half-hourly 0.1°x 0.1° of latitude and longitude horizontal resolution.

2.2 FLEXPART simulations

Global outputs from a modeling experiment using the FLEXPART v9.0 [17] were utilized to investigate the Hurricane Irma water budgets from 0000 UTC 30 August to 1200 UTC 13 September 2017. Initially, the model considers the atmosphere homogeneously divided into approximately 2 million particles (the number of air particles that must be higher than the meteorological model levels) uniformly distributed over the entire globe and permits one to track them backward and/or forward in time.

In this study, the particles residing over the area enclosed (target region) by the outer radius of each Hurricane Irma best track position were tracked backward in time up to 10 days; which is considered the residence time of the water vapour in the atmosphere [18].

2.3 Methodology

2.3.1 Lagrangian water budget formulation

Following Stohl and James [12], the net change of the water vapour content of a particle is estimated as:

$$(e - p) = m\left(\frac{dq}{dt}\right) \tag{1}$$

where e and p are the rates of moisture increases and decreases along the trajectory, m is the mass of each particle assumed as constant and q is the specific humidity. Furthermore, to computed the surface freshwater flux over an area A, the moisture changes of all particles in the atmospheric column over A are computed as:

$$(E - P) = \frac{\sum_{k=1}^{N} (e - p)_k}{A} \tag{2}$$

where N is the number of particles residing over A. To identify the moisture source, the regions where the total evaporation (E) exceeds the total precipitation (P) should be selected, so only those regions showing $(E-P) > 0$ values are taken into account. We consider here that the moisture uptake (E-P > 0) is the net water vapour flux that arrived at the target region at each position every 6-h of the Hurricane Irma best track, and in its calculation is not included the precipitation over the target region.

3. Results and Discussion

3.1 Identification of the moisture sources for hurricane Irma genesis and intensification

The moisture uptake composite from 0000 UTC 30 August to 1200 UTC 13 September reveals the moisture sources for hurricane Irma (2017) genesis and intensification. Clearly, from Figure 2 we identified the eastern North Atlantic along the northwest coast of Africa, from the Iberian Peninsula to the genesis position, and the Sahel region, as the main moisture sources that favored the activation of the convection when Irma was still a tropical disturbance embedded in an easterly wave [14]. The circulation of the North Atlantic Subtropical High-Pressure system (NASH) and the easterly winds acted as the moisture transport mechanisms from the source regions to the genesis location.

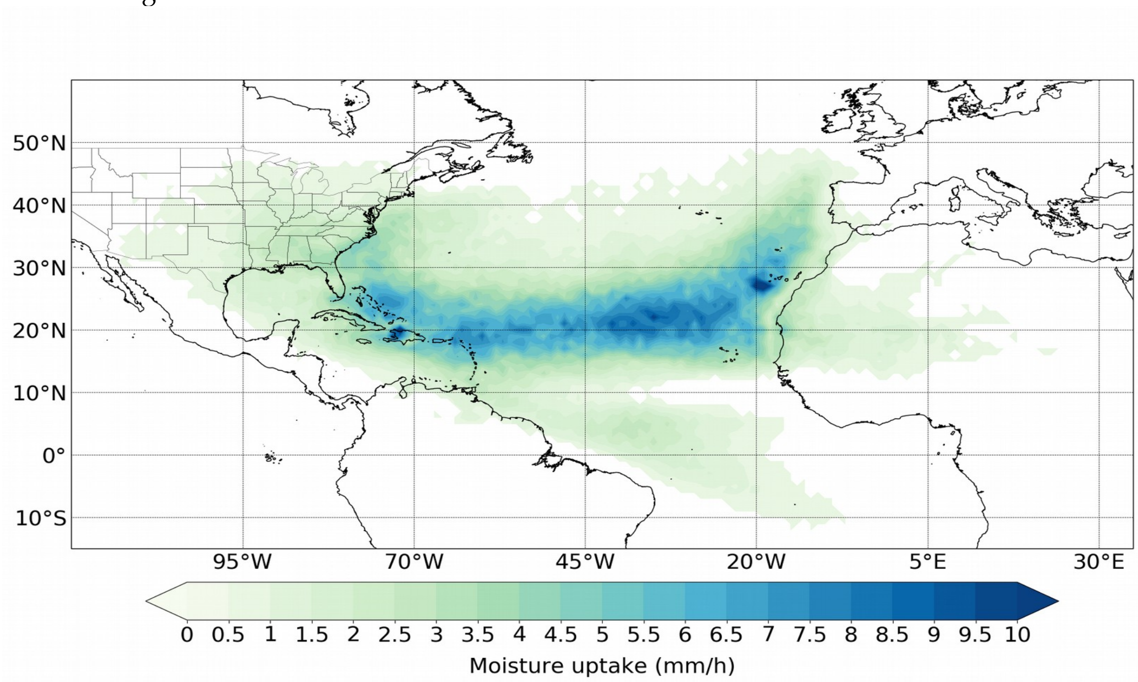

Figure 1. Moisture uptake composite along the Hurricane Irma trajectory from 0000 UTC 30 August to 1200 UTC 13 September.

Along the trajectory of Hurricane Irma, the easterly winds and the trade winds continued supplying atmospheric humidity to TC, which favored the intensification processes. Furthermore, the South Atlantic Subtropical High-Pressure system (SASH) transport water vapour from the South Atlantic Ocean to the Caribbean Sea, and then, the easterly winds move it towards Irma position. Additionally, the Caribbean Sea and the Gulf of Mexico contributed the atmospheric humidity required by Irma to keep the deep convection and warm core by releasing latent heat. Nevertheless, the band between 15° and 30° North latitude over the Atlantic Ocean exhibits the greatest moisture contribution for Irma development. At the end of Irma's lifetime over the southeastern United States, we assume that a recycling process played an important role in moisture supplying. These findings are supported by the vertical integrated moisture flux pattern.

3.2 Precipitation rate spatial distribution

Figure 2 shows the precipitation rate from GPM along the Hurricane Irma trajectory. Although Irma was already a major hurricane just 48 hours after the genesis, the intensity of the precipitation was less than 8 mm/h during the initial lifetime. This features may be linked to the fact that the inner core was quite compact at this time, with an estimated extension of 40 km [14].

After the hurricane reached its maximum intensity close to the islands at north of the Lesser Antilles Arc, the intensity of precipitation increased to be maximum higher than 36 mm/h during its movement along the North coast of Cuba, the Straits of Florida. and the Florida Peninsula, as shown in Figure 2. At this time, the most intense precipitation rates nuclei were located towards the northeast (NE) quadrant of the storm, coinciding with the regions with the highest moisture uptake, as can be easily verified in Figures 1 and 2.

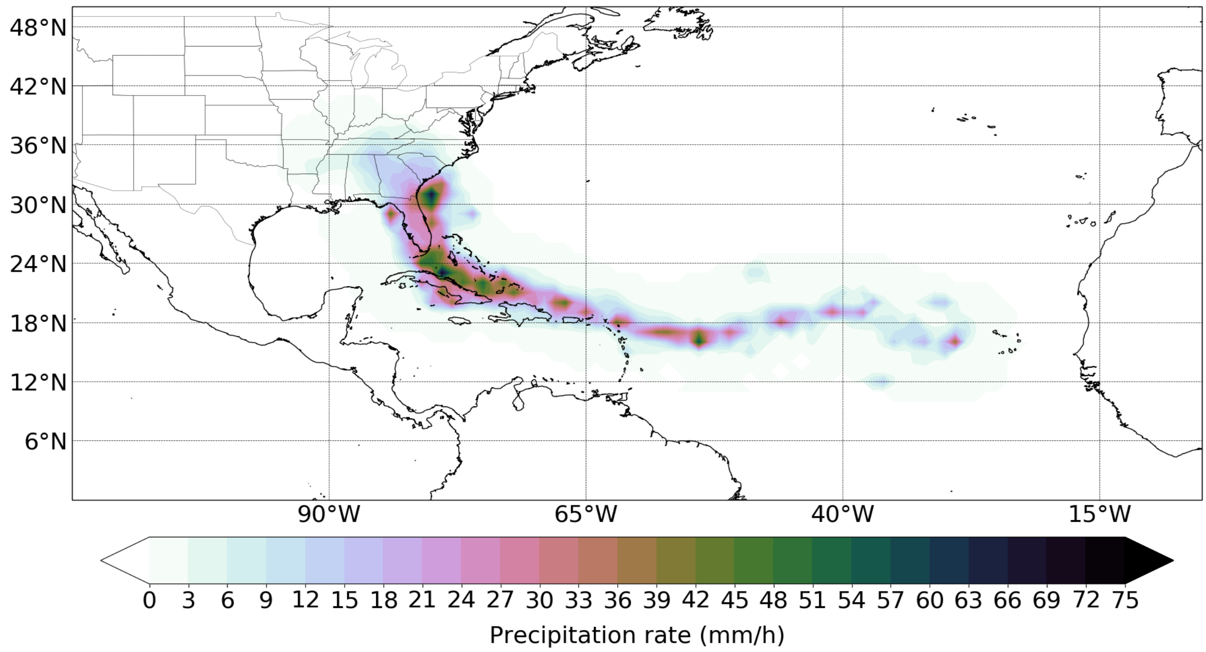

Figure 2. Rain rate from GPM composite along the Hurricane Irma trajectory from 0000 UTC 30 August to 1200 UTC 13 September.

As Cangialosi et al. [14] pointed out , Irma produced very heavy rainfall across a central-eatern portion of Cuba and over the large portion of Florida Peninsula, the accumulated rainfall ranging from 250 to 380 mm.

3.3 Moisture uptake vs rain rate

From Figure 3 it can be inferred that in the 8 days after the Irma genesis, the moisture uptake was higher than the precipitation rate, which favored the continuous release of latent heat, a key factor in the intensification of TCs in agreement with Emanuel [19].. Nevertheless, in the last five days (from day 9 to day 14) of Irma as a TC, the moisture uptake and the rain rate temporal evolution is very similar, which corresponds to the high accumulated rainfall during its movement along the north coast of Cuba and the Florida Peninsula. It is notable that both magnitudes reach the maximum value at this time.

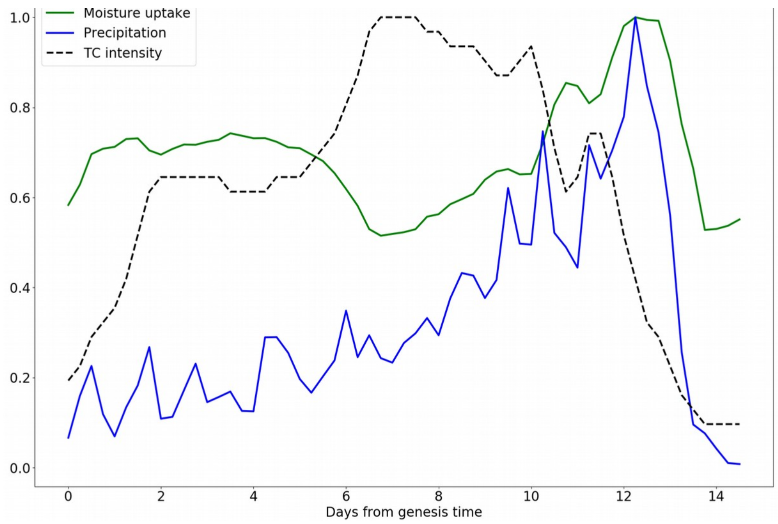

Figure 3. Normalized **t**emporal evolution of moisture uptake from Lagrangian approach (green) and rain rate from GPM (blue) during hurricane Irma (2017) lifetime from 0000 UTC 30 August to 1200 UTC 13 September. The gray dashed line represents the hurricane Irma intensity. The moisture uptake and rain rate plotted here represent the sum of all grid point within the area enclosed by the Hurricane Irma outer radius.

Figure 4 reveals that Irma took most moisture from the environment no related to TC circulation than moisture from ocean evaporation within the area enclosed by the outer radius in each best track position. Therefore, the secondary circulation then transports more moisture inward and, thus, induces a stronger moist core. In other words, the strong radial inflow transports highly moist air parcels from the surrounding environment inward to the inner core.

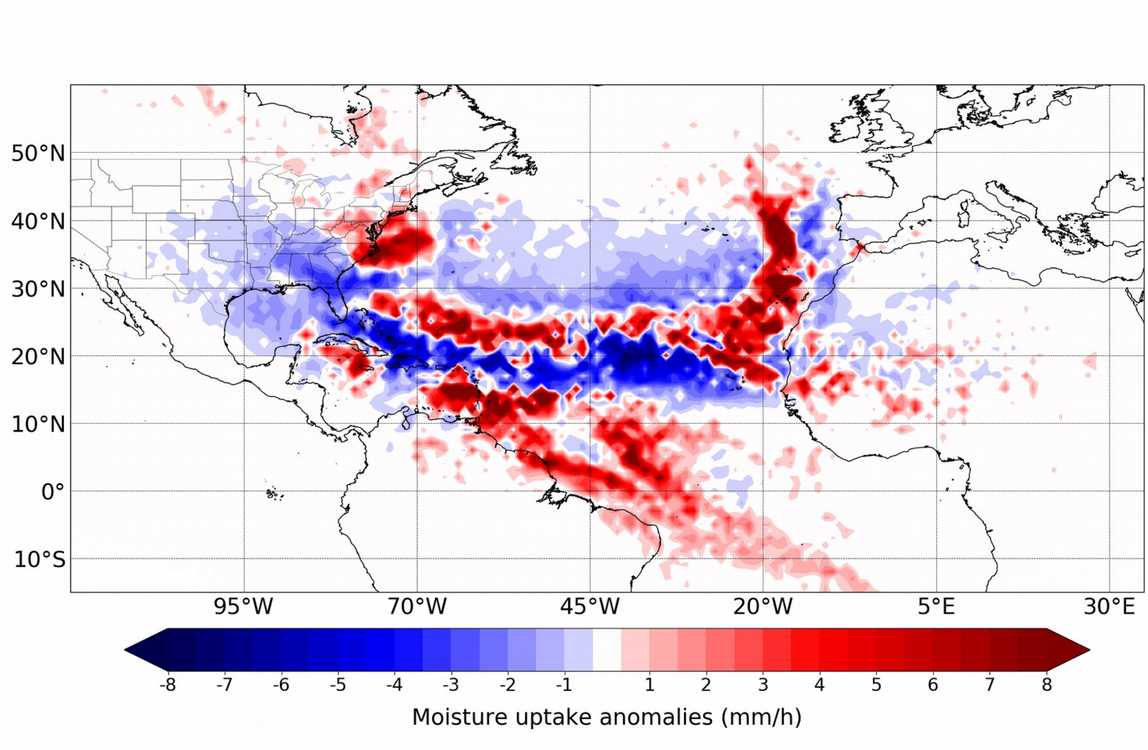

Figure 4. Accumulated moisture uptake anomalies (blue – red colors) along the Hurricane Irma trajectory from 0000 UTC 30 August to 1200 UTC 13 September. The moisture uptake anomalies were compute using the period 1980-2018.

4. Conclusions

In this study we performed the Hurricane Irma (2017) water budget analysis through a Lagrangian approach. The Hurricane Irma was one of the most severe hurricanes of the 2017 cyclonic season on the North Atlantic basin, and caused heavy rainfall along the north coast of Cuba and Florida Peninsula. To determine the moisture uptake for each position of the Irma best track and the water budget inside the system, the particle dispersion model FLEXPART.

The results showed that the North Atlantic Ocean between 15°-30° North latitude, the Sahel region, and the South Atlantic were the main moisture sources for the genesis and development of Irma. Although, the Caribbean Sea, the Gulf of Mexico, and the southeastern of United States of America also contributed, but to a lesser extent. Furthermore, the North Atlantic Subtropical High-Pressure system, the South Atlantic Subtropical High-Pressure system, and the easterly winds were identified as the main moisture transport mechanisms for supplying atmospheric humidity to Irma.

Despite the great intensity of Irma, during the first five-six days after genesis, the precipitation rate was less than 8 mm/h, however, when the hurricane center crossed over the Greater Antilles as an intense hurricane, the precipitation rate was greater than 20 mm/h, which supports the accumulated rainfall reported in Cuba and La Florida.

As expected, the moisture supplied from the surface under the area delimited by hurricane size is small, thus, the water vapour supplied from the environment through the secondary circulation transports more moisture inward. The accumulated moisture uptake anomalies along the hurricane Irma trajectory showed that both the Tropical North and South Atlantic Oceans were important sources of moisture for Irma development. However, the region of West Africa and the North Atlantic Ocean near the African continent and the Iberian Peninsula also provided humidity.

Author Contributions: A.P-A., R.N, and L.G. conceived the idea of the study. A.P-A., R.S., J.C.F-A. and P.C-H processed the data and made the figures. A.P-A. analyzed the results and wrote the manuscript. All authors analyzed the results and revised the final version of the manuscript.

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Data Availability Statement: The datasets used in this study are freely available on internet. The HURDAT2 database is accessible from https://www.nhc.noaa.gov/data/#hurdat, and the GPM dataset is available at https://gpm.nasa.gov/data/directory. The FLEXPART outputs to reproduce our results is obtained upon request from the corresponding author.

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