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Identification of Tropical Cyclones' Critical Positions Associated with Extreme Precipitation Events in Central America

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Abstract: Tropical cyclones are one of the most important causes of disasters in Central America. Using historical (1970–2010) tracks of cyclones in the Caribbean and Pacific basin, we identify critical path locations where these low-pressure systems cause the highest number of floods in a set of 88 precipitation stations in the region. Results show that tropical cyclones from the Caribbean and Pacific basin produce a large number of indirect impacts on the Pacific slope of the Central American isthmus. Although the direct impact of a tropical cyclone usually results in devastation in the affected region, the indirect effects are more common and sometimes equally severe. In fact, the storm does not need to be an intense hurricane to cause considerable impacts and damage. The location of even a lower intensity storm in critical positions of the oceanic basin can result in destructive indirect impacts in Central America. The identification of critical positions can be used for emergency agencies in the region to issue alerts of possible flooding and catastrophic events.

Keywords: tropical cyclones; Central America; extreme precipitation events; impacts; rain

1. Introduction

Among the main transient synoptic-scale hydrometeorological hazards that affect Central America are cold fronts, easterly waves, and tropical cyclones [1,2]. The first type of hazard occurs during boreal winter, especially from December through January [3], while the other two types occur usually from middle boreal spring to middle autumn, peaking during the August-October quarter [4]. Sometimes, a particular easterly wave becomes an atmospheric disturbance that evolves into a tropical cyclone [5]. Ref. [6] also discusses other systems associated with tropical-depression wave disturbances that could be associated with tropical cyclogenesis in the tropical Atlantic and in the Eastern Tropical Pacific. These systems are characterized by troughs or segregated low-pressure systems from the Inter Tropical Convergence Zone (ITCZ).

Central America is located between two very active cyclogenetic regions, the Atlantic basin and the Eastern Tropical Pacific [4]. Tropical cyclones in these two regions can affect Central America in two different ways [7]. The first and more dramatic is the storm landfall, with important impacts associated with strong winds and heavy rains. This is called a "direct effect". In some cases, the tropical cyclone crosses the isthmus from one basin to the other, normally from the Caribbean Sea to the Eastern Tropical Pacific [8]. A recent example is the 2016 Hurricane Otto, crossing at the Nicaraguan and Costa Rican border [9]. The second, and more recurrent influence, is called "indirect effect" associated with an induced circulation of the tropical cyclone low-pressure center over the region. In this case, the cyclone is not over the isthmus but induces a flow that interacts with the mountain chain that crosses Central America in a northwest–southeast axis that divides the isthmus in two slopes, Pacific and Caribbean. For example, a tropical cyclone located in the Caribbean Sea, close to Central America, could have the associated low-level wind response blowing from the Eastern Tropical Pacific to the Caribbean Sea. The mechanical rise of this warm and humid air originated in the Pacific, forces condensation, and can be associated with persistent rain over the Pacific slope. A recent example was Tropical Storm Nate in 2017 [10]. These events are called "temporales" if they persist for several days and can cause important stream flows [11]. Countries on the northern part of the isthmus (i.e., Belize, Guatemala, Honduras, El Salvador, and Nicaragua), are impacted by both, direct and indirect effects, meanwhile Costa Rica and Panama, at the southeast, are impacted normally by indirect effects and rarely by storm landfalls as with the tropical storm 19 in 1887 [12], Hurricane Martha in 1969 [13] and Hurricane Otto in 2016 [9]. Details from historical studies of the past impacts of Tropical Cyclones in Central America can be found in [14–18].

The tropical cyclone impacts registered over the region are not strictly associated with the intensity of the cyclone. There are two additional important variables to consider when the impacts databases are reviewed, the position of the system relative to the isthmus, and its velocity over the basin [18,19]. If the low pressure is located in the right position to induce a temporal for several days due to its low system velocity, it would cause important damage in the region [10]. Impacts are normally associated with extremely high stream flows or landslides and would have effects in important socioeconomic sectors like agriculture, infrastructure (both public and private), water supply for human consumption, transport, tourism, and others [1,2,20–25]. For the Central American economies, the cost of these impacts may be an important part of their gross domestic products, and sometimes they could have an associated loss of lives [22,22–24,26]. It is worth mentioning that impacts are also a function of the population's exposure and vulnerability. For this reason, the local governments having important population centers living in poverty and extreme poverty, usually present high indices of vulnerability and exposure to hydrometeorological hazards. The emergency reports from these locations are among the highest when compared with the other municipalities [1,27].

As examples of the direct and indirect effects, we selected some events for each oceanic basin: Tropical Depression 16 (2008) in the Caribbean Sea; and Alma and Agatha Tropical Storm in the Eastern Tropical Pacific Ocean. The trajectories and impacts were mapped to identify the municipalities injured by these events. The impacts were extracted from two databases: DesInventar and EM-DAT. Some photographs were included to exemplify the damage.

The objective of this work is to identify the regions in the Caribbean Sea and in the Eastern Tropical Pacific, having the critical position occurrences of tropical cyclones but associated with extreme precipitation events (above the 90th percentile) in Central America, recorded by the gauge network of the national meteorological and hydrological services. This information could be useful for emergency preparedness institutions in the region, as it can help in planning and disaster prevention.

2. Data and Methodology

Daily precipitation data from 88 meteorological stations covering Central America during the period 1970–2010 were obtained from the database of the Center for Geophysical Research at the University of Costa Rica (CIGEFI-UCR in Spanish). The data originated from meteorological stations owned and administered by the region's meteorological and hydrological agencies. Tables 1 and 2 show metadata and statistics of the station data.

Table 1. Station metadata and median value [mm/day] by month.

No.	Country	Station Name/Code	Latitude	Longitude	January	February	March	April	May	June	July	August	September	October	November	December
1	Belice	Pswgia	17.500	−88.300	0.00	0.00	0.00	0.00	0.00	0.40	1.00	0.90	1.30	1.00	0.30	0.10
2	Costa Rica	Bagaces	10.533	−85.250	0.00	0.00	0.00	0.00	0.00	0.60	0.10	0.40	3.00	1.49	0.00	0.00
3	Costa Rica	Batan	10.083	−83.333	1.00	0.60	0.10	0.30	1.20	1.50	3.50	1.50	0.30	0.50	2.00	2.10
4	Costa Rica	Catie	9.883	−83.633	0.40	0.10	0.00	0.10	2.10	3.30	3.50	3.60	3.10	2.80	2.80	1.40
5	Costa Rica	Ciudad_Quesada	10.333	−84.433	0.20	0.00	0.00	0.00	2.60	7.30	7.40	7.50	9.00	7.50	4.90	1.90
6	Costa Rica	Coto 47	8.602	−82.968	0.00	0.00	0.00	0.50	5.59	5.10	5.80	8.00	10.20	10.20	5.90	0.00
7	Costa Rica	El Carmen	10.200	−83.480	1.50	0.80	0.20	0.50	1.70	2.90	6.00	3.20	0.60	1.40	3.30	3.20
8	Costa Rica	Fabio Baudrit	10.000	−84.250	0.00	0.00	0.00	0.00	1.90	3.00	1.00	2.30	5.40	5.00	0.20	0.00
9	Costa Rica	Jilguero	10.450	−84.717	6.40	3.75	1.90	1.51	7.60	12.20	15.40	13.10	10.85	12.70	11.95	10.45
10	Costa Rica	Juan Sria	10.000	−84.217	0.00	0.00	0.00	0.00	2.40	2.90	0.80	2.30	5.55	4.70	0.20	0.00
11	Costa Rica	La Argentina	10.033	−84.350	0.00	0.00	0.00	0.00	2.07	2.90	1.20	3.20	7.50	5.80	0.00	0.00
12	Costa Rica	La Lola	10.100	−83.380	1.30	0.60	0.10	0.30	1.50	2.30	4.10	2.30	0.50	0.90	2.80	3.00
13	Costa Rica	Liberia	10.599	−85.541	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.50	4.20	2.60	0.00	0.00
14	Costa Rica	Limón	9.950	−83.017	1.80	1.10	0.40	0.70	1.20	1.70	4.70	1.70	0.20	0.60	2.05	2.90
15	Costa Rica	Linda Vista del Guarco +Lankester CIGEFI	9.850	−83.900	0.00	0.00	0.00	0.00	1.30	3.10	1.30	2.60	6.10	4.20	0.30	0.00
16	Costa Rica	Linda_Vista	9.933	−84.083	0.00	0.00	0.00	0.00	0.00	1.20	0.00	0.50	2.45	2.30	0.00	0.00
17	Costa Rica	Llorona	9.400	−84.083	0.00	0.00	0.00	0.00	3.60	3.80	4.04	5.60	7.60	8.00	4.20	0.00
18	Costa Rica	Monteverde	10.136	−84.192	0.00	0.00	0.00	0.00	4.20	7.30	4.70	6.20	10.20	8.10	2.80	0.40
19	Costa Rica	Monteverde+ Monteverde CIGEFI	10.133	−84.825	0.70	0.40	0.20	0.10	2.00	4.20	3.40	4.90	6.70	6.10	2.45	1.40
20	Costa Rica	Nicoya	10.150	−85.450	0.00	0.00	0.00	0.00	0.10	2.00	0.10	1.70	6.80	3.70	0.00	0.00
21	Costa Rica	Palo_Seco	9.433	−84.150	0.00	0.00	0.00	0.00	2.80	3.40	4.10	4.20	7.55	6.50	3.65	0.00
22	Costa Rica	Piñera	9.138	−83.319	0.00	0.00	0.00	0.00	5.00	4.00	1.00	4.70	9.00	9.40	1.80	0.00
23	Costa Rica	Playón	9.533	−84.300	0.00	0.00	0.00	0.00	2.20	3.10	3.40	4.00	5.00	5.50	1.50	0.00
24	Costa Rica	Quepos	9.461	−84.159	0.00	0.00	0.00	0.00	3.80	4.00	4.60	6.00	8.00	7.20	4.00	0.00
25	Costa Rica	Repunta	9.300	−83.650	0.00	0.00	0.00	0.00	3.90	3.50	2.50	5.00	7.40	7.40	2.60	0.00
26	Costa Rica	San Miguel	10.417	−83.983	0.00	0.00	0.00	0.10	7.30	7.30	5.40	7.20	10.58	11.00	2.70	0.00
27	Costa Rica	San_José	9.633	−84.283	3.00	1.60	0.30	0.90	5.30	8.00	10.50	8.90	5.90	6.80	7.20	4.80
28	Costa Rica	Santa Cruz Balanya	10.261	−85.584	0.00	0.00	0.00	0.00	0.10	1.30	0.10	1.00	4.40	2.70	0.00	0.00
29	Costa Rica	Volcán Buenos Aires	9.217	−83.450	0.00	0.00	0.00	0.70	6.20	4.65	2.00	5.90	10.25	11.20	3.70	0.00
30	El Salvador	Ilopango	13.438	−88.158	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.40	2.70	0.60	0.00	0.00
31	Guatemala	Asunción Mita	14.334	−89.706	0.00	0.00	0.00	0.00	0.00	2.00	0.20	0.50	2.20	0.00	0.00	0.00
32	Guatemala	Camotan	15.044	−91.024	0.00	0.00	0.00	0.00	0.00	5.20	3.80	3.60	6.10	0.30	0.00	0.00
33	Guatemala	Chinique	15.467	−90.408	0.20	0.00	0.00	0.00	0.00	4.80	3.80	3.70	4.90	2.90	0.80	0.20
34	Guatemala	Coban	15.109	−90.614	0.00	0.00	0.00	0.00	0.00	3.30	1.22	1.60	3.20	0.10	0.00	0.00
35	Guatemala	El asintal	17.183	−89.000	0.00	0.00	0.00	0.00	0.00	0.30	1.10	0.50	0.50	0.70	0.30	0.10
36	Guatemala	Esquipulas	14.533	−89.033	0.00	0.00	0.00	0.00	0.00	3.30	1.10	1.60	3.70	0.20	0.00	0.00
37	Guatemala	Flores	17.250	−88.700	0.00	0.00	0.00	0.00	0.00	1.50	2.20	1.50	1.60	1.00	0.10	0.00
38	Guatemala	Huehuetenango	15.317	−91.503	0.00	0.00	0.00	0.00	0.00	1.90	0.10	0.20	2.15	0.00	0.00	0.00
39	Guatemala	Isivumeth	14.583	−90.533	0.00	0.00	0.00	0.00	0.00	2.65	0.70	0.70	2.70	0.00	0.00	0.00

Table 1. *Cont.*

No.	Country	Station Name/Code	Latitude	Longitude	January	February	March	April	May	June	July	August	September	October	November	December
40	Guatemala	La Ceibita	14.493	−89.876	0.00	0.00	0.00	0.00	0.00	0.74	0.00	0.00	1.00	0.00	0.00	0.00
41	Guatemala	La Fragua	14.964	−89.584	0.00	0.00	0.00	0.00	0.00	0.40	0.00	0.00	0.50	0.00	0.00	0.00
42	Guatemala	La Unión	15.733	−88.583	0.40	0.00	0.00	0.00	0.00	1.30	5.40	5.00	2.40	2.00	1.25	1.00
43	Guatemala	Labor Ovalle	14.870	−91.480	0.00	0.00	0.00	0.00	0.00	2.00	0.60	0.70	2.30	0.00	0.00	0.00
44	Guatemala	Nebaj	16.983	−88.317	0.00	0.00	0.00	0.00	0.00	0.60	1.50	1.30	2.00	1.00	0.30	0.00
45	Guatemala	Quezada	14.535	−91.678	0.00	0.00	0.00	0.00	2.52	7.17	4.00	5.20	10.79	4.07	0.00	0.00
46	Guatemala	Sabana Grande	14.030	−91.050	0.00	0.00	0.00	0.00	2.87	8.12	7.50	8.40	12.00	7.50	0.00	0.00
47	Guatemala	Sacapulas	14.301	−90.786	0.00	0.00	0.00	0.00	0.00	0.80	0.20	0.40	1.00	0.00	0.00	0.00
48	Guatemala	San Jerónimo	16.517	−89.867	0.00	0.00	0.00	0.00	0.00	1.04	1.40	1.80	2.60	0.60	0.00	0.00
49	Guatemala	San Pedro Soloma	14.632	−91.231	0.00	0.00	0.00	0.00	0.10	3.85	0.70	0.80	3.10	0.00	0.00	0.00
50	Guatemala	Santa Cruz Balanya	14.801	−90.640	0.00	0.00	0.00	0.00	0.00	1.10	0.60	1.00	2.10	0.00	0.00	0.00
51	Honduras	78719	14.059	−87.216	0.00	0.00	0.00	0.00	0.00	0.40	0.10	0.10	1.00	0.20	0.00	0.00
52	Honduras	Choluteca	13.318	−87.154	0.00	0.00	0.00	0.00	0.10	2.20	0.00	0.50	4.95	1.00	0.00	0.00
53	Honduras	Jaral	14.938	−88.005	0.00	0.00	0.00	0.00	0.00	5.03	8.76	8.56	6.85	3.44	1.32	0.20
54	Honduras	La Ceiba	15.730	−86.870	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.68	0.40	0.80	1.30	0.00
55	Honduras	La Mesa	15.400	−87.900	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.20	0.29	0.10	0.00	0.00
56	Honduras	Pitosolo	14.780	−88.010	0.00	0.00	0.00	0.00	0.00	2.50	4.50	5.60	4.23	3.00	0.60	0.00
57	Honduras	Sjeronimo	15.070	−90.250	0.00	0.00	0.00	0.00	0.80	1.20	1.20	2.00	0.00	0.00	0.00	0.00
58	Honduras	Vallecillo	14.520	−87.400	0.00	0.00	0.00	0.00	0.00	2.10	2.10	3.00	4.20	2.13	0.00	0.00
59	Nicaragua	45018	13.339	−86.385	0.00	0.00	0.00	0.00	0.00	0.60	0.50	0.40	0.80	0.40	0.00	0.00
60	Nicaragua	55026	12.763	−85.627	0.00	0.00	0.00	0.00	0.00	3.25	3.60	2.90	2.30	1.60	0.40	0.20
61	Nicaragua	60006	12.427	−86.913	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	3.40	1.67	0.00	0.00
62	Nicaragua	61009	12.583	−81.700	0.32	0.02	0.02	0.02	0.02	0.86	1.40	1.50	1.72	2.82	2.20	0.90
63	Nicaragua	61010	13.350	−81.350	0.30	0.00	0.00	0.00	0.00	1.00	1.20	1.50	1.35	2.56	2.00	0.80
64	Nicaragua	61025	12.633	−87.133	0.00	0.00	0.00	0.00	0.00	1.60	0.00	1.30	5.60	2.70	0.00	0.00
65	Nicaragua	69026	12.143	−86.164	0.00	0.00	0.00	0.00	0.00	0.60	0.50	0.60	1.30	0.60	0.00	0.00
66	Nicaragua	69031	11.722	−86.047	0.00	0.00	0.00	0.00	0.00	0.90	0.40	0.80	2.00	1.80	0.00	0.00
67	Nicaragua	69068	11.435	−85.833	0.00	0.00	0.00	0.00	0.00	1.10	0.70	0.90	2.20	1.70	0.00	0.00
68	Nicaragua	Corinto	12.517	−87.200	0.00	0.00	0.00	0.00	0.00	0.60	0.00	0.50	5.38	1.84	0.00	0.00
69	Nicaragua	Juigalpa	12.100	−85.367	0.00	0.00	0.00	0.00	0.00	1.00	1.10	1.00	2.10	1.10	0.00	0.00
70	Nicaragua	Ocotal	13.625	−86.477	0.00	0.00	0.00	0.00	0.00	0.30	0.20	0.20	0.60	0.20	0.00	0.00
71	Nicaragua	Puerto Cabezas	14.047	−83.375	1.10	0.20	0.00	0.00	0.20	4.20	5.60	4.90	3.00	4.00	2.71	1.80
72	Panamá	Agua_Clara	9.364	−79.706	0.00	0.00	0.00	0.00	2.50	5.10	2.50	5.10	2.50	5.10	7.60	1.00
73	Panamá	Anton	7.400	−80.450	0.00	0.00	0.00	0.00	0.00	1.00	0.90	1.00	1.20	3.00	1.90	0.00
74	Panamá	Balboa Heights	8.959	−79.554	0.00	0.00	0.00	0.00	0.30	1.31	0.80	2.50	2.50	2.50	2.50	0.00
75	Panamá	Boca de Toabre	9.424	−79.578	0.00	0.00	0.00	0.00	2.50	2.50	2.50	2.50	2.50	5.10	5.10	2.50
76	Panamá	Bocas Toro	9.340	−82.245	1.90	1.14	0.50	1.30	1.70	2.10	4.15	2.70	0.90	1.30	2.70	3.70
77	Panamá	Cerro Punta	8.508	−81.073	0.00	0.00	0.00	0.00	0.70	1.70	0.80	2.00	4.20	4.40	1.80	0.20
78	Panamá	Cocle del Norte	8.383	−80.267	0.00	0.00	0.00	0.00	0.00	0.90	0.50	0.80	0.70	2.10	1.10	0.00
79	Panamá	Cuesta de Piedra	8.065	−78.366	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.50	0.40	1.00	0.00	0.00
80	Panamá	David	8.397	−82.428	0.00	0.00	0.00	0.00	1.20	1.85	1.10	2.50	4.00	4.20	1.50	0.00

Table 1. *Cont.*

No.	Country	Station Name/Code	Latitude	Longitude	January	February	March	April	May	June	July	August	September	October	November	December
81	Panamá	Divisa	8.314	−81.209	0.00	0.00	0.00	0.00	1.20	3.00	0.60	2.80	7.05	7.00	1.95	0.00
82	Panamá	Escandalosa	9.167	−79.083	0.00	0.00	0.00	0.00	1.00	2.00	1.50	2.00	2.50	4.00	2.50	0.00
83	Panamá	Gatun	9.268	−79.921	0.00	0.00	0.00	0.00	2.50	2.50	2.50	2.50	2.50	3.00	5.10	0.50
84	Panamá	Icacal	9.205	−80.146	0.40	0.10	0.00	0.30	3.40	4.50	5.50	5.30	3.50	4.10	7.90	2.30
85	Panamá	Santiago	8.140	−80.704	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.50	1.00	2.30	1.00	0.00
86	Panamá	Tocumen	9.066	−79.392	0.00	0.00	0.00	0.00	0.80	1.20	0.60	0.80	1.30	2.90	1.50	0.00
87	Panamá	Tonosi	8.087	−80.978	0.00	0.00	0.00	0.00	1.50	2.20	1.10	2.50	3.60	4.60	2.50	0.00
88	Panamá	Valle Rico	7.941	−80.418	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.30	0.70	0.00	0.00

Table 2. Station metadata and 90th percentiles [mm/day] by month.

No.	Country	Station Name/Code	Latitude	Longitude	January	February	March	April	May	June	July	August	September	October	November	December
1	Belice	Pswgia	17.500	−88.300	14.28	7.60	2.78	2.35	10.34	21.25	19.00	17.80	26.35	25.14	21.60	16.00
2	Costa Rica	Bagaces	10.533	−85.250	0.00	0.00	0.00	0.75	24.34	24.65	13.00	20.88	32.15	28.98	8.40	0.40
3	Costa Rica	Batan	10.083	−83.333	27.80	22.48	14.74	20.75	28.58	25.20	34.98	29.44	15.40	22.84	37.90	38.47
4	Costa Rica	Catie	9.883	−83.633	15.00	14.05	7.94	13.50	24.60	27.40	25.74	25.30	25.25	22.74	26.45	25.84
5	Costa Rica	Ciudad_Quesada	10.333	−84.433	27.62	16.42	7.40	11.25	33.88	40.28	46.32	42.70	42.50	43.76	40.85	44.08
6	Costa Rica	Coto 47	8.602	−82.968	9.80	6.47	11.40	29.20	38.94	43.30	43.01	49.94	48.45	52.74	44.30	18.26
7	Costa Rica	El Carmen	10.200	−83.480	31.44	24.41	18.00	22.90	32.54	31.35	41.00	33.10	21.00	28.14	46.25	48.14
8	Costa Rica	Fabio Baudrit	10.000	−84.250	0.00	0.00	0.20	6.10	28.24	25.90	19.24	25.78	30.70	27.74	15.20	2.10
9	Costa Rica	Jilguero	10.450	−84.717	38.14	33.00	23.09	21.75	37.80	43.20	44.98	43.94	36.61	42.36	43.80	55.10
10	Costa Rica	Juan Sria	10.000	−84.217	0.00	0.00	0.10	9.00	27.70	26.20	18.34	25.84	31.65	29.78	16.61	1.80
11	Costa Rica	La Argentina	10.033	−84.350	0.00	0.00	0.00	3.90	28.18	27.40	23.70	29.04	34.00	31.88	16.60	1.00
12	Costa Rica	La Lola	10.100	−83.380	29.20	25.14	16.00	21.60	34.58	29.15	37.38	32.84	19.45	25.98	40.70	42.90
13	Costa Rica	Liberia	10.599	−85.541	0.00	0.00	0.00	0.10	24.70	28.60	17.00	28.08	37.51	30.54	11.10	0.20
14	Costa Rica	Limón	9.950	−83.017	27.44	25.09	18.38	28.30	35.24	34.10	38.70	32.86	16.90	19.88	38.30	39.54
15	Costa Rica	Linda Vista del Guarco +Lankester CIGEFI	9.850	−83.900	2.50	2.10	1.06	2.60	21.00	20.55	13.70	16.74	26.75	25.50	12.35	5.70
16	Costa Rica	Linda_Vista	9.933	−84.083	0.10	0.00	0.10	2.85	25.12	26.75	19.34	25.40	29.61	28.00	13.25	2.84
17	Costa Rica	Llorona	9.400	−84.083	5.24	1.00	3.80	18.35	49.50	40.60	48.20	48.14	55.00	59.48	40.80	15.20
18	Costa Rica	Monteverde	10.136	−84.192	12.04	7.00	4.30	14.69	39.17	40.60	33.36	38.48	48.35	46.06	34.05	20.96
19	Costa Rica	Monteverde+ Monteverde CIGEFI	10.133	−84.825	7.90	6.27	3.70	4.85	30.18	33.50	24.50	29.04	41.20	41.30	21.70	14.60
20	Costa Rica	Nicoya	10.150	−85.450	0.00	0.00	0.00	4.90	29.40	30.50	25.48	35.04	37.90	37.76	14.85	0.00
21	Costa Rica	Palo_Seco	9.433	−84.150	4.40	0.00	3.04	19.80	48.30	43.65	48.42	50.12	60.90	57.88	42.45	17.92
22	Costa Rica	Piñera	9.138	−83.319	1.50	1.60	9.88	25.55	43.00	40.35	37.64	45.64	47.00	50.00	29.10	7.68
23	Costa Rica	Playón	9.533	−84.300	0.68	0.00	1.79	12.75	38.10	31.70	34.12	40.48	43.00	50.62	25.35	9.88

Table 2. *Cont.*

No.	Country	Station Name/Code	Latitude	Longitude	January	February	March	April	May	June	July	August	September	October	November	December
24	Costa Rica	Quepos	9.461	−84.159	4.02	1.20	3.81	18.15	42.60	39.30	42.04	46.64	51.60	52.35	35.98	14.14
25	Costa Rica	Repunta	9.300	−83.650	1.20	0.27	3.06	16.10	29.50	27.45	27.60	33.50	32.55	34.50	26.55	8.10
26	Costa Rica	San Miguel	10.417	−83.983	27.82	23.52	16.76	22.45	35.44	42.75	45.44	41.15	35.50	36.76	41.55	44.72
27	Costa Rica	San_José	9.633	−84.283	1.30	1.09	5.33	21.66	46.50	43.70	40.90	41.97	54.00	55.62	33.60	9.34
28	Costa Rica	Santa Cruz Balanya	10.261	−85.584	0.00	0.00	0.00	2.30	23.84	28.02	19.24	27.64	35.40	33.24	10.55	0.00
29	Costa Rica	Volcán Buenos Aires	9.217	−83.450	4.04	2.87	8.54	27.95	41.20	41.85	36.04	43.64	47.65	50.38	32.25	9.95
30	El Salvador	Ilopango	13.438	−88.158	0.00	0.00	0.00	0.20	21.80	25.20	22.50	27.32	29.75	22.38	2.25	0.00
31	Guatemala	Asunción Mita	14.334	−89.706	0.00	0.00	0.00	0.60	17.58	30.95	22.50	23.42	28.30	16.58	0.00	0.00
32	Guatemala	Camotan	15.044	−91.024	0.00	0.00	0.00	2.83	17.54	27.50	23.70	24.05	26.70	17.64	3.60	1.00
33	Guatemala	Chinique	15.467	−90.408	9.51	8.84	7.14	8.70	16.24	26.65	21.00	21.70	27.55	25.16	18.45	10.10
34	Guatemala	Coban	15.109	−90.614	0.10	0.00	0.00	2.60	16.58	23.55	15.70	18.80	21.77	13.61	3.10	0.30
35	Guatemala	El asintal	17.183	−89.000	12.48	7.60	2.74	2.00	6.10	19.25	20.18	17.00	18.26	21.92	19.80	14.46
36	Guatemala	Esquipulas	14.533	−89.033	0.90	0.50	0.14	2.60	18.70	30.75	28.50	31.24	33.45	20.52	2.35	1.40
37	Guatemala	Flores	17.250	−88.700	14.20	7.17	4.60	3.25	9.96	27.90	27.64	23.90	27.40	25.27	24.07	17.58
38	Guatemala	Huehuetenango	15.317	−91.503	0.00	0.00	0.00	4.70	13.00	20.25	11.40	13.22	23.05	11.64	1.90	0.00
39	Guatemala	Isivumeth	14.583	−90.533	0.00	0.00	0.00	1.00	12.44	24.15	18.90	18.64	24.60	12.20	1.10	0.00
40	Guatemala	La Ceibita	14.493	−89.876	0.00	0.00	0.00	0.00	11.74	23.40	16.64	18.12	20.40	11.00	0.20	0.00
41	Guatemala	La fragua	14.964	−89.584	0.00	0.00	0.00	0.00	8.84	18.30	12.60	13.04	15.33	6.00	0.50	0.00
42	Guatemala	La Unión	15.733	−88.583	24.16	20.20	11.80	14.05	18.76	27.00	36.00	37.34	32.60	35.96	39.22	29.68
43	Guatemala	Labor Ovalle	14.870	−91.480	0.00	0.00	0.00	2.85	14.34	16.05	10.84	12.64	15.45	10.24	1.15	0.00
44	Guatemala	Nebaj	16.983	−88.317	16.24	6.88	3.90	3.00	11.44	26.50	25.12	22.60	31.05	30.58	24.35	19.10
45	Guatemala	Quezada	14.535	−91.678	0.00	0.00	0.20	13.00	40.48	49.59	39.00	41.00	50.10	39.14	10.80	0.00
46	Guatemala	Sabana Grande	14.030	−91.050	0.00	0.00	2.54	20.00	46.58	55.90	46.19	49.68	56.00	51.34	16.85	0.14
47	Guatemala	Sacapulas	14.301	−90.786	0.00	0.00	0.00	0.40	20.39	31.65	24.48	29.18	29.77	22.00	1.85	0.00
48	Guatemala	San Jerónimo	16.517	−89.867	7.24	3.20	1.44	2.51	11.94	23.43	20.83	20.88	25.15	22.40	15.00	9.68
49	Guatemala	San Pedro Soloma	14.632	−91.231	0.00	0.00	0.00	5.65	15.88	23.80	13.21	16.64	23.00	13.34	2.00	0.00
50	Guatemala	Santa Cruz Balanya	14.801	−90.640	0.00	0.00	0.00	0.37	18.60	31.40	24.42	25.82	32.07	21.97	1.35	0.00
51	Honduras	78719	14.059	−87.216	0.30	0.10	0.10	1.30	14.74	16.85	8.08	9.80	16.90	12.08	2.60	0.40
52	Honduras	Choluteca	13.318	−87.154	0.00	0.00	0.00	1.60	32.14	29.10	18.68	25.14	37.60	31.42	2.35	0.00
53	Honduras	Jaral	14.938	−88.005	13.81	9.34	4.34	6.85	20.74	38.90	44.34	42.76	47.13	37.14	29.17	16.72
54	Honduras	La Ceiba	15.730	−86.870	34.06	20.39	14.30	5.65	8.30	23.95	27.44	24.52	28.46	51.07	59.65	40.38
55	Honduras	La Mesa	15.400	−87.900	8.05	4.50	1.04	0.65	5.74	16.31	14.86	13.50	16.00	15.70	18.15	10.09
56	Honduras	Pitosolo	14.780	−88.010	16.39	12.11	6.28	8.15	18.04	33.63	39.22	36.66	40.90	38.80	28.57	17.68
57	Honduras	Sjeronimo	15.070	−90.250	0.70	0.46	0.50	8.40	17.00	16.96	21.29	21.14	14.83	6.91	2.50	0.50
58	Honduras	Vallecillo	14.520	−87.400	5.30	2.37	1.48	6.85	23.21	29.35	26.40	27.22	33.25	31.08	13.92	5.90
59	Nicaragua	45018	13.339	−86.385	0.65	0.30	0.10	0.00	13.38	14.15	7.40	9.80	14.70	15.70	3.20	1.30
60	Nicaragua	55026	12.763	−85.627	3.80	2.50	1.20	1.30	13.68	25.05	21.26	20.80	18.75	17.78	9.20	5.60
61	Nicaragua	60006	12.427	−86.913	0.00	0.00	0.00	0.00	24.44	24.10	13.16	21.02	38.10	29.68	8.25	0.00
62	Nicaragua	61009	12.583	−81.700	7.31	3.79	1.72	1.82	11.71	23.34	19.25	21.51	25.81	29.60	28.21	12.91
63	Nicaragua	61010	13.350	−81.350	8.72	5.17	2.20	2.10	11.24	19.61	17.05	20.13	26.16	32.98	25.80	11.34
64	Nicaragua	61025	12.633	−87.133	0.00	0.00	0.00	0.00	27.28	32.70	19.44	27.38	40.40	32.68	6.70	0.00

Table 2. *Cont.*

No.	Country	Station Name/Code	Latitude	Longitude	January	February	March	April	May	June	July	August	September	October	November	December
65	Nicaragua	69026	12.143	−86.164	0.00	0.00	0.00	0.00	15.70	16.65	14.04	16.00	22.20	20.30	4.00	0.20
66	Nicaragua	69031	11.722	−86.047	0.10	0.00	0.00	0.00	25.16	23.95	14.74	16.04	29.20	31.12	7.05	0.80
67	Nicaragua	69068	11.435	−85.833	0.34	0.00	0.00	0.00	18.69	23.80	13.92	20.30	28.90	25.82	9.70	2.00
68	Nicaragua	Corinto	12.517	−87.200	0.00	0.00	0.00	0.00	28.24	28.05	19.96	25.20	39.49	30.64	5.53	0.00
69	Nicaragua	Juigalpa	12.100	−85.367	0.80	0.30	0.00	0.00	15.98	19.60	12.71	15.34	25.65	19.20	5.40	1.30
70	Nicaragua	Ocotal	13.625	−86.477	0.10	0.00	0.00	0.20	15.34	15.20	7.40	9.14	16.05	12.18	2.10	0.30
71	Nicaragua	Puerto Cabezas	14.047	−83.375	13.34	8.47	4.50	5.15	20.04	36.53	41.86	35.00	31.90	35.08	31.50	17.20
72	Panamá	Agua_Clara	9.364	−79.706	10.20	5.10	5.10	17.80	35.60	38.10	33.00	40.60	38.10	45.70	53.30	33.00
73	Panamá	Anton	7.400	−80.450	0.00	0.00	0.00	2.17	18.96	20.05	18.24	21.64	22.45	28.40	25.90	8.34
74	Panamá	Balboa Heights	8.959	−79.554	2.50	0.00	0.00	7.60	23.19	22.90	21.75	21.95	20.99	27.90	27.90	15.20
75	Panamá	Boca de Toabre	9.424	−79.578	10.20	7.60	5.67	20.30	33.00	33.00	33.00	30.50	27.90	30.50	43.20	30.50
76	Panamá	Bocas Toro	9.340	−82.245	24.45	20.30	16.94	26.55	31.02	28.85	34.02	29.54	20.40	21.24	32.25	38.00
77	Panamá	Cerro Punta	8.508	−81.073	3.34	1.90	1.44	6.00	24.04	28.40	22.58	28.14	33.05	33.64	24.75	10.44
78	Panamá	Cocle del Norte	8.383	−80.267	0.00	0.00	0.00	1.95	16.68	19.75	19.70	19.78	20.45	25.94	24.80	8.84
79	Panamá	Cuesta de Piedra	8.065	−78.366	0.40	0.00	0.00	4.39	17.68	16.75	16.27	17.34	17.86	26.17	22.38	10.61
80	Panamá	David	8.397	−82.428	0.60	0.00	1.00	9.10	33.60	33.60	31.24	34.94	37.75	36.14	27.95	7.50
81	Panamá	Divisa	8.314	−81.209	0.00	0.00	0.00	7.80	37.94	37.00	32.86	43.54	46.84	46.44	33.45	8.10
82	Panamá	Escandalosa	9.167	−79.083	1.00	0.50	0.50	5.50	27.20	26.50	21.20	25.50	31.50	38.50	31.50	11.00
83	Panamá	Gatun	9.268	−79.921	7.60	5.10	2.50	16.35	30.50	27.90	27.90	30.75	28.21	33.00	40.60	25.40
84	Panamá	Icacal	9.205	−80.146	10.66	5.64	5.64	19.60	42.28	36.80	42.34	36.90	35.85	41.84	53.95	37.28
85	Panamá	Santiago	8.140	−80.704	0.00	0.00	0.00	0.80	23.54	23.75	17.08	21.88	27.40	28.82	24.00	4.74
86	Panamá	Tocumen	9.066	−79.392	0.30	0.00	0.00	5.75	24.34	25.00	19.14	22.94	26.00	31.30	27.10	11.64
87	Panamá	Tonosi	8.087	−80.978	0.20	0.00	0.00	11.30	34.30	32.15	25.14	35.00	35.42	37.84	29.90	8.98
88	Panamá	Valle Rico	7.941	−80.418	0.00	0.00	0.00	0.00	10.88	13.85	8.54	11.68	17.05	23.68	13.95	2.40

Gridded sea level pressure (SLP) and surface wind vectors from 1979 to 2010 at 0.75 by 0.75 degrees spatial resolution were obtained from the European Centre for Medium-Range Forecasts Interim Re-Analysis [28]. Daily means were based on basic synoptic hour observations. The data were used to determine the synoptic-scale atmospheric circulations related to extreme precipitation events in Central America associated with tropical cyclones.

Diverse information of the trajectories and other characteristics of tropical cyclones at hourly time steps from 1970 to 2010 were obtained from the combination of two databases: HURDAT [29] from the United States (US) National Hurricane Center and Central Pacific Hurricane Center part of the National Oceanographic and Atmospheric Administration and the final tracks from Unisys database from the repositories of the US National Aeronautics and Space Administration. The hourly data were concatenated from both data sources. The data includes the following information: hour, day, month, year, latitude, longitude, wind velocity, pressure, and instantaneous classification of the event (tropical depression, tropical storm, category 1 hurricane, category 2 hurricane, category 3 hurricane, category 4 hurricane, and category 5 hurricane). Tropical storms and hurricanes categories 1 to 5 represent named cyclones. Unless otherwise specified, extreme precipitation events (above the climatological 90th percentile) were associated with all the hourly cyclone data of that day to create composites and other subsequent analyses. The cyclone data were used as input to determine the relationship between extreme precipitation events and the locations of the tropical cyclones in the Caribbean Sea and Eastern Tropical Pacific Ocean. In Table 3, the classification of tropical cyclones according to their maximum wind speed is shown.

Table 3. Classification of tropical cyclones according to the Saffir–Simpson scale (for hurricanes) and other related classifications. Wind speed refers to the 1-min maximum sustained winds.

Category	Windspeed [km/h]	Damage
Five (major)	>252	Catastrophic
Four (major)	209–251	Catastrophic
Three (major)	178–208	Devastating
Two	154–177	Extremely dangerous
One	119–153	Very dangerous
Tropical storm	63–118	-
Tropical depression	<62	-

A visualization tool was developed in C++ (openframeworks). The selection of this platform was due to the response features that are many times superior to other programming languages such as Java or JavaScript [30]. Besides, the openframeworks platform allows the multiplatform use of the resulting application (Apple OS X, Windows, and Linux); these two parameters, efficiency and universality of use, were the most important for the selection of the programming environment of the tool. The map was georeferenced with data from Natural Earth, a public domain map dataset.

The data of meteorological events, in turn, were uploaded locally through .csv files that were prepared ad hoc to increase the efficient use of the tool. The result is a tool that is capable of handling more than 40,000 events in real-time. The tool allows the user to select a particular group of meteorological stations. Selecting the stations allows the user to visualize a composite of the trajectories of the tropical cyclones that produced extreme precipitation events (daily precipitation above the 90th percentile of the precipitation climatology of the corresponding month). The tool allows the user to select all types of tropical cyclones or only certain type(s). The regions where there is a large accumulation of critical trajectories are shown with a dense shading.

The visualization tool was used to determine the critical positions of tropical cyclones that produce extreme precipitation events in each Central American region. The results are shown separately for tropical cyclones that originated in the Eastern Pacific and Caribbean/Atlantic oceanic basins. The data from the visualization tool was used to determine the foci of critical locations that produce a large number of extreme precipitation events in Central America. Note that this analysis of the critical regions was based only on their trajectories, regardless of the cyclone intensity (the only requirement is that the maps were constructed from named storms only).

The regions that produce extreme weather in Central America were identified from the trajectory density maps. For each critical region (where the density of trajectories was higher), an index was produced to analyze the associated atmospheric patterns and the time evolution of the presence of storms (of different ranges of categories) in the critical zones.

Contour maps of the number of stations in extreme precipitation events were plotted at the median daily position of the cyclone. This was used to identify critical cyclone locations associated with the largest quantity of impacts. To obtain a better geovisualization, the data were improved in a Geographic Information System Software (GISS) like ArcMap 10.7 from ArcGIS UCR license.

3. Results and Discussion

3.1. Caribbean Oceanic Basin Results

The density maps of the trajectories of hurricanes categories 1 to 5 in the Caribbean basin, associated with extreme precipitation events in the countries of Central America are shown in Figure 1. Although it is evident that hurricanes can produce impacts when they are located anywhere around the Caribbean basin, there are indications of several poles of the high density of trajectories associated with extreme precipitation events. To illustrate the atmospheric circulation associated with one pole of high accumulation of trajectories located off the Yucatan Peninsula and the Gulf of Honduras (which is present in several of the country maps), we produced SLP and wind composites during extreme precipitation events concurrent to days when the hurricanes were located in that pole (positions inside the box bounded by 14.5° N to 23° N and 84° W to 90° W) (Figure 2). As expected, there is a low-pressure anomaly near the composited average location of the hurricanes inside the box. The low-pressure system implies a gradient between the pressure anomalies in the Pacific and the Caribbean, and this configuration drives anomalous winds from the Pacific Ocean to the west coast, which causes indirect impacts by orographic lifting in the slope opposite to the location of the hurricane. This type of hurricane impact is well known to the emergency response authorities in the Central American countries and mentioned in impact studies literature [1], but here a better identification of critical zones will be provided below. The mechanism was also previously illustrated in the schematic shown in Figure 3 of [7], but here we used actual data for analyzing the circulation patterns.

Two aspects are interesting to note from Figure 2: first, the coloring of the meteorological stations evidences the relative difference in the number of extreme precipitation events on both slopes of the isthmus (also consistent with the difference of impacts in both slopes reported by [1]). That is, the largest number of extreme precipitation events are reported on the Pacific slope of Nicaragua, a moderate number on the Pacific slope of Guatemala and on the Pacific northwestern coast of Costa Rica with fewer reports observed in the Caribbean slopes, southern Costa Rica, and Panama. This is interesting, as it confirms that the atmospheric circulation patterns of Figure 2 are consistent with the precipitation response and that emergency response resources associated with hurricane indirect effects in Central America should be focused on the Pacific slope. Indirect effects are an important threat in southern Central American countries, as a direct hit of a hurricane in these countries is rare considering the normal patterns of Caribbean cyclone tracks. Colon (1969) cited by [18], determined that the probability of a Caribbean hurricane landing in Costa Rica is less than 5 %. Along with indirect effects, northern countries experience occasional direct hits of hurricanes from the Caribbean, and several large events (e.g., hurricanes Mitch and Stan) have resulted in catastrophes of large proportions. The second issue that is interesting to note is that although in Figure 1 the analyzed pole of higher track density is located in the Gulf of Honduras, the SLP pattern depicted in Figure 2a is located further north within the interest box, just offshore the Yucatan Peninsula. A possible reason is that Figure 1 does not take into consideration the hurricane intensity, while in Figure 2a the composite is constructed by averaging the SLP anomalies during days of extreme precipitation events, and therefore the larger SLP anomalies from stronger hurricanes dominate the composite. This may result in the difference in the critical hurricane position shown. Nevertheless, trajectories that end up in the critical box identified before, may result in significant indirect impacts on the Pacific slope of the Central American countries. This is an important observation, as the forecasts of storm trajectories (regardless of the intensity of the cyclone) that may contain this zone, should be considered for issuing suitable emergency alerts. The use of the software tool mentioned before can be used in an interactive manner to determine possible critical regions, associated with extreme precipitation events in one or more user-selected meteorological stations. This tool is a valuable asset for emergency response institutions in the region.

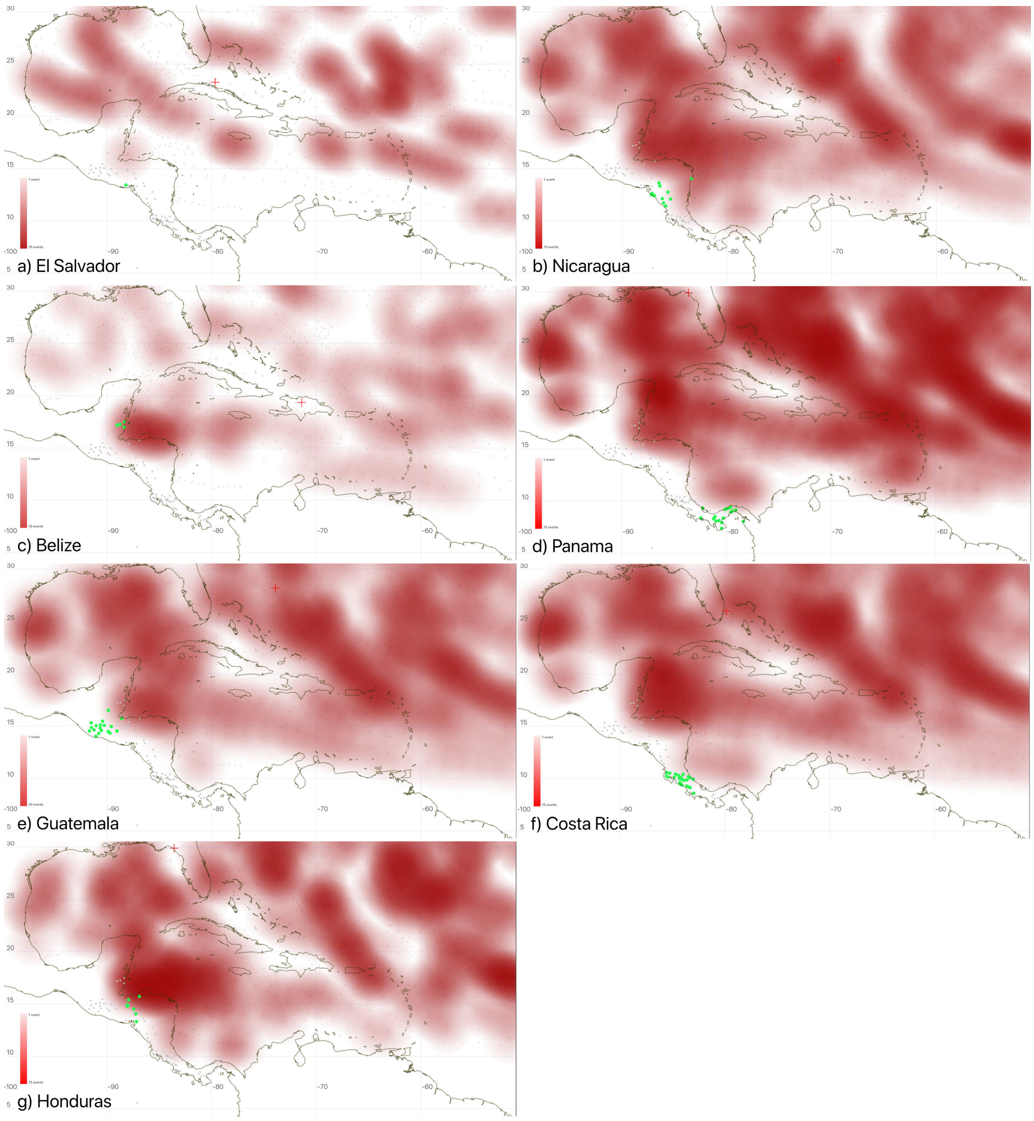

Figure 1. Densities of Caribbean tropical cyclones trajectories that produce extreme precipitation events in countries of Central America (data 1970–2010). The shades are shown with an arbitrary intensity scale (only their relative spatial pattern is of interest within each of the maps). The scale of the shading represents the density of red color shades of the intersection from 1 to 15 trajectories. Gray dots are the location of the inactive stations, light green dots are the stations active in the tool that are associated with the red cyclone densities shadings. The subfigures correspond to the densities of tropical cyclones trajectories associated with extreme precipitation events in the meteorological stations of the different Central America countries shown with green dots in the figure. The subfigures are shown for El Salvador (**a**), Nicaragua (**b**), Belize (**c**), Panama (**d**), Guatemala (**e**), Costa Rica (**f**) and Honduras (**g**). Data 1970–2010.

In Figure 2b the streamlines associated with extreme precipitation events in each of the countries combined with critical hurricane positions in the high-density pole of interest are shown. As can be seen, there is cyclonic circulation near the position of low pressure shown in Figure 2a that draws wind and moisture from the Pacific, especially affecting Nicaragua.

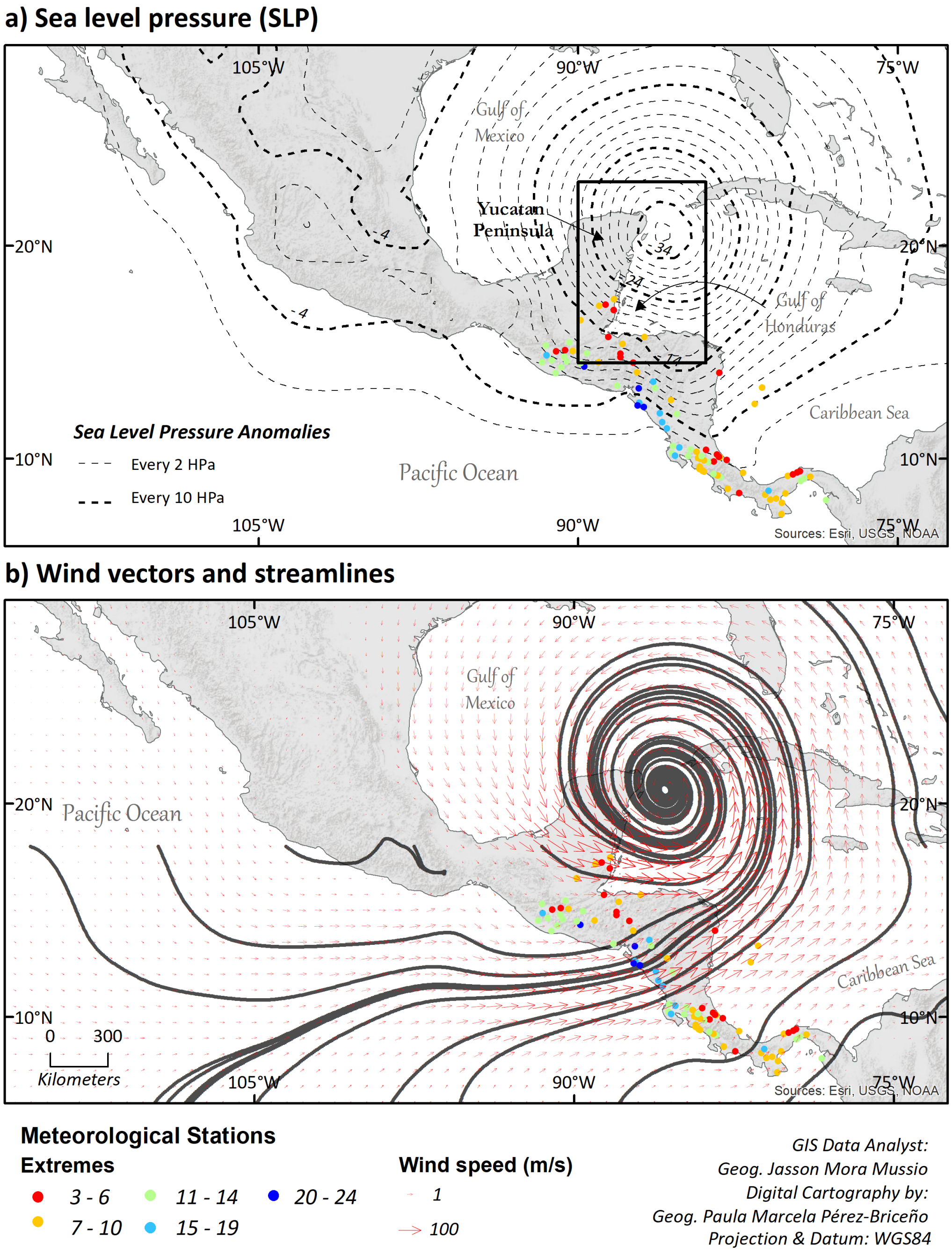

Figure 2. Average anomalies of sea level pressure (SLP) (**a**) and wind vectors with associated streamlines (**b**) during extreme precipitation events in Central America meteorological stations and when the hurricanes occupied the region bounded by 14.5° N to 23° N and 84° W to 90° W. Cold (warm) colors of the land meteorological precipitation stations denote a large (small) number of registered extreme precipitation events during the period that produces the composite. SLP contours every 2 hPa (thin lines) and every 10 hPa (thick lines). Although the trajectories data cover the period 1970 to 2010, this illustrative figure was constructed using data from 1979 to 2010 due to limitations in the availability of SLP data.

We counted the number of trajectories from 1948 to 2010 reaching the critical zone defined before. The results are shown in Figure 3. As can be seen, although the trends are positive in all cases, none of them are significant at the 95 % confidence level according to the Mann-Kendall test [31,32] applied to the data, in agreement with the previous results of [16,17,33], and partially with the results of [34].

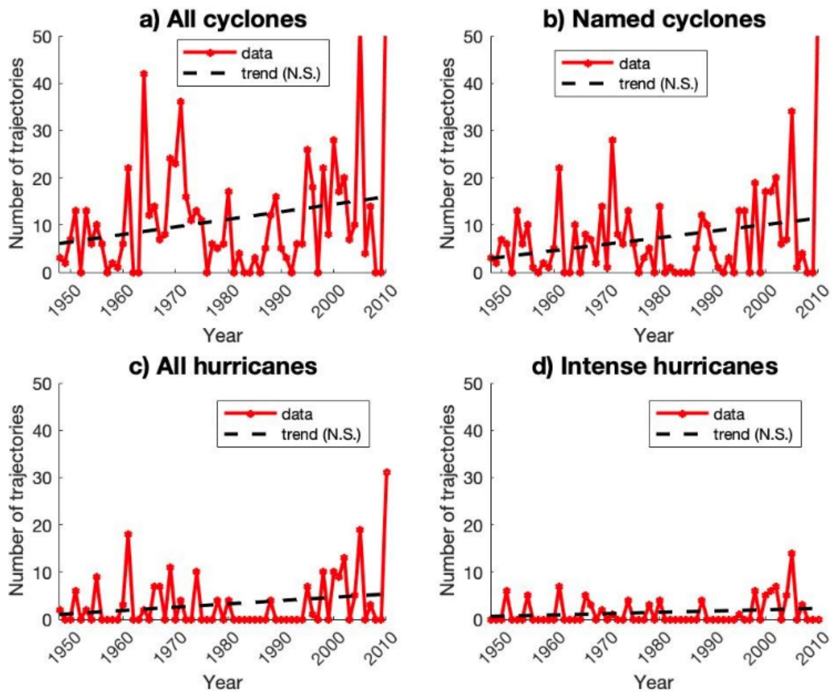

Figure 3. Annual number of tropical cyclones in the region bounded by 14.5° N to 23° N and 84° W to 90° W. Named cyclones refer to tropical storms and hurricanes category 1 to 5. All hurricanes refer to hurricanes categories 1 to 5. Intense hurricanes are those reaching category 3 to 5. Each subfigure correspond to the number of trajectories for all cyclones The red lines are the number of trajectories en the selected region and the dashed black line is the trend. Non-significant trends at the 95% confidence level are indicated with N.S.. Data 1948–2010. (**a**) All cyclones, (**b**) named cyclones, (**c**) all hurricanes, (**d**) intense hurricanes.

Note that although there are extreme precipitation events in the Caribbean coast near the low-pressure critical zone, probably associated with the direct impacts of the hurricanes, the number of stations reporting extreme precipitation events (red dots in Figure 2) is greater on the Pacific slope, where the effects are indirect. The direct hit of a hurricane usually brings destruction and a large number of impacts to the affected region, but the indirect effects are more frequently reported in the precipitation stations of the Pacific slope. The prevalence of impacts in this subregion is also shown in the spatial distribution of tropical cyclone impacts analyzed by [1]. Another important issue is that even a relatively lower intensity storm located in a critical position can result in a catastrophe. For example, that was the case of Tropical Depression 16 of 2008, an unnamed storm that caused a disaster on the Costa Rican Pacific slope [35]. Around 490 communities were affected by flooding, landslides, and infrastructure damages [35]. In Costa Rica, there were around 1850 people directly affected by flooding and landslides and approximately 92,600 people, directly and indirectly, impacted [35]. The trajectory and municipalities impacted by the storm are shown in Figure in the Appendix A Figure A1.

In Figure 4, we identified the critical cyclone locations that produce the largest number of stations reporting extreme precipitation events. One of the most consistent critical regions in the different classification of events used in Figure 4 is the zone of the Gulf of Honduras. It is evident that the location of the cyclones in this position directly affects the Caribbean coast and a large number of indirect effects in the stations of the Pacific slope.

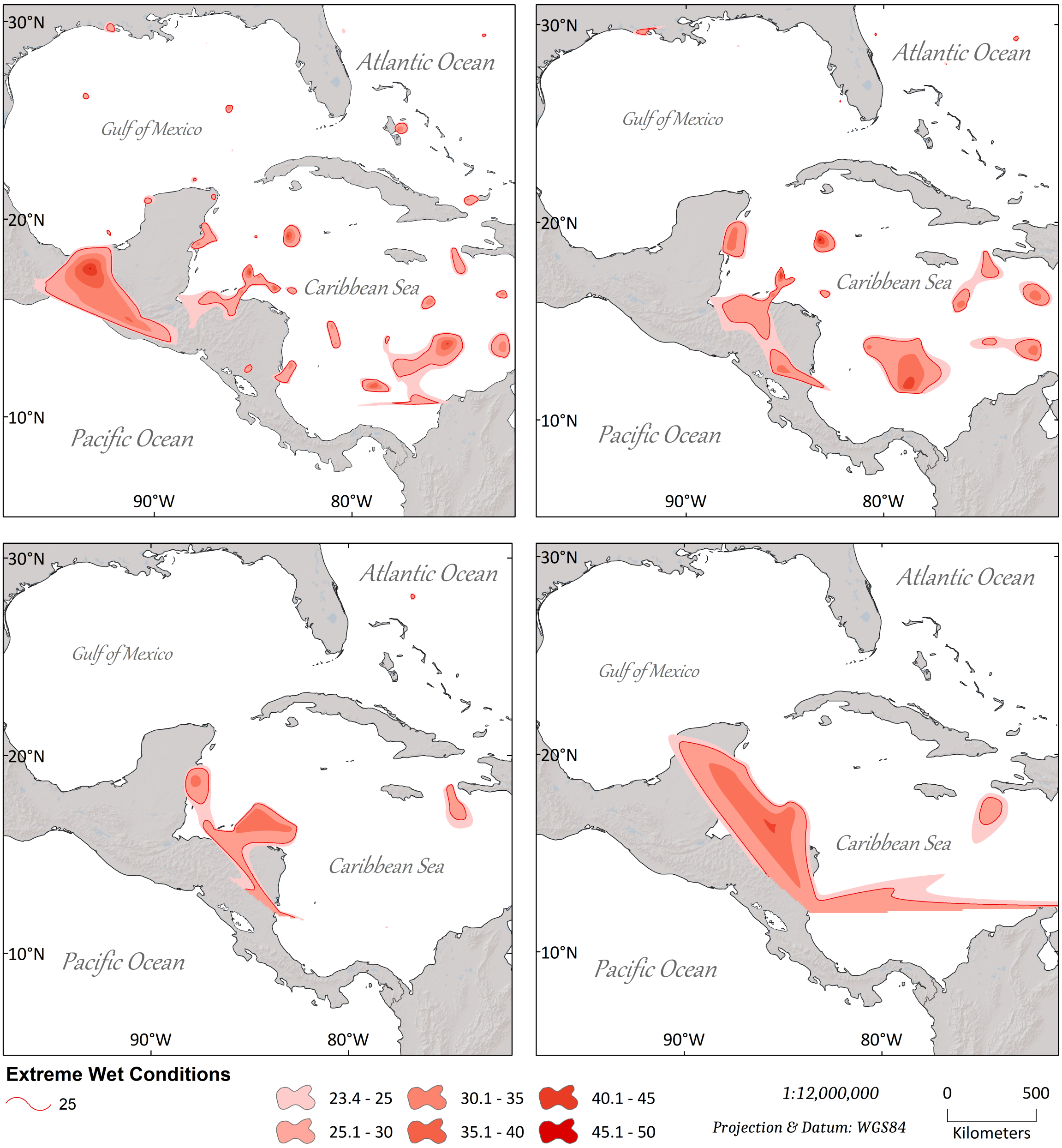

Figure 4. Contours depicting the number of meteorological stations in Central America reporting extreme precipitation events (above 90th percentile) plotted in the median corresponding daily location of the Caribbean cyclones. The category of the cyclone was determined from the median category identifier number of the hourly data of each day. Data from 1970 to 2010. (**upper left**) All cyclones, (**upper right**) named cyclones, (**lower left**) all hurricanes, (**lower right**) intense hurricanes.

3.2. Eastern Tropical Pacific Oceanic Basin Results

In the Eastern Tropical Pacific Ocean, the spatial distribution of trajectories associated with heavy rainfall in Central America is scattered in a large region (Figure 5). In a similar fashion as for the Caribbean, we selected a critical region of high trajectory density. In this case the box defined by 10° N to 25° N and 101° W to 121° W was selected for studying the associated circulation, which is shown in Figure 6. As can be seen, the box is now significantly larger and contains a large number of dispersed events. The contours of Figure 6a are more closely plotted, but even so, the low-pressure anomaly is significantly weaker than for the Caribbean. The streamlines in the Pacific are widely spaced and there is a vortex in the Caribbean associated with curled low velocities, that may be marginally affecting the Pacific moisture carrying mechanism pattern.

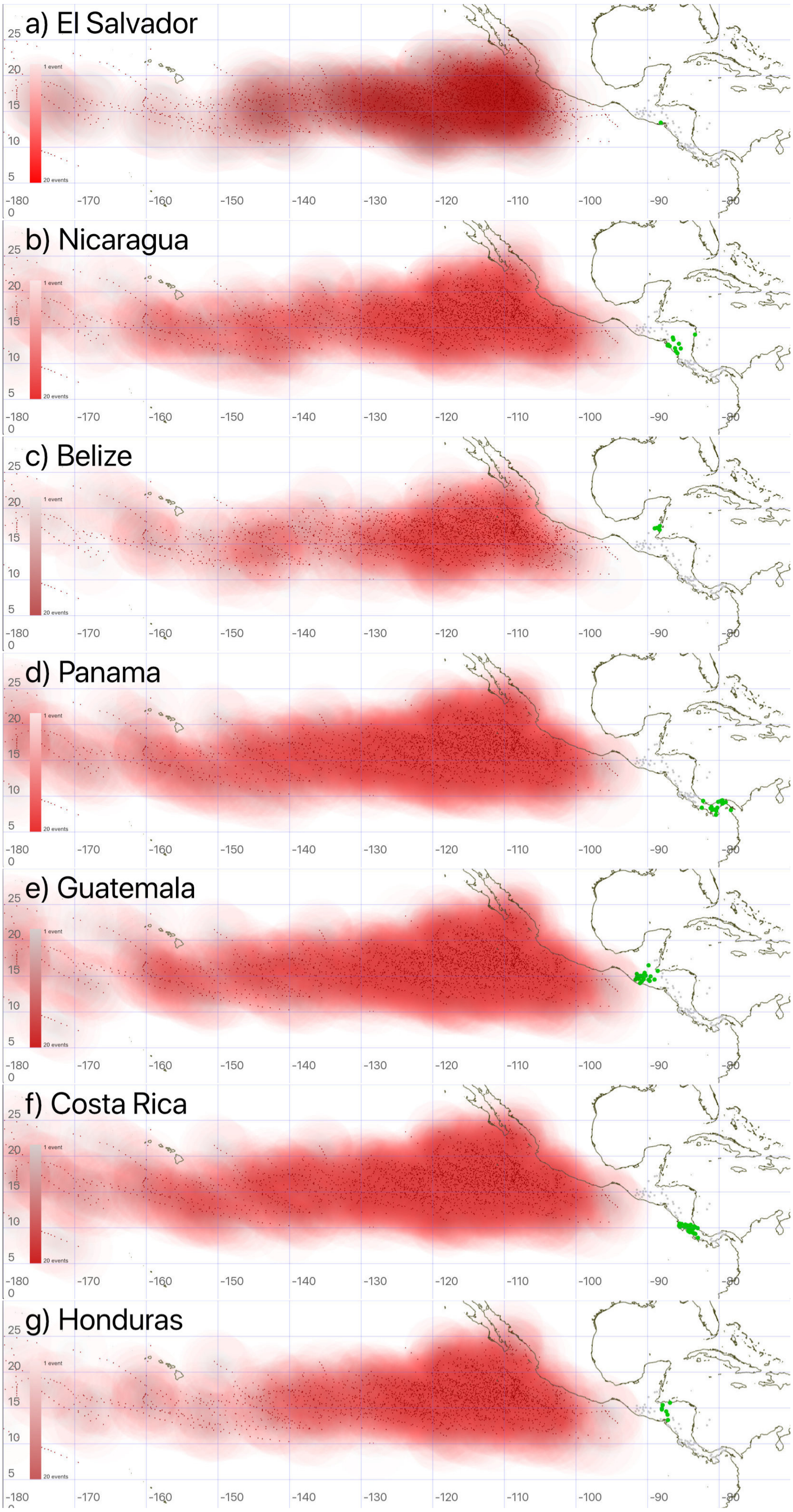

Figure 5. Same as Figure 1, but for cyclones in the Eastern Tropical Pacific basin. The subfigures are shown for El Salvador (**a**), Nicaragua (**b**), Belize (**c**), Panama (**d**), Guatemala (**e**), Costa Rica (**f**) and Honduras (**g**).

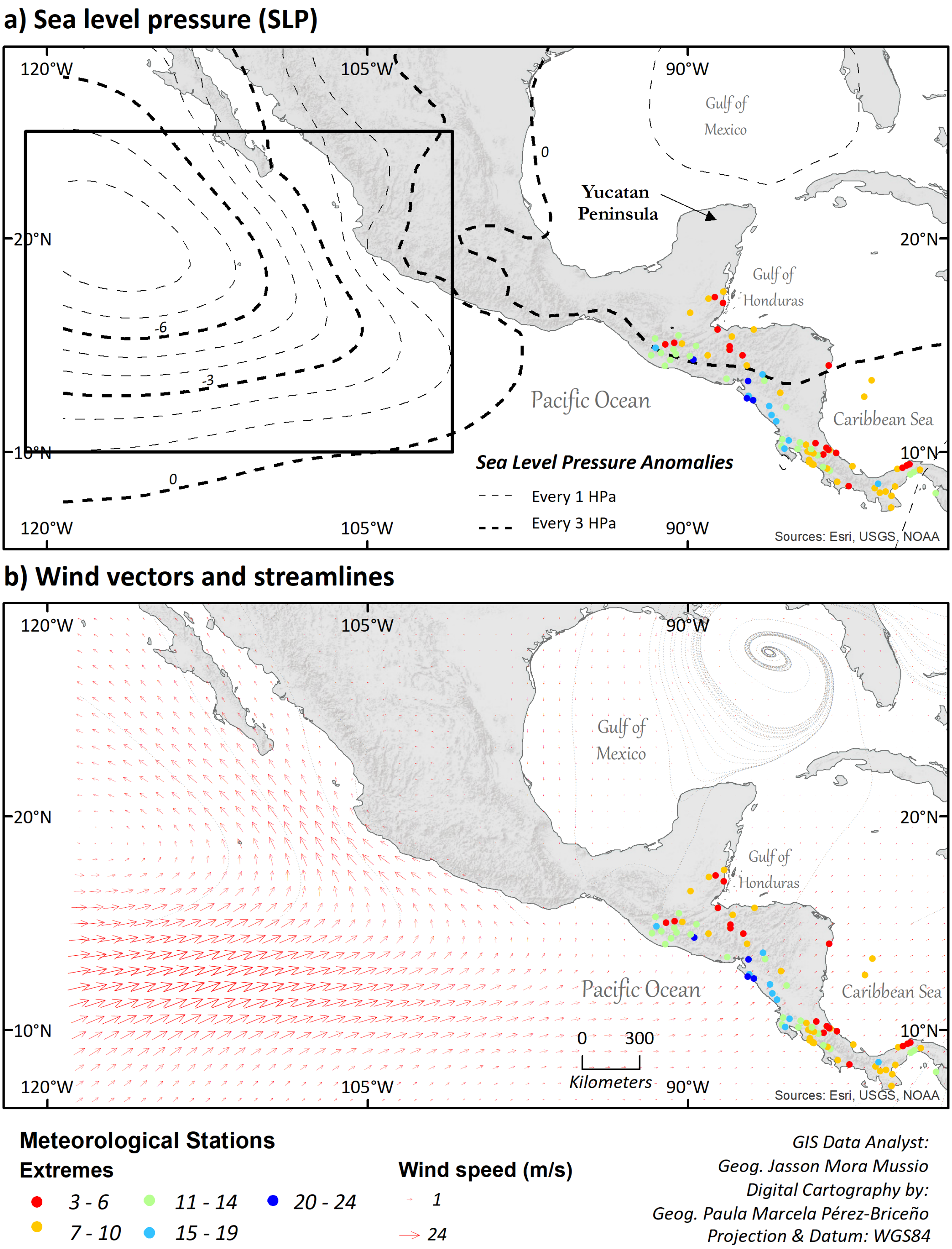

Figure 6. Same as Figure 2 but for anomalies of sea level pressure (SLP) (**a**) and wind vectors with associated streamlines (**b**) for a Pacific Ocean box 10° N to 25° N and 101° W to 121° W. SLP contours every 1 hPa (thin lines) and every 3 hPa (thick lines).

In Figure 7 the locations of the critical zones are identified. As can be seen, there are a lot of dispersed locations in the Pacific that cause extreme precipitation events, but in a smaller number of stations with respect to the Caribbean. The exception is when lower intensity cyclones (Figure 7) are located near and on the coast of Nicaragua and Costa Rica, for example, when the Tropical

Storm Alma landed in Nicaragua in 2008. However, comparing Figure 7 to Figure 4 it is evident that these types of cyclone locations are rare. Another important issue is that as in the Atlantic basin, even a relatively lower intensity storm located in a critical position at the Eastern Tropical Pacific can induce a circulation over Central America that could result in important impacts, like the low-pressure system located offshore Guanacaste and causing damage on the Costa Rican slope from 22 to 28 May at this early cyclone stage. This system evolved later into Tropical Storm Agatha [36]. The trajectory and municipalities impacted by Tropical Storm Alma and Tropical Storm Agatha are shown in Figure A2.

The number of storms in the Pacific's critical zone appear to be decreasing from 1970 to 2010 (Figure 8).The trends are significant when all cyclones and only named cyclones are considered. In general, the impacts of Pacific oceanic basin cyclones are also located on the Pacific slope of the isthmus. These results are in partial agreement with those of [34,37], who found no evidence of positive trends in the annual time series of Tropical Cyclone occurrences in the Eastern Tropical Pacific basin.

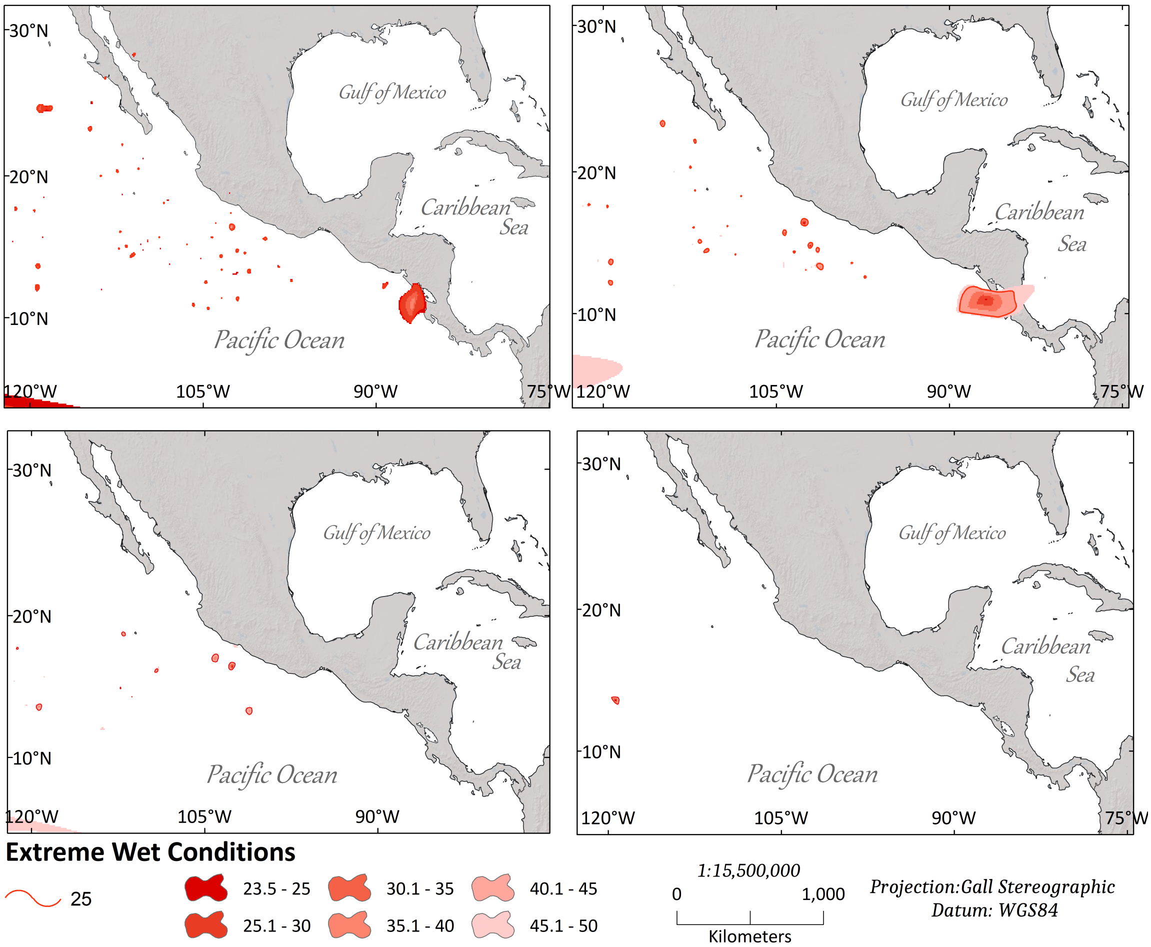

Figure 7. Same as Figure 4, but for Eastern Tropical Pacific ocean cyclones.(**upper left**) All cyclones, (**upper right**) named cyclones, (**lower left**) all hurricanes, (**lower right**) intense hurricanes.

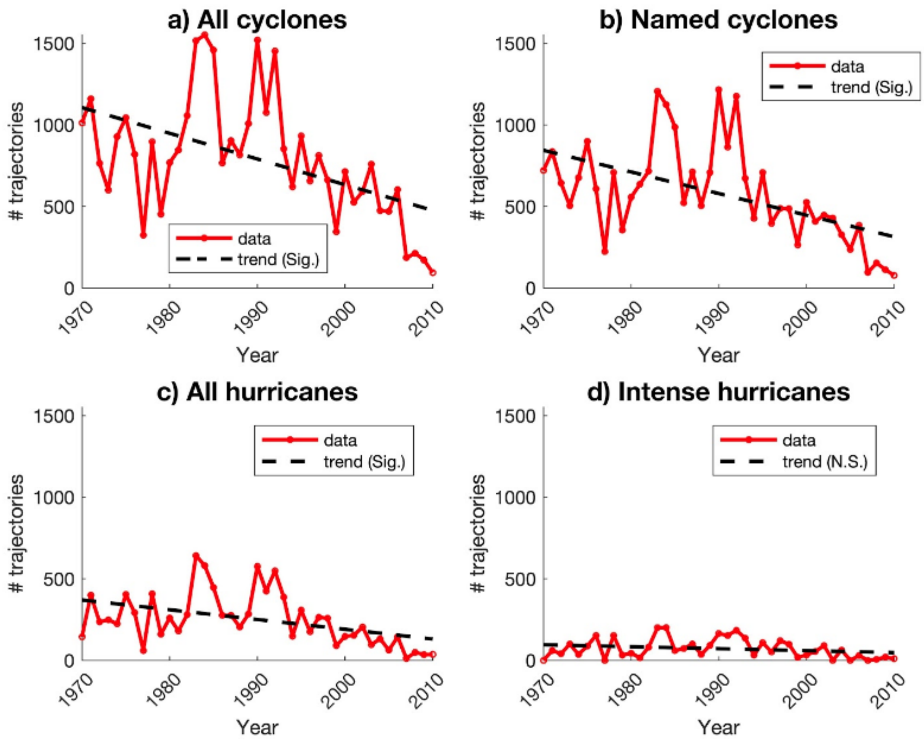

Figure 8. Same as Figure 3, but for a Pacific Ocean box 10° N to 25° N and 101° W to 121° W. (**a**) All cyclones, (**b**) named cyclones, (**c**) all hurricanes, (**d**) intense hurricanes.

4. Conclusions

Tropical cyclones from the Caribbean and Pacific basin produce a large number of indirect impacts on the Pacific slope of the Central American isthmus. Although the direct impact of a tropical cyclone usually results in devastation in the affected region, the indirect effects are more common and sometimes equally severe. In fact, the storm does not need to be an intense hurricane to cause considerable impacts and damage. The location of even a lower intensity storm in critical positions of the oceanic basin can result in destructive indirect impacts in Central America.

Storms' critical locations in the Caribbean oceanic basin are identified with more precision compared to the Pacific basin. One important critical zone is located in the Gulf of Honduras and surrounding areas. The Pacific basin location is more widespread, and the largest number of extreme precipitation events were observed when the cyclone was located off the Pacific coast of Nicaragua and Costa Rica and inside the continent (i.e., Tropical Storm Alma in 2008). For other positions, the number of impacted stations is smaller, and the locations of critical regions are not very well defined.

Positive (but not significant) trends (1948–2010) in the number of incursions of tropical cyclones in the Caribbean critical region were observed. There is great variability from year to year in these data. In the Pacific, a larger area of influence showed significant decreasing trends (1970–2010) when summing the incursions of all cyclones and when only named storms were considered. Although the influence of low-frequency climate modes can not be discarded, attention should be given by the authorities to the possible increase of indirect effects from Caribbean cyclones entering critical zones.

Identifying these critical locations is important for emergency preparedness. Forecasts issued that contain cyclones' projected trajectories into those critical zones must result in adequate alerts in potentially affected communities. The information from this work will be shared with the emergency agencies of the region.

Author Contributions: Conceptualization, H.G.H., and E.J.A.; methodology, H.G.H., E.J.A. and F.H.-C.; software, F.H.-C., H.G.H. and P.M.P.-B.; validation, H.G.H., E.J.A. F.H.-C.; formal analysis, H.G.H. and E.J.A.; investigation, H.G.H., E.J.A. F.H.-C. and P.M.P.-B.; resources, H.G.H. and E.J.A.; data curation, H.G.H., F.H.-C. and P.M.P.-B.;

writing–original draft preparation, H.G.H., E.J.A. and P.M.P.-B.; writing–review and editing, H.G.H., E.J.A., P.M.P.-B. and F.H.-C.; visualization, F.H.-C., P.M.P.-B. and H.G.H.; supervision, H.G.H. and E.J.A.; project administration, H.G.H., E.J.A.; funding acquisition, H.G.H. and E.J.A. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

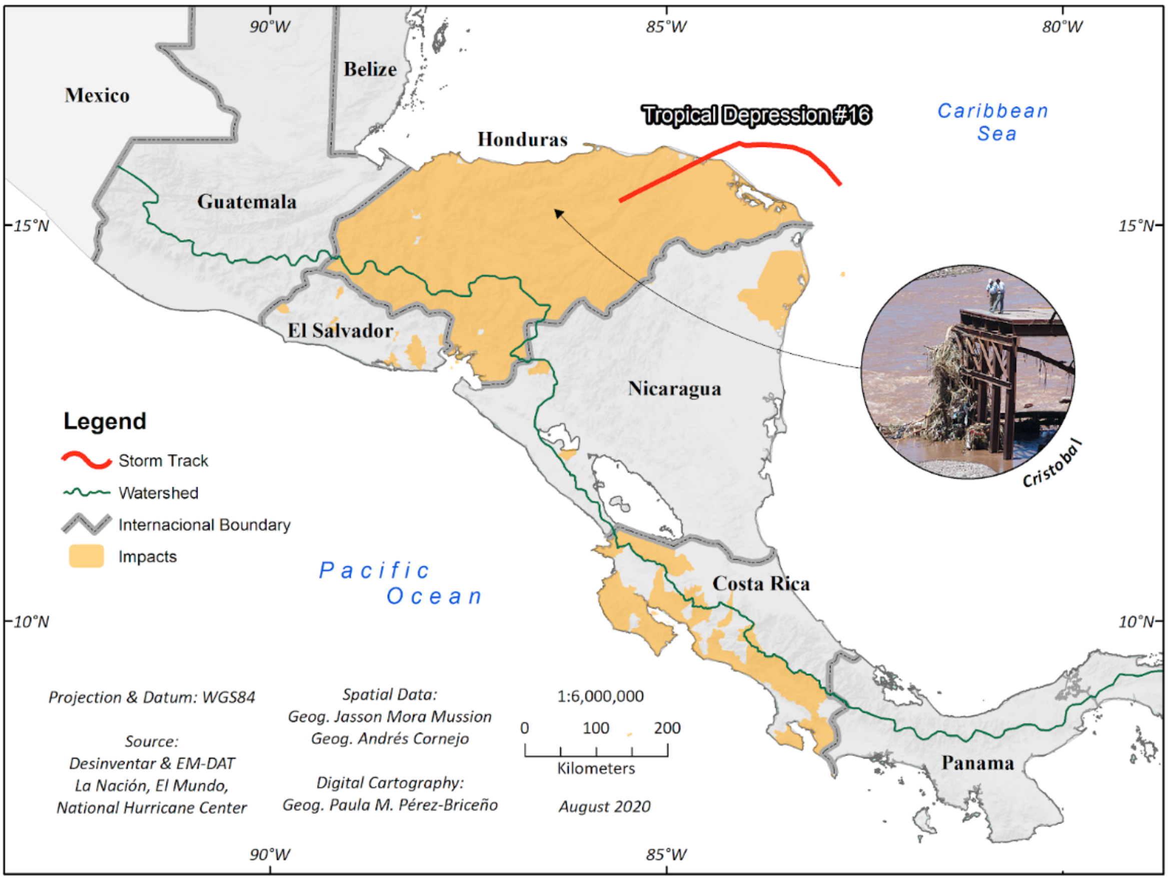

Figure A1. Examples of tropical cyclones in the Caribbean that caused widespread direct and indirect impacts.

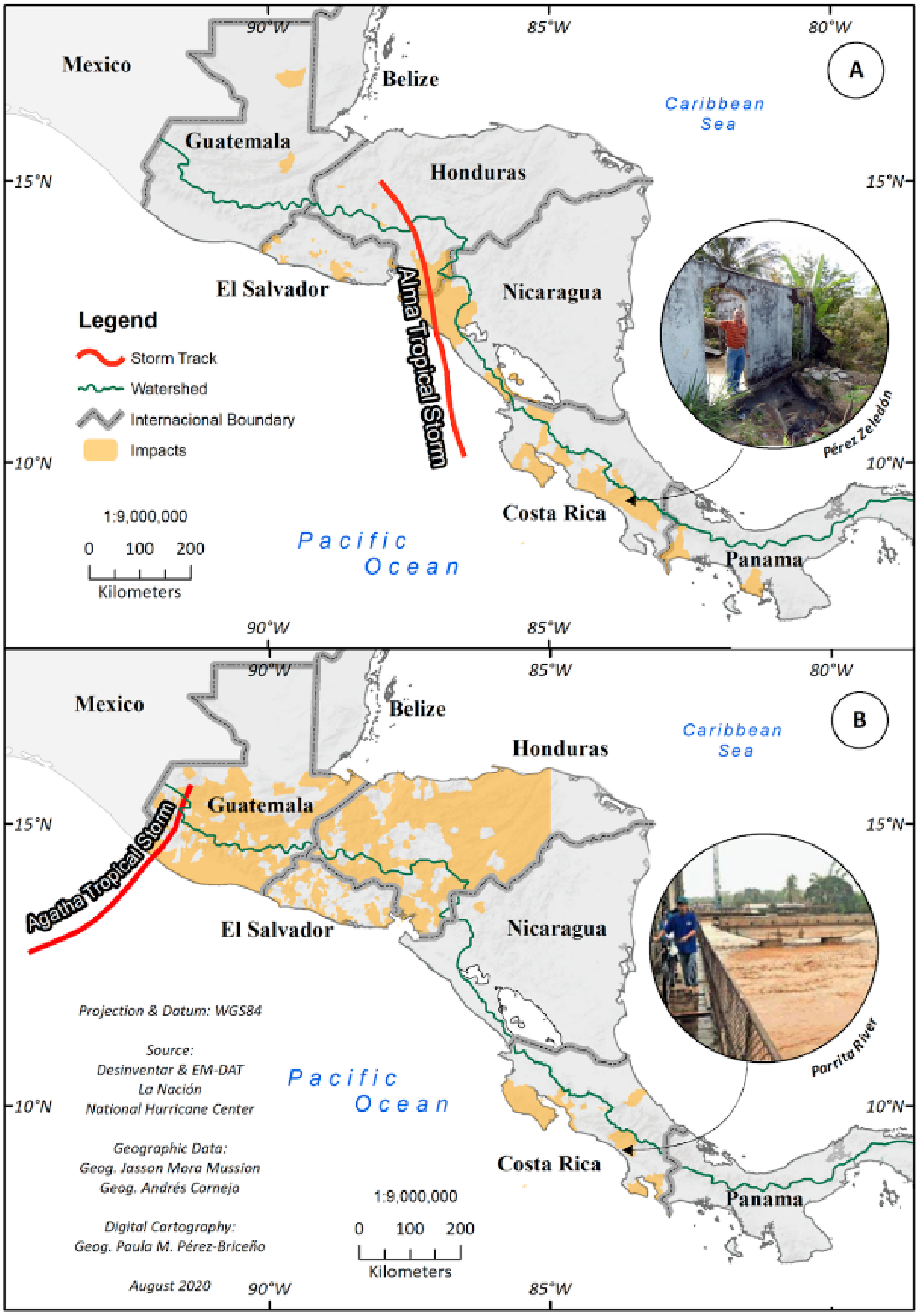

Figure A2. Same as Figure A1, but for the Pacific.

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