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Variability and trends of coastal flooding in Cuba (1901-2020)

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Abstract: The variability and trends of coastal flooding in the Cuban archipelago from 1901 to 2020 were analyzed. The chronology and classification of these extreme events by province were used, along with the proportion hypothesis test to compare two samples from the same population. The results confirm a statistically significant increase (at the 5% significance level) in the frequency of coastal flooding along all Cuban coasts since 1981; the most intense events occurred during the 21st century, due to Cuba being affected by eleven major hurricanes.

Key words: coastal flooding; statistics trends; climatic variability; tropical cyclones

1 Introduction

The occurrence of coastal flooding in a region is determined by sea level rise, resulting from the meteorological system that generates it, its movement relative to the coastline, and local physical and geographical characteristics (Mitrani et al. 2017). In nature, three forms of sea level rise due to meteorological causes are identified: cyclonic upwelling, wave breaking, and wind drag; these can be combined in any combination, but one or the other will predominate depending on the forces at play and the local conditions of the study area.

Several researchers have studied the variability of tropical cyclone activity in Region IV (which includes the Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico) of the World Meteorological Organization. Among them, Frank and Young (2007) analyzed the interannual variations of tropical cyclones (TCs) and their relationship with the El Niño-Southern Oscillation (ENSO) event. Ballester et al. (2010) studied the variability and trend of TCs throughout this region, using the period 1851–2008 as a reference, finding no statistically significant trend, although they did observe an increase in these events in Cuba since 1996. Finally, Montoya et al. (2017) explored the change in wave activity associated with hurricanes in the Caribbean Sea.

In Cuba, the main research on coastal flooding conducted between the 1980s and 1990s is compiled in Moreno (1998), which highlights the Havana seawall as the most studied areas, followed by the Gulf of Batabanó and the Baracoa seawall. Studies on these phenomena carried out during the current century are grouped in Mitrani et al. (2017), which delves into the thermohaline structure (the increase in water temperature and salinity in the first 500 meters of depth) and its relationship with El Niño-Southern Oscillation (ENSO). Meanwhile, the results of the project "Chronology of Coastal Flooding Due to Sea Level Intrusion for the Cuban Archipelago", published by Hidalgo et al. (2017), allowed for the study of all Cuban coasts and the establishment of a specific classification of these extreme events for each coastal settlement.

Based on the results and considerations presented above, this work emphasizes the analysis of the variability and trend of coastal flooding events on the Cuban coasts during the period 1901-2020, primarily associated with tropical cyclones (TCs). This work aims to contribute to the measures implemented by the Cuban State for climate-change adaptation, mainly within the coastal zone.

2 Materials and methods

2.1 Sources of information

For the analysis and plotting of tropical cyclone (TC) tracks, the HURDAT2.0 database from the National Hurricane Center (NHC) was used. The database is available via the website www.nhc.noaa.gov. Hurricanes were classified according to the Saffir-Simpson Scale based on the one-minute maximum sustained wind speed: Category 1 (119-153 km/h), Category 2 (154-177 km/h), Category 3 (178-208 km/h), Category 4 (209-251 km/h), and Category 5 (>252 km/h).

The maps were created using the WGS84 map projection with the Grads (Grid Analysis and Display System) and RStudio version 4.2.2 programs, employing the ggplot, sp and mapdata packages available at https://CRAN.R_project.org/.

The chronology of flooding events during the period 1901-2020, for each of the coastal settlements shown in Figure 1, were obtained from the scientific result "Chronology of coastal flooding by sea penetration for the Cuban archipelago", published by (Hidalgo et al. 2017), and updated by the authors of this work from 2016.

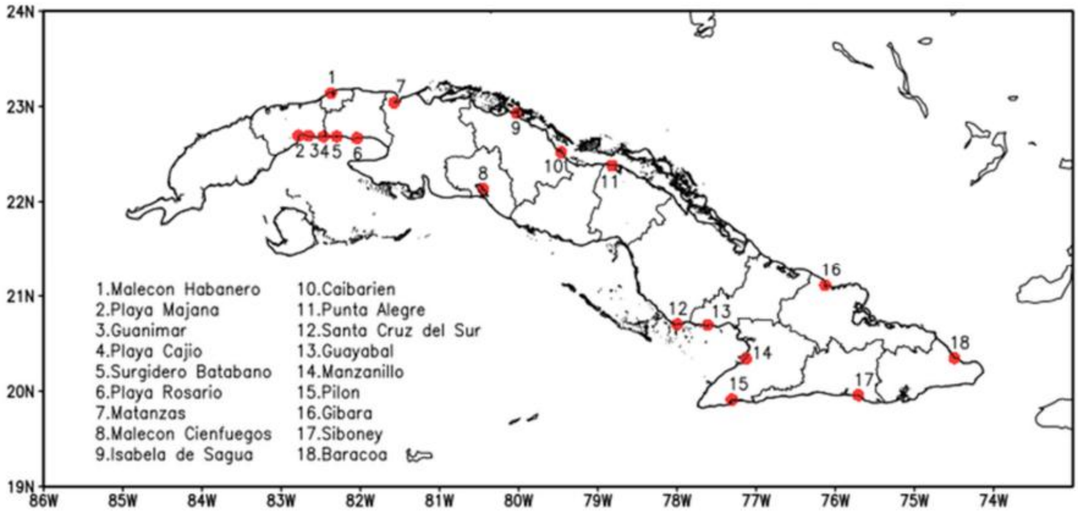

Figure 1. Cuban settlements that report coastal flooding according to (Hidalgo et al. 2017).

In this research, coastal flooding events are considered to be those in which seawater advanced inland, affecting one or more coastal settlements shown in Figure 1. The classification of flooding events in Cuba, according to (Hidalgo et al. 2017), is presented in Table 1, which is based on the horizontal reach of seawater inland, the physical-geographic conditions, and the rise in sea level due to meteorological causes generated by the weather systems that affect the coastal sections of the Cuban territory.

Table 1. Classification of coastal flooding for Cuban coastal settlements according to the horizontal reach of seawater inland

Classification	Group 1	Group 2	Group 3	Group 4
Light	0 – 500 m	0 – 250 m	0 – 100 m	0 – 50 m
Moderate	501 – 1000 m	251 – 500 m	101 – 200 m	51 – 100 m
Severe	≥ 1,001 m	≥ 501 m	≥ 201 m	≥ 101 m
Coastal settlements	2,3,4,5,6,12	8,9,10,13,16	7,14,15	11,17
Compiled from (Hidalgo et al. 2017)				

2.2 Statistical trend analysis

For flood events, the hypothesis test comparing two proportions to the same population was applied (Calero 2008) using the Z statistic.

$$Z = \frac{x - nP_r}{\sqrt{nP_r(1 - P_r)}} \quad (1)$$

Where *Pr* is the reference proportion (1901-1980), *x* and *n* are the absolute frequency and sample size of the test period (1981-2020) respectively. This research hypothesizes that the frequency of flooding events has changed since the 1980s compared to the period 1901-1980, which will be rejected at a 5% significance level if $|Z|>1.96$.

The selection of 1981 as the change-point year using Equation (1) is justified by the approximation of the binomial distribution to the Gaussian (normal) distribution under the Central Limit Theorem. This condition is satisfied in the present study, as the sample sizes used are in all cases greater than 30 years. Furthermore, the 1981-2020 period includes phases of low cyclonic activity (1981-1995) and high cyclonic activity (from 1996 onward), as documented by multiple authors for Region IV (Ballester et al. 2010; Montoya et al. 2017). This avoids bias-related errors within the two selected samples.

3 Results and discussion

3.1 Variability of coastal flooding in Cuba

In the Cuban archipelago, sea-level surges capable of triggering coastal flooding via marine inundation depend on the meteorological systems that generate them, their movement relative to the coastline, and the physical-geographical characteristics of the affected area. In general terms, the frequency and magnitude of such events are modulated by the inter-annual and multi-annual variability exhibited by their driving meteorological systems. These systems are principally: tropical cyclones (TCs) affecting all Cuban coasts (June-November); cold fronts (northern coasts of the western and central regions, November-April); the "Sures" events (coastal settlements of the Batabanó Gulf, February-April); and the combination of migratory high-pressure systems with extratropical lows (from Gibara to Baracoa, October-March), particularly under ENSO conditions.

Table 2 shows coastal-flooding events classified into three intensity levels, together with the relative frequency of events generated by tropical cyclones (TCs). Tropical-cyclone-driven events exceed 80% of total cases across all settlements, except for the Havana seawall (Malecón Habanero), coastal settlements of the Batabanó Gulf, and Baracoa. In this regard, Punta Alegre in Ciego de Ávila stands out: half of the flood events in the chronology originated from cold-front impacts, corresponding exclusively to moderate (sustained winds 35-55 km/h) and strong events (sustained winds above 55 km/h); five of these cold-front-driven events occurred during 1924-1959.

During the period 1901-2020, the average frequency of flood events per decade was between 0.75-2.0 in all coastal settlements analyzed, except those located in the Gulf of Batabanó, the Havana seawall and Baracoa where these values are between 7-8 cases/decade.

Multi-annual variability of coastal-flooding events across the Cuban archipelago is directly related to ENSO. This ocean-atmosphere teleconnection phenomenon alters the position of the subtropical jet stream over North America, increasing the number of cold fronts impacting Cuba during the low-rainfall season (PPLL, November-April). Meanwhile, cyclonic activity over Region IV decreases under ENSO conditions (Ballester et al. 2010), although its influence on flood magnitude is less pronounced than during the low-rainfall season (PPLL).

Table 2. Number of coastal-flooding events at Cuban coastal settlements associated with tropical cyclones (TCs) over the period 1901-2020

Coastal Settlements	Total	Associated with TCs	Relative frequency
Malecón Habanero	87	20	23.0%
Settlements of the Gulf of Batabanó	89	40	44.9%
Matanzas	15	12	80.0%
Malecón Cienfuegos	9	9	100.0%
Isabela de Sagua_Caibarién	16	16	100.0%
Punta Alegre	12	6	50.0%
Santa Cruz del Sur	12	12	100.0%
Guayabal	14	14	100.0%
Manzanillo_Pilón	23	23	100.0%
Gibara	22	19	86.4%
Siboney	21	21	100.0%
Baracoa	57	23	40.4%

In this regard, severe flood events during the low-rainfall season (PPLL) linked to the ENSO episodes of 1982-1983, 1992-1993 and 1997-1998 stand out for the settlements of the Batabanó Gulf, Baracoa and the Havana seawall. At this last site, the well-known "Storm of the Century" took place on 12-13 March 1993. According to Mitrani et al. (2017), this was the most intense coastal-flooding event recorded in Cuba that was not associated with a tropical cyclone (TC).

Figure 2 shows the typical synoptic patterns associated with cold fronts, "Sures" events, and the combination of migratory anticyclones and extratropical lows. Although these three phenomena are part of the synoptic evolution of the extratropical synoptic systems that affect Cuba (the trajectory of extratropical lows within the westerly flow from central United States toward the Atlantic Ocean) during the PPLL, their classification is based on differences in wind intensity and direction induced as they pass across the Cuban coast (Hidalgo et al., 2017).

In this work, the term synoptic pattern represents the average of synoptic-situation types (TSS) for a given region. In turn, TSS refers to the relationship among synoptic-scale meteorological phenomena that determine the weather conditions of a region, including air masses, frontal systems, cyclones, anticyclones, and other mesoscale atmospheric systems observed at surface level.

At the national level, according to the event chronology used in the present study and taken from Hidalgo et al. (2017), the largest flood events at all analysed localities occurred in the current century, except for the settlements of the Gulf of Batabanó and Santa Cruz del Sur. Their floods were triggered by the passage of the 1944 and 1932 hurricanes respectively; the latter is regarded as the worst natural disaster in Cuban history, with more than 3,000 fatalities (Ramos, 2009). This situation results from eleven intense hurricanes that have directly impacted Cuba since 1996: Michelle (2001), Ivan (2004), Charley (2004), Dennis (2005), Gustav (2008), Ike (2008), Paloma (2008), Sandy (2012), Matthew (2016), Irma (2017) and Ian (2022). Wilma (2005) is also included; although it did not strike Cuban territory directly, it caused severe coastal flooding along the Havana Malecón.

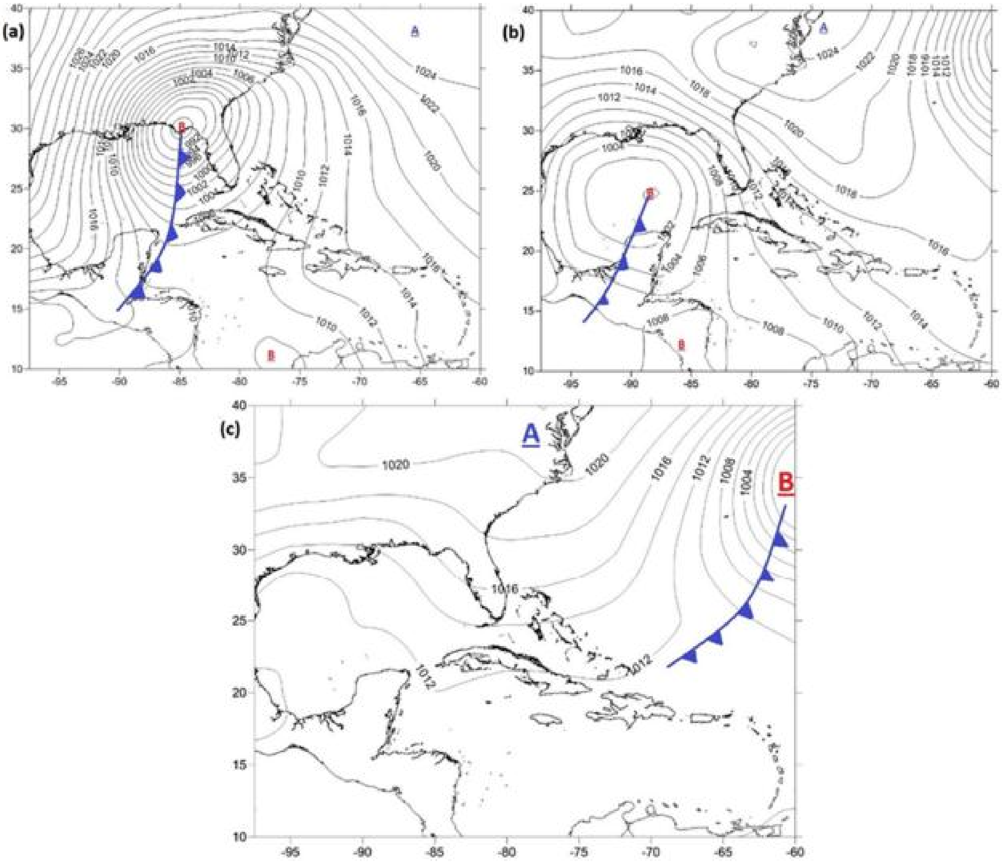

Figure 2. Typical surface-level synoptic patterns of extratropical meteorological systems generating coastal flooding: (a) cold fronts (Havana Malecón), (b) "Sures" events (settlements of the Gulf of Batabanó), and (c) combination of extratropical lows and migratory anticyclones (Baracoa).

Table 3 summarizes the impacts of the most notable coastal floods for each analyzed coastal settlement. All floods were produced by the passage of intense hurricanes (Saffir-Simpson scale greater than 3). Here, DH denotes the horizontal inland penetration distance of seawater, and HV denotes the seawater height over land (defined by the Cuban Institute of Meteorology as the water mark on a solid object behind the flooded zone). For Hurricane Dennis at Manzanillo and Pilón, Hurricane Paloma at Guayabal, and Hurricane Sandy at Siboney, seawater height-over-land data could not be obtained during the development of the event chronology for these territories.

It is worth noting that the greatest reach of seawater inland at the national level occurred in Santa Cruz del Sur and the settlements of the Gulf of Batabanó, due to the combination of the intensity of the meteorological system that generated the flooding (hurricanes of 1932 and 1944 respectively) and the physical-geographic characteristics of the place (coasts of wide platform and gentle slope with coastal plain).

Table 3. Summary of the most significant coastal flooding events that occurred in Cuban coastal settlements

Coastal settlement	Tropical Cyclone	Date	Magnitude
Malecón Habanero	Hurricane Irma, Category 4	9-10/Sep/2017	DH: 400-600 m HV: 1-2.25 m
Settlements of the Gulf of Batabanó	Hurricane of 1944, Category 4	17/Oct/1944	DH: 3-10 km HV: 3.8-7 m
Matanzas	Hurricane Irma, Category 4	9-10/Sep/2017	DH: 300-450 m HV: 4-7 m
Malecón Cienfuegos	Hurricane Dennis, Category 4	8-9/Jul/2005	DH: >200 m HV: 2 m
Isabela de Sagua-Caibarién	Hurricane Irma, Category 4	9/Sep/2017	DH: >3 km HV: 2 m
Punta Alegre	Hurricane Irma, Category 5	9/Sep/2017	DH: >800 m HV: 3-3.5 m
Santa Cruz del Sur	Hurricane of 1932, Category 4	9-1/Nov/1932	DH: >20 km HV: 6.8 m
Guayabal	Hurricane Paloma, Category 3	8/Nov/2008	DH: >700 m
Manzanillo-Pilón	Hurricane Dennis, Category 4	7/Jul/2005	DH: >200 m
Gibara	Hurricane Ike, Category 4	7-8/Sep/2008	DH: >1000 m HV: 2-2.5 m
Siboney	Hurricane Sandy, Category 3	24-25/Oct/2012	DH: > 100 m
Baracoa	Hurricane Matthew, Category 4	4-5/Oct/2016	DH: 300-500 m HV: 3.5 m

In Havana, although Casals et al. (2019) analyze inland flooding in reference to streets in the Plaza de la Revolución and Centro Habana municipalities, the authors of this study preferred to calculate the distance from the coastline (Malecón) to the reference points mentioned by the cited authors. This was done to ensure that the horizontal extent was consistent with the other coastal settlements listed in the column regarding flood magnitude. Furthermore, the flooding from the 1926 hurricane and Hurricane Juan in 1985 was identified as very intense along the Havana Malecón, the latter with wave trains in the form of a swell lasting more than 72 hours (Mitrani et al. (2017)). However, in both cases, the urbanization was different from what it is today, so the impacts were not as severe as those of Hurricanes Wilma (2005) and Irma (2017).

Finally, Figure 3 shows the tracks of the hurricanes that produced the most severe coastal-flood events in Cuban coastal settlements. It is noteworthy that six of these tropical systems occurred between 2005 (Dennis) and 2017 (Irma).

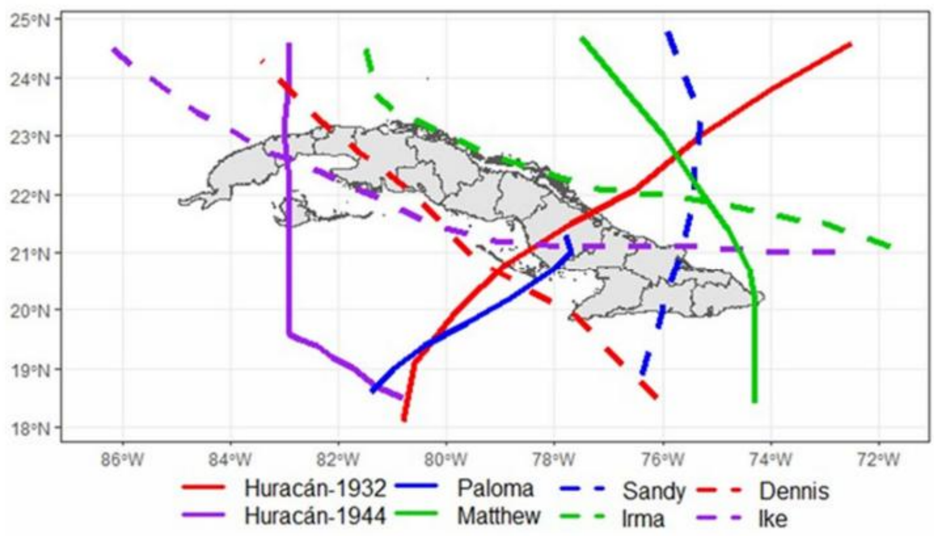

Figure 3. Tracks of the hurricanes over Cuba that caused the most significant coastal events in each of the coastal settlements analyzed in the present investigation

3.2 Trends in coastal flooding in Cuba

Table 4 summarizes flood events (classified into three intensity levels) over the period 1901-2020 for the 18 coastal settlements analyzed in the present investigation. It also reports the proportion of events occurring from the 1980s onward and the Z- statistic calculated using Equation (1). For all sites except Matanzas, the proportion hypothesis test yielded a statistically significant difference at the 5 % significance level when comparing flood frequencies after the 1980s against the 1901- 1980 period, because the absolute value of the test statistic exceeds the critical value of 1.96.

Table 4. Summary of coastal- flood events classified into three intensity levels, together with the Z- statistic calculated from Equation (1), for the various coastal settlements considered in the present investigation

Coastal settlements	Total	After 1981	Proportion from 1981 onward	Z- statistic
Malecón Habanero	87	34	39.1%	3.121
Settlements of the Batabanó Gulf	89	55	61.8%	12.925
Matanzas	15	10	66.7%	-1.118
Malecón Cienfuegos	9	5	55.6%	-4.066
Isabela de Sagua- Caibarién	16	7	43.8%	-4.940
Punta Alegre	12	4	33.3%	-7.603
Santa Cruz del Sur	12	6	50.0%	-4.427
Guayabal	14	8	42.9%	-3.560
Manzanillo- Pilón	23	8	34.8%	-1.963
Gibara	22	14	63.6%	-4.506
Siboney	21	9	42.9%	-2.031
Baracoa	57	45	78.9%	14.187

This decadal increase ranges from 0.5 to 1.0 events for Malecón Cienfuegos, Isabela de Sagua, Caibarién, Punta Alegre, Santa Cruz del Sur, Guayabal, Manzanillo, Pilón and Siboney; it reaches 1.4 events for Gibara. Meanwhile, for the coastal settlements of the Batabanó Gulf, Malecón Habanero and Baracoa, the decadal increase exceeds 3.5 events. It is also noteworthy that for all settlements, the relative frequency of flood events during 1981- 2020 is more than 30 % higher compared with the 1901- 1980 period. In the coastal settlements of Batabanó Gulf, Matanzas, Gibara and Baracoa, flood events account for more than 60 % of total recorded events.

The difference in the frequency of this type of extreme meteorological event between the cities of Baracoa and Gibara is caused by the higher vulnerability and exposure of the former, rather than changes in the frequency of the meteorological systems triggering these events, which are similar in this study (Hidalgo et al., 2022). Furthermore, the higher event frequency recorded at Malecón Baracoa is largely conditioned by the available time- series (1950- 2020). This period corresponds to a phase of high cyclonic activity across the whole country (Ballester et al., 2010), a pattern also reported by other authors for the Caribbean region (Montoya et al., 2017).

4 Conclusion

According to documentary records compiled for the national- scale coastal- flood chronology, the frequency of severe coastal floods has increased since the 1980s. Nevertheless, several catastrophic floods were recorded in the settlements of Batabanó Gulf and Santa Cruz del Sur throughout the 20th century, triggered by the infamously destructive hurricanes of 1944 and 1932, respectively. In the current century, eleven intense hurricanes have struck Cuba directly and produced severe coastal flooding: Michelle (2001), Ivan (2004), Charley (2004), Dennis (2005), Gustav (2008), Ike (2008), Paloma (2008), Sandy (2012), Matthew (2016), Irma (2017) and Ian (2022). Hurricane Wilma (2005) is also noted, even though it did not make a direct landfall over Cuban territory.

For all Cuban coastal settlements except Matanzas, the proportion test at the 5 % significance level yielded a statistically- significant increase in flood events starting from the 1980s. This decadal increase ranges from 0.5 to 1.0 events for Malecón Cienfuegos, Isabela de Sagua, Caibarién, Punta Alegre, Santa Cruz del Sur, Guayabal, Manzanillo, Pilón and Siboney; it reaches 1.4 events for Gibara. For the coastal settlements of Batabanó Gulf, Malecón Habanero and

Malecón Baracoa, the decadal increase exceeds 3.5 events.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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He performed data processing, data analysis and interpretation of results. He drafted the manuscript and carried out the final editing of the paper.

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She took part in research design and result analysis, and also revised the manuscript.