Hurricane *Otis*: the costliest and strongest hurricane at landfall on record in Mexico

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Tropical Storm *Otis* formed on 22 October 2023 several hundred kilometres off the western coast of Mexico. Only 72h later, *Otis* made landfall as the strongest hurricane ever recorded at the Mexican Pacific coast. The eyewall of Hurricane *Otis* crossed directly through the harbour of Acapulco and the impact took the lives of at least 51 people, according to official sources (Associated Press, 2023). The Mexican government as well as insurance and catastrophe risk companies have reported that *Otis* caused damages estimated between 3.5 and 15 billion US dollars making it the costliest hurricane in Mexican history (Gallager, 2023; Merida, 2023; Moody, 2023).

After its genesis, official intensity forecasts on 23 October by the National Hurricane Center (NHC) suggested that *Otis* would remain a Tropical Storm (Figure 1a) and public advisories did not suggest it would become a strong hurricane (NHC, 2023). However, on 24 October satellite imagery (such as Figure 1b) showed a clear eye and

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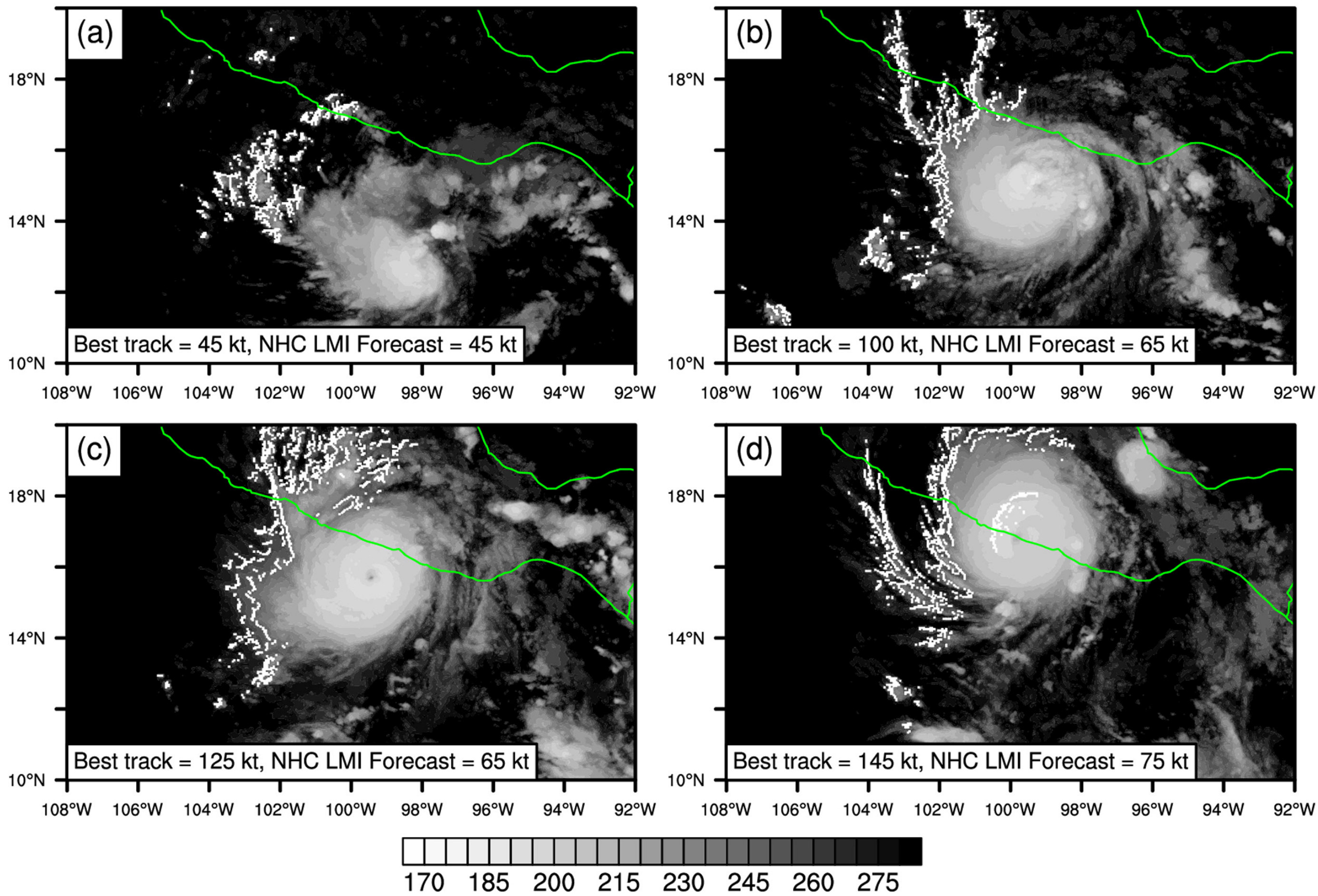

Figure 1. Brightness temperature (K) from the Global Microwave Imager (GMI) on board the Global Precipitation Measurement (GPM) mission for: (a) 23 October 2023 at 1800 UTC, (b) 24 October 2023 at 1800 UTC, (c) 25 October 2023 at 0000 UTC and (d) 25 October 2023 at 0600 UTC. The Best Track intensity and the NHC intensity forecast at each timestamp are shown in each panel.

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a prominent eyewall and flight reconnaissance measured wind speeds of a Category 3 hurricane. Hurricane *Otis* intensified unexpectedly only 12h before making landfall, as the maximum sustained wind speeds increased in this period by nearly 125kmh^{-1} (67 kts). On 25 October 2023 at around 12:30 local time (0630 UTC), it made landfall as the strongest hurricane ever recorded at the Mexican Pacific coast (Figures 1c and d).

Figure 2 shows the track of Hurricane *Otis* and the average environmental fields for 22/23 October, when it was still a Tropical Storm. The sea-surface temperature (SST) field shows that *Otis* would later pass over a pool of warm waters a few kilometres south of Acapulco. The SST in this region exceeded 30.5°C which was +1.2degC warmer than climatology for these dates. These warm SST anomalies along *Otis*' track likely played an important role in its intensification and were partially due to the positive phase of the El Niño-Southern Oscillation event of 2023 (Climate Change Service, 2023). The trough observed in northern Mexico (Figure 2) may have played a role in the track and intensification of *Otis*. For instance, the environmental wind shear (850–200hPa) within 500km of Acapulco 1–2 days prior to the landfall of Otis was 15ms^{-1} according to ERA5 data, which is considered a strong value (Rios-Berrios *et al.*, 2023). Further research is required to understand the intensification of *Otis* and the roles of the vertical wind shear and SSTs.

The probability distribution of the intensification rates (kt 24h^{-1}) in the Eastern Pacific (EP) Basin since 1979, using data from the International Best Track Archive (IBTrACS, Knapp *et al.*, 2018), illustrates how extreme the intensification of Hurricane *Otis* was (Figure 3). Rapid intensification (RI) is defined by an intensification rate higher than the threshold of +30 knots in a 24h period. Figure 3 shows that RI is a rare occurrence (5% of cases). Hurricanes *Patricia* (2015) and *Otis* (2023) underwent the first and second most extreme RI processes in the EP basin, respectively. One key difference is that Hurricane *Patricia* weakened rapidly several hours before landfall (Rogers *et al.*, 2017) whereas Hurricane *Otis* reached its life-time maximum intensity only a few dozen kilometres off the coast.

The strengthening of *Otis* just prior to landfall led to a worst-case scenario. IBTrACS data show how the maximum sustained wind speed peaked right at the time of landfall (Figure 4a). The Mexican National Sea Level Monitoring Service has a station located in the Port System Administration facilities of Acapulco (Acapulco ASIPONA), equipped with meteorological and sea level sensors. At this station, during the landfall of Hurricane *Otis*, wind gusts of 329kmh^{-1} (178kn) were recorded (Figure 4b), which are considered amongst the top 10 strongest wind gusts ever recorded on Earth with digital anemometers (Masters, 2023; WMO, 2023). The maximum sustained wind speeds at landfall were 182kmh^{-1} (98kn) when a minimum pressure of 963hPa was recorded, having fallen from 1008hPa just 6h earlier (Figure 4c). Precipitation from the Multi-Source Weighted-Ensemble Precipitation (MSWEP) v2 dataset (Beck *et al.*, 2019) shows that precipitation rates within 500km of the storm were relatively low for a TC in this intensity range (García-Franco *et al.*, 2023). The average precipitation within 100km of the storm increased notably as the storm intensified and approached land (Figure 4d).

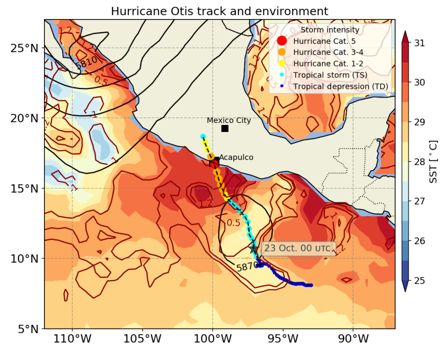

Figure 2. Track of Hurricane Otis *(IBTrACS) and environmental fields from ERA5 (Hersbach et al., 2020). The full track is shown as the dotted line and colour-coded per the storm intensity at each time-step. The environmental fields are averaged for 22–23 October 2023 and show the sea-surface temperatures (SST, shading in °C and dark red contours for anomalies in degC), the geopotential height at 500hPa (contours in m). The storm centre on 23 October 0000 UTC is labelled to indicate the position of* Otis *at the time for which the environmental fields are shown.*

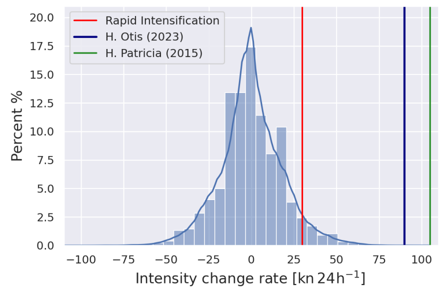

Figure 3. Probability distribution (in percent %) and histogram of tropical cyclone intensification rates (kn 24h^{-1}) in the East Pacific basin. The maximum rates of intensification observed in Hurricanes Otis (2023) and Patricia (2015) are highlighted in blue and green, respectively. Data are from IBTrACS.

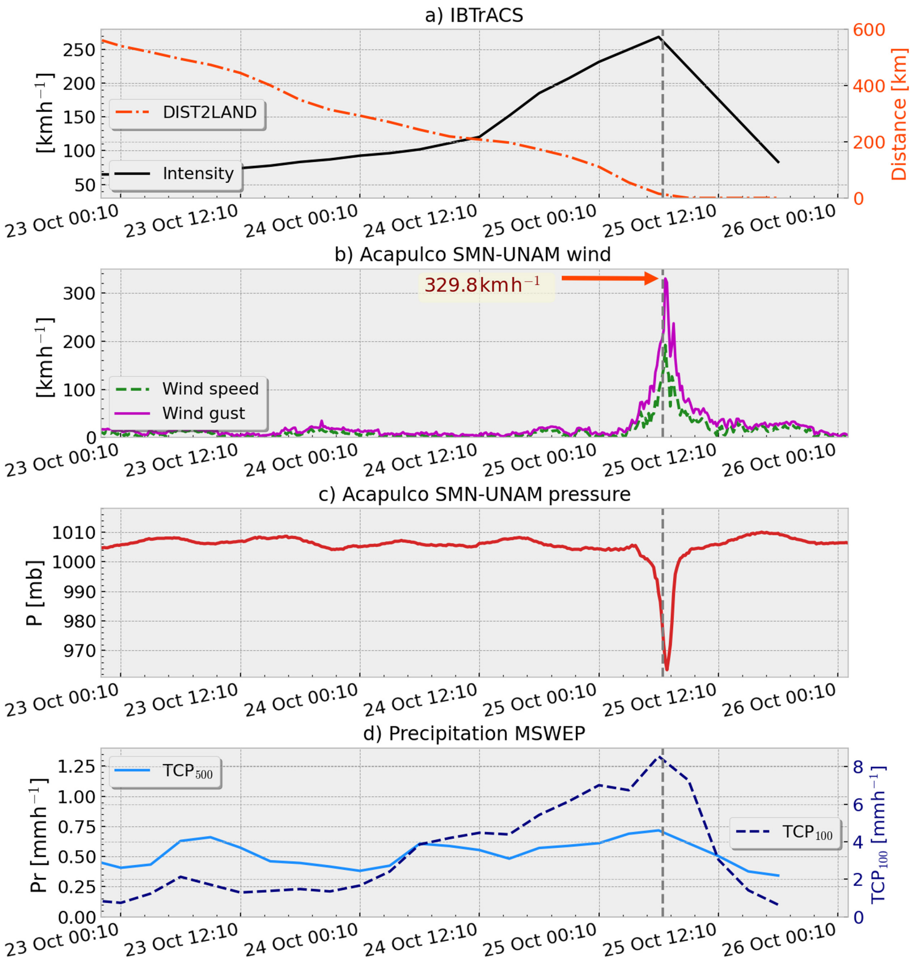

Figure 4. (a) IBTrACS maximum sustained wind speed and distance from eye to land, (b) wind gust and sustained wind recorded at the Acapulco ASIPONA station, (c) atmospheric pressure recorded at the Acapulco ASIPONA station, (d) precipitation from the MSWEP v2 showing average rates within 100km (dashed dark line) and within 500km (solid light line).

The population of Acapulco was warned of the landfall of Hurricane *Otis* as a Category 5 storm <6h prior to landfall due to its unexpected RI. RI remains difficult to forecast in numerical weather prediction models (DeMaria *et al*., 2021) due to gaps in our observations and the insufficient spatial resolution of mesoscale numerical weather prediction models (DeMaria *et al*., 2021; Rogers, 2021). Evidence suggests that climate change is making RI more frequent and tropical cyclones are expected to produce more rainfall (Emanuel, 2017; Knutson *et al*., 2020). Even though climate change does not cause a single hurricane to undergo RI, the environment that favours RI is made more likely by climate change through increases in SSTs and potential intensity (Bhatia *et al*., 2022).

The landfall of *Otis* caused severe infrastructure damage, loss of life and left over one million people without access to food, water and power and cut off telecommunications and roads for weeks. Local vulnerabilities, such as infrastructure that is not designed to withstand these types of events, and the lack of preparation in the local decision-makers and in the population, exacerbate the impacts of hydrometeorological events such as *Otis* (Dominguez *et al*., 2021). Future strategic planning must include measures that build resilience to *Otis*-like events and early warning systems that consider a multi-hazard approach as a first step to reducing disaster risk (Bowman *et al*., 2014).

Author contributions

Jorge L. García-Franco: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; software; validation; visualization and writing—original draft. **Octavio Gómez-Ramos:** Data curation; investigation; supervision; validation; writing—original draft and methodology. **Christian Dominguez:** Data curation; formal analysis; investigation; methodology; visualization and writing—original draft.

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Data availability statement

All the datasets used in this study are publicly available. ERA5 reanalysis data are available from the Copernicus Climate Change Service Climate Data Store at https://doi.org/10.24381/cds.bd0915c6 (Hersbach *et al*., 2020). The IBTrACS dataset is publicly available (Knapp *et al*., 2018) at https://www.ncei.noaa.gov/products/international-best-track-archive. The GPM dataset is available at https://gpm.nasa.gov/data/ (doi:10.5067/GPM/GMI/BASE/07). MSWEP (Beck *et al*., 2019) is available for download via Google Drive after applying at www.gloh2o.org/mswep/.

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