Observing ECCO Model vs Tide Gauges Affected by Hurricane Maria

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Introduction

Sea level rise is a multifaceted phenomenon where individualized parameterization of changes and data sources is critical to understanding the full extent of future impacts. Tide Gauge (TG) networks and satellites are among the most prolific data sources for tracking global sea level rise. However, numerous mechanical, technical, and calibration issues exist when interpolating data from each source (Heimback et al., 2019). Finding correlation methods between, for example, TG and satellite altimetry networks provides valuable insight into the weighted measuring system of remote and in-situ observation systems, especially during extreme storm events in understudied areas, such as small island states.

Looking at the correlation between the Estimating the Circulation and Climate of the Ocean (ECCO) model and the NOAA University of Hawaii Sea Level Center TG network during Hurricane Maria, we contribute to a growing body of literature, analyzing the accuracy of observational weighted systems during extreme storm events using multiple types of statistical corollary analysis. Testing the observational network has significant implications for future climate and storm models (Pascual et al., 2008), as well as for checking the accuracy of each observational system.

Our preliminary analysis investigated how the resolution and reliability of SSH data compare between TG and ECCO before, during, and after Hurricane Maria. The insights derived from this analysis led us to extend our focus to the longest available period where both ECCO and TG data are available to observe when differences occur in the measurements of SSH, giving rise to the following research questions: How does the resolution and reliability of SSH data compare between TG and ECCO across the years and during severe weather events? How does the correlation between TG and ECCO reveal the influence of a severe weather event on two measurements of the same property (SSH), and what underlying factors contribute to their divergence?

By looking at one of the most powerful hurricanes ever recorded, the robustness of each data network can be utilized with more precise placement and value for future modelers and local climate and ocean scientists.

Description

Maria was an extremely severe Hurricane that hit Dominica at a category 5 (on the Saffir-Simpson Hurricane Wind Scale) and later devastated Puerto Rico as a high-end category 4 hurricane, tracked from September 17th to October 2nd of 2017 with pressures reaching 908 MB and wind reaching 150 knots (Pasch et al., 2023). The storm surge in Puerto Rico during Maria's landfall ranged from 2.35 to 5.44 meters above the mean sea level for the region. Knowledge of how the SSH is modeled in ECCO vs verified in the TG network shows the extent they can be relied on during a severe storm.

The sea level data from TGs are different from SSH measured by satellite altimeters because the latter is measured relative to a global reference frame (not local benchmarks). Therefore, SSH data from satellite altimeters are unaffected by land movement (Caldwell et al., 2001).

Tracking the changes in sea level and SSH as they relate to extreme storm events is critical for storm prediction analysis. Tidal amplitudes and phases are affected by determinants such as higher average temperatures and more extreme storms, including changes in coastal morphology, extent of ice sheets, and baroclinicity (Haigh et al., 2019). Changes in tides, at the local level include absolute and relative ranges and spring tide maximums, all of which contribute to a hurricane surge. These nonlinear interactions between water depth, tide, waves, wind forcing, and atmospheric surge lead to changes in the peak water levels and synoptic sea level fluctuations which vary significantly from the changes in the global average sea level (Arns et al., 2015); (Idier et al., 2019); (Volkov et al., 2023), therefore localized analysis of SSH before, during, and after a storm are critical for understanding the local future storm projections and predictions.

Methods

We used ECCO Version 4: Fourth Release (ECCO v4r4), dated from 1992 to 2017, with a grid cell resolution interpolated to a 0.5-degree latitude-longitude. While this still has a lower resolution around low latitudes, the difference in grid cells is scaled at 1/48° and refined in the meridional direction to resolve the tropical system of zonal currents better (Forget et al., 2015). We extracted the daily values of SSH from precise corresponding to the TG available in Maria's trajectory in the 17-18° latitudinal range (Meridional ranges in the ECCO model only vastly increase at the -10° to 10° latitude, which is outside of our current range, but still critical mapping information when comparing global ocean state mapping). SSH values from the TGs at these locations thanks to the University of Hawaii Sea Level Center (UHSLC), a member of the Global Sea Level Observing System (GLOSS).

We used the six TGs in Puerto Rico active during Hurricane Maria (i.e., Penuelas, Isabel Segunda, Esperanza, Arecibo, Mayaguez, and Fajardo), and chose the nearest ECCO grid cell corresponding to the coordinate for each location. For the preliminary analysis, we plotted the normalized time series for TG and ECCO a month before, during the dates of, and a month after Hurricane Maria (see Part A). Bland-Altman analysis (see Part B) and correlation measures were used. Expanding the analysis, SSH time series for the longest available time for each TG, including Hurricane Maria's timeframe, against ECCO, for the same period, were plotted for comparison (see Part C). To smoothen the temporal coarseness of the SSH data, both TG and ECCO time series were put through a 1000-hour rolling window computing the mean and standard deviation of the data (see Part D and E). We then calculated the Pearson correlation coefficients of the ECCO and TG rolling means and rolling standard deviations (see Part F).

Discussion

Preliminary results suggest that TGs have a higher degree of localized accuracy than ECCO, but could be faulty during an extreme event, therefore it is necessary to understand better the correlation between ECCO and TGs over larger time scales. Next, a time series analysis of SSH data showing the intersection between the TG and ECCO reveals that the SSH data is incomplete for some time series, i.e., Fajardo, suggesting that the TG was destroyed. Furthermore, the amplitude and variability of the TG data is higher than the normalized ECCO data. Pearson correlation coefficients calculated from the rolling mean and standard deviation for TG and ECCO time series show the following relationships: Fajardo, Mayaguez, and Arecibo show a strong positive correlation, Esperanza shows a moderate positive correlation and Isabel Segunda shows a weak positive correlation for the rolling mean. Isabel Segunda shows a weak positive correlation, Esperanza and Arecibo show a weak negative correlation, while Mayaguez and Fajardo show almost no correlation for the rolling standard deviation.

In conclusion, ECCO is fairly reliable over long time scales but hardly accounts for rise in SSH due to extreme weather events. Furthermore, although TGs seem more accurate over short time scales, especially in depicting rise in SSH during extreme events, TGs are vulnerable to extreme weather. Understanding the correlation between ECCO and TGs may quantify the extent to which researchers can rely on TG data with increasing range in SSH and, in turn, give insight into the reliability of ECCO SSH during those extreme events. This may provide valuable information regarding its use for locations lacking TGs.

Future Work

Further investigation is needed on other atmospheric conditions such as steric height, or the parcel of the ocean that has a different density due to changes in temperature and salinity. These "thermosteric" and "halosteric" changes are key when analyzing SSH under an ever-changing ocean. Shifting baselines will have a degree of impact on local mean dynamic sea level (MDSL), tidal range, and wave pattern as well as in hurricane-induced water levels (Kleptsova et al., 2021). Taking into consideration bottom drag coefficients to better determine tidal energy displacement via continental shelves will also be necessary for fully parameterized detail of storm anomalies effects since the North East Caribbean is two continental plates (Kerr et al., 2013). All in all, this work could inform the Sea Level Explorer Visualizer tool to help account for the differences in TGs and altimetry systems writ large.

A. TG locations affected by Hurricane Maria and SSH ECCO and TG time series plot for each TG a month before, during, and a month after Hurricane Maria

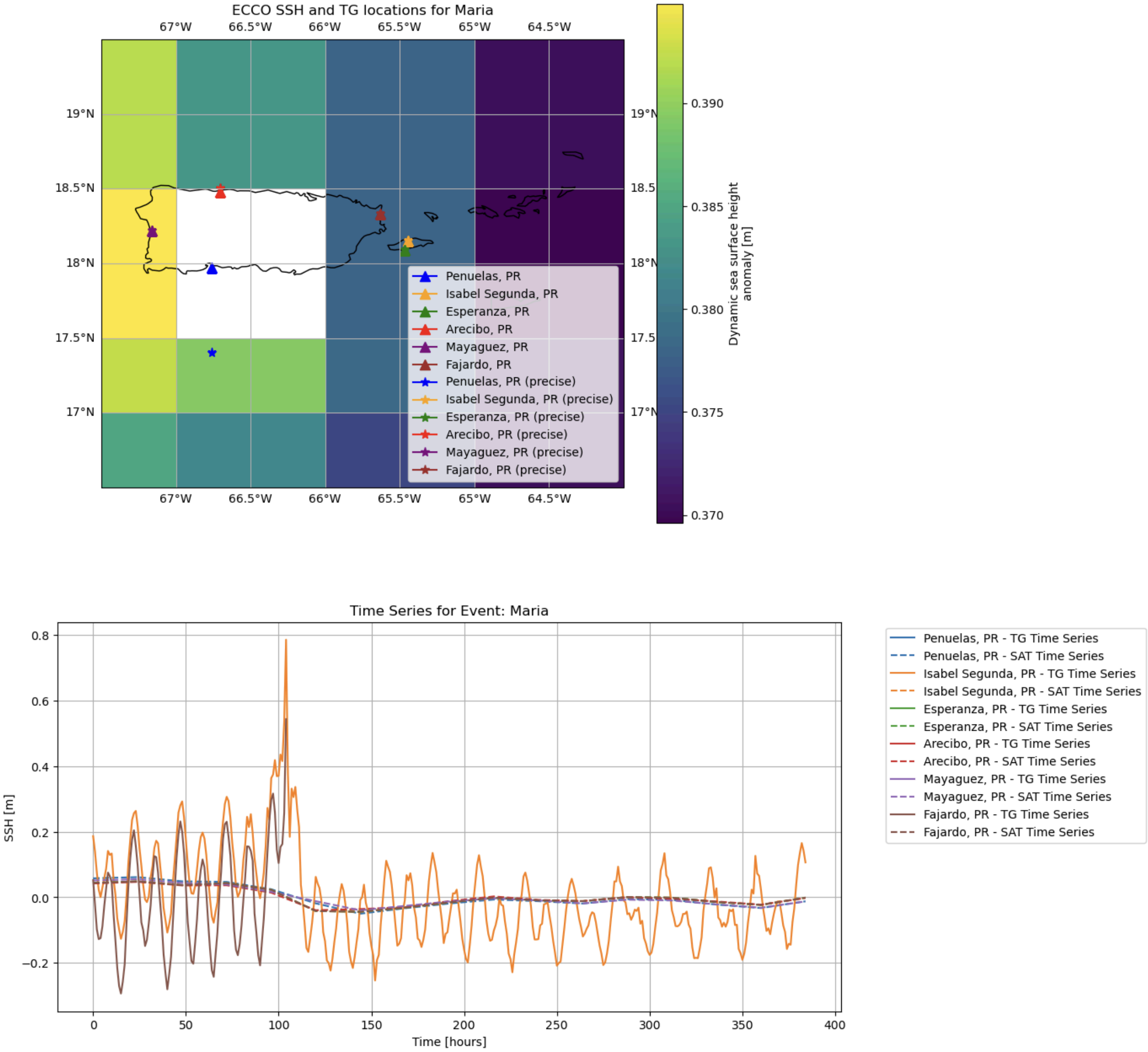


Figure 1. (A) The first image shows a map of Puerto Rico with TGs which were active during Hurricane Maria. The second image shows the SSH time series for ECCO and all TGs a month before, during the dates of, and a month after Hurricane Maria.

B. Bland Altman plots of SSH agreement between ECCO and TG

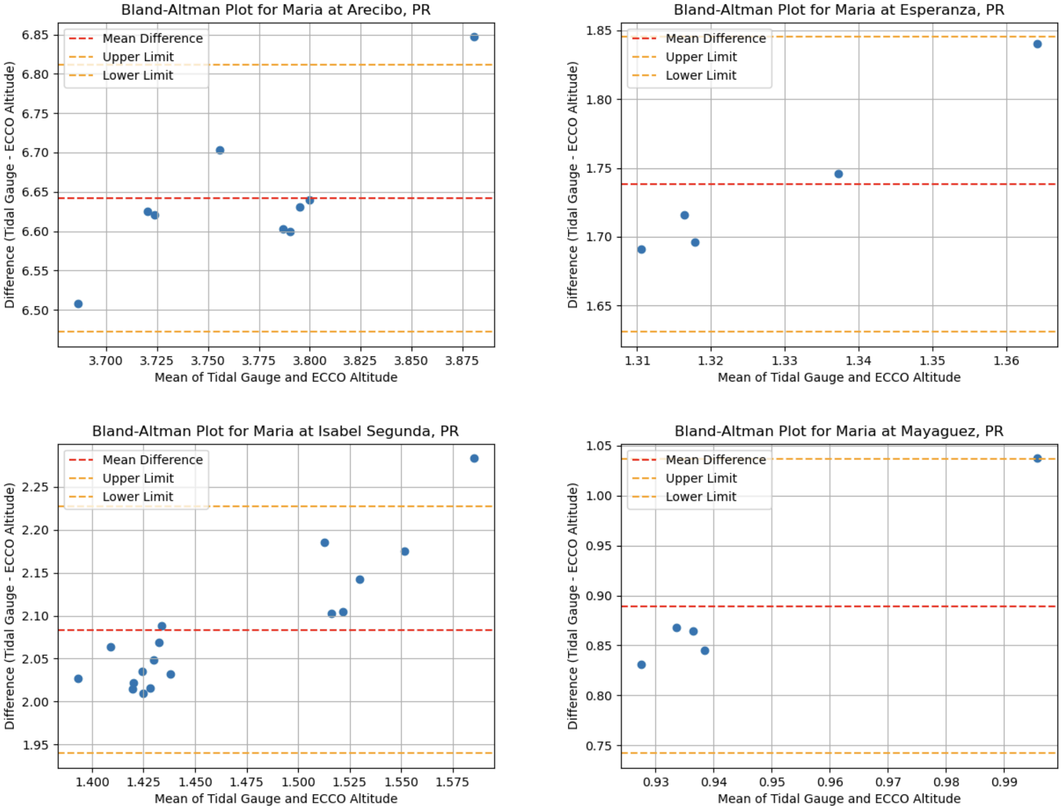


Figure 1. (B) Bland Altman plots showing the agreement of SSH data between ECCO and TG sources for Arecibo, Esperanza, Isabel Segunda and Mayaguez TGs.

C. SSH time series analysis for period intersecting both ECCO and TG

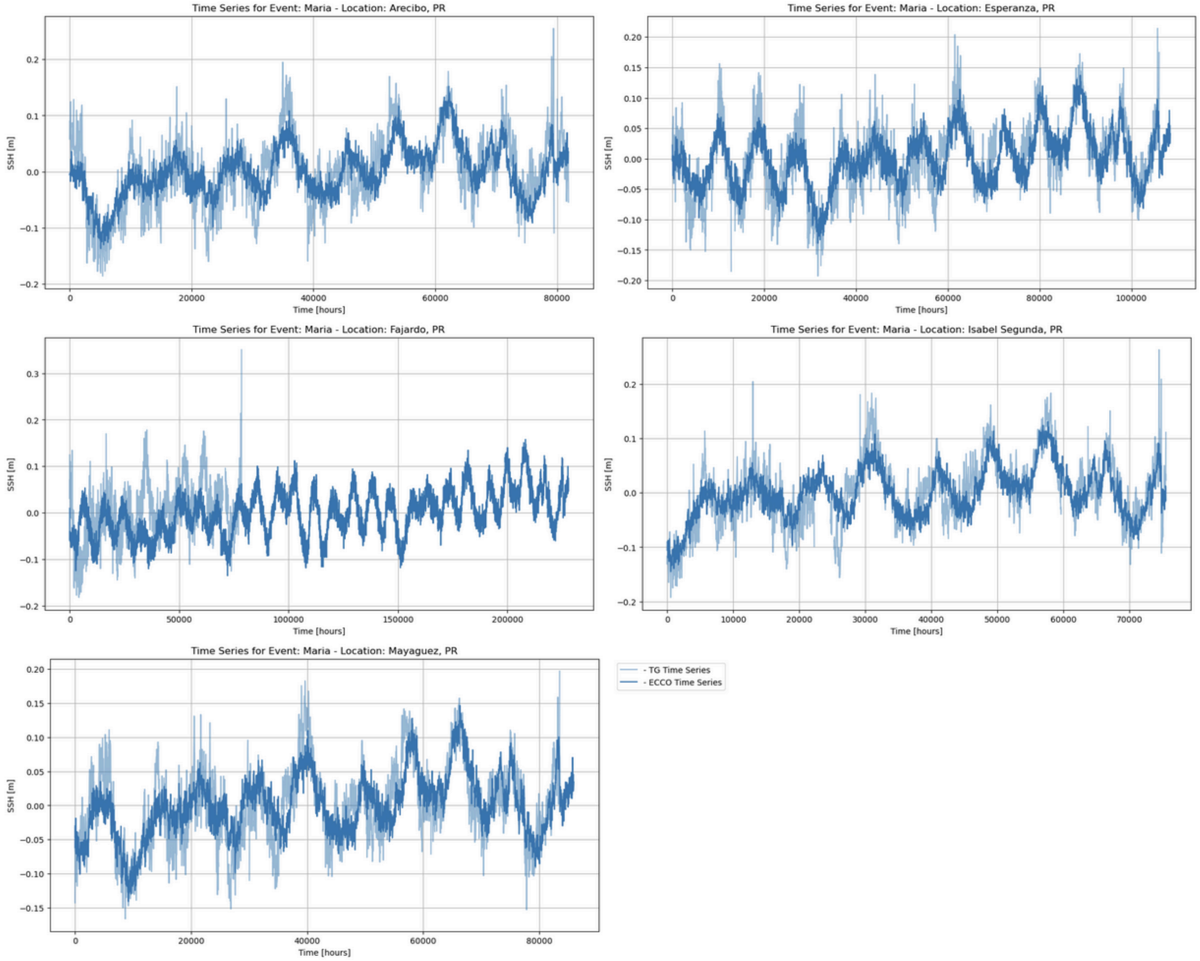
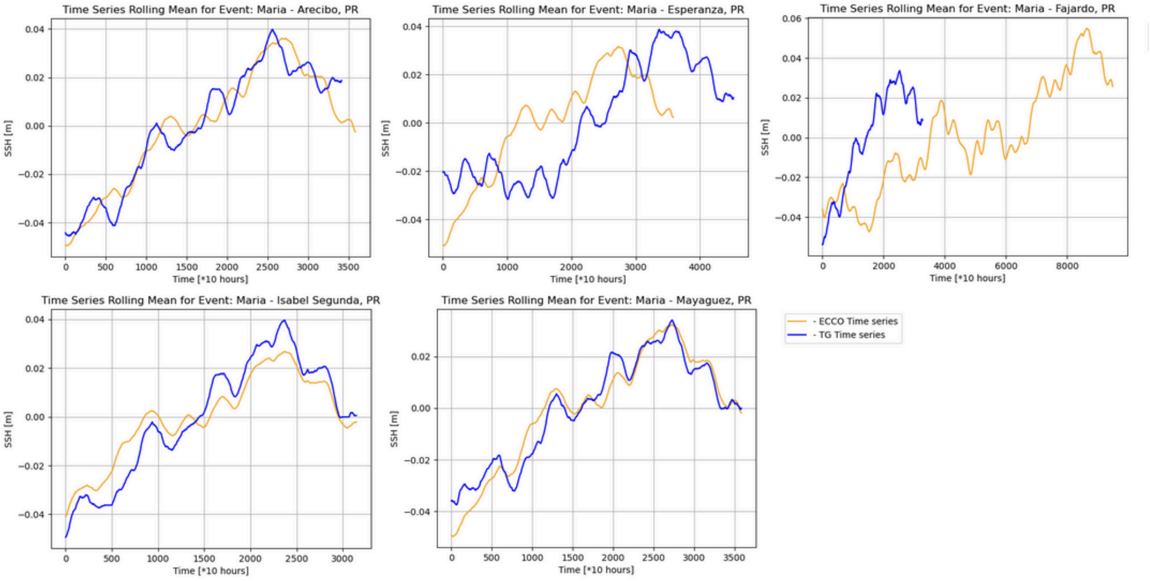
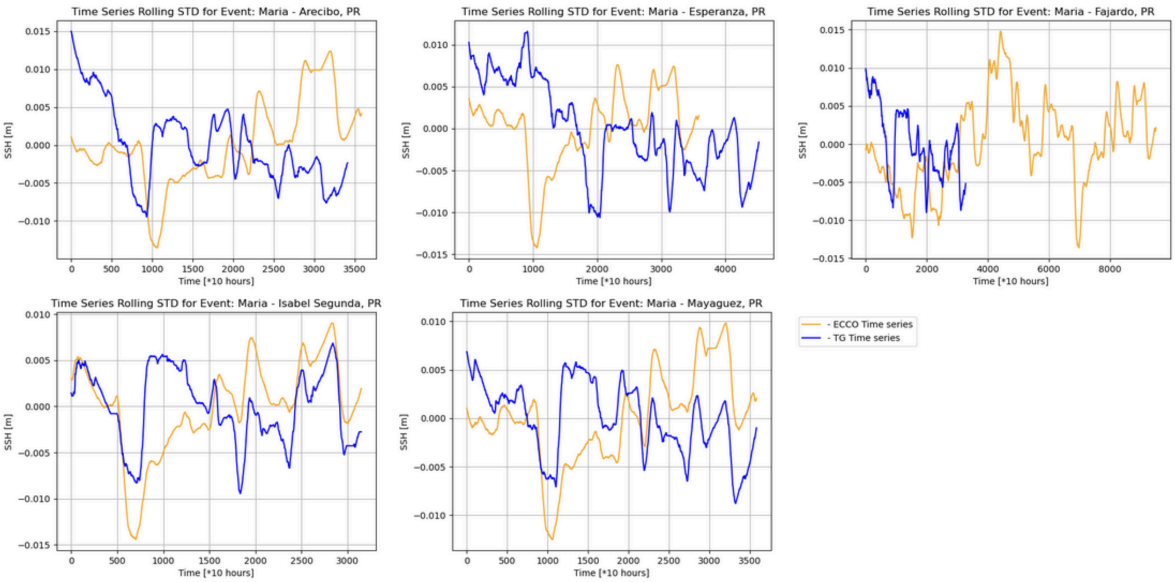


Figure 1. (C) SSH data time series where ECCO and TGs intersect for the entire period when the TGs were active. (D) SSH rolling mean of the time series for each TG and ECCO. (E) SSH rolling standard deviation of the time series for each TG and ECCO. (F) Pearson's correlation coefficients and P-values obtained from the SSH time series rolling mean and rolling standard deviation between ECCO and TG, for each TG

D. SSH time series rolling mean comparing ECCO and TG



E. SSH time series rolling standard deviation comparing ECCO and TG



F. Pearson's correlation coefficients and P-values for SSH time series rolling mean and rolling STD between ECCO and TG

Location	(mean) Pearson's correlation coefficient	(mean) P-value	(STD) Pearson's correlation coefficient	(STD) P-value
Isabel Segunda, PR	0.39	p<0.01	0.39	p<0.01
Esperanza, PR	0.55	p<0.01	-0.32	p<0.01
Arecibo, PR	0.96	p<0.01	-0.35	p<0.01
Mayaguez, PR	0.93	p<0.01	0.07	p<0.01
Fajardo, PR	0.96	p<0.01	0.07	p<0.01

Bibliography

Arns, A., T. Wahl, S. Dangendorf, and J. Jensen. (2015) “The Impact of Sea Level Rise on Storm Surge Water Levels in the Northern Part of the German Bight.” Coastal Engineering 96 (February 2015): 118–31. https://doi.org/10.1016/j.coastaleng.2014.12.002

Caldwell, Patrick C., Mark A. Merrifield, and Philip R. Thompson. (2001) “Sea Level Measured by Tide Gauges from Global Oceans as Part of the Joint Archive for Sea Level (JASL) since 1846.” NOAA National Centers for Environmental Information. https://doi.org/10.7289/V5V40S7W

“ECCO Consortium, Fukumori, I. et al. (2022) ECCO Central Estimate (Version 4 Release 4), https://ecco-group.org/products-ECCO-V4r4.htm (05/31/2022)

Forget, G., J.-M. Campin, P. Heimbach, C. N. Hill, R. M. Ponte, and C. Wunsch. (2015) “ECCO Version 4: An Integrated Framework for Non-Linear Inverse Modeling and Global Ocean State Estimation.” Geoscientific Model Development 8, no. 10 (October 6, 2015): 3071–3104. https://doi.org/10.5194/gmd-8-3071-2015

Haigh, Ivan D., Mark D. Pickering, J. A. Mattias Green, Brian K. Arbic, Arne Arns, Sönke Dangendorf, David F. Hill, et al. (2020) “The Tides They Are A‐Changin’: A Comprehensive Review of Past and Future Nonastronomical Changes in Tides, Their Driving Mechanisms, and Future Implications.” Reviews of Geophysics 58, no. 1 (March 2020): e2018RG000636. https://doi.org/10.1029/2018RG000636

Heimbach, Patrick, Ichiro Fukumori, Christopher N. Hill, Rui M. Ponte, Detlef Stammer, Carl Wunsch, Jean-Michel Campin, et al. “Putting It All Together: Adding Value to the Global Ocean and Climate Observing Systems With Complete Self-Consistent Ocean State and Parameter Estimates.” Frontiers in Marine Science 6 (March 4, 2019): 55. https://doi.org/10.3389/fmars.2019.00055

Horsburgh, K. J., and C. Wilson. (2007) “Tide-Surge Interaction and Its Role in the Distribution of Surge Residuals in the North Sea.” Journal of Geophysical Research 112, no. C8 (August 3, 2007): C08003. https://doi.org/10.1029/2006JC004033

Idier, Déborah, Xavier Bertin, Philip Thompson, and Mark D. Pickering. (2019) “Interactions Between Mean Sea Level, Tide, Surge, Waves and Flooding: Mechanisms and Contributions to Sea Level Variations at the Coast.” Surveys in Geophysics 40, no. 6 (November 2019): 1603–30. https://doi.org/10.1007/s10712-019-09549-5

Kemp, Andrew C., Timothy A. Shaw, and Christopher G. Piecuch. (2022) “The Importance of Non-Tidal Water-Level Variability for Reconstructing Holocene Relative Sea Level.” Quaternary Science Reviews 290 (August 2022): 107637. https://doi.org/10.1016/j.quascirev.2022.107637

Kerr, P. C., R. C. Martyr, A. S. Donahue, M. E. Hope, J. J. Westerink, R. A. Luettich, A. B. Kennedy, J. C. Dietrich, C. Dawson, and H. J. Westerink. (2013) “U.S. IOOS Coastal and Ocean

Modeling Testbed: Evaluation of Tide, Wave, and Hurricane Surge Response Sensitivities to Mesh Resolution and Friction in the Gulf of Mexico." Journal of Geophysical Research: Oceans 118, no. 9 (September 2013): 4633–61. https://doi.org/10.1002/jgrc.20305

Kleptsova, Olga S., Henk A. Dijkstra, René M. van Westen, Carine G. van der Boog, Caroline A. Katsman, Rebecca K. James, Tjeerd J. Bouma, et al. (2021) "Impacts of Tropical Cyclones on the Caribbean Under Future Climate Conditions." Journal of Geophysical Research: Oceans 126, no. 9 (September 2021): e2020JC016869. https://doi.org/10.1029/2020JC016869

Muis, Sanne, Maialen Irazoqui Apecechea, Job Dullaart, Joao De Lima Rego, Kristine Skovgaard Madsen, Jian Su, Kun Yan, and Martin Verlaan. (2020) "A High-Resolution Global Dataset of Extreme Sea Levels, Tides, and Storm Surges, Including Future Projections." Frontiers in Marine Science 7 (April 29, 2020): 263. https://doi.org/10.3389/fmars.2020.00263

Pasch, Richard J. "Pasch, Richard J., Andrew B. Penny, and Robbie Berg. (2019) 'National Hurricane Center Tropical Cyclone Report: Hurricane Maria (AL152017).' National Hurricane Center. https://www.nhc.noaa.gov/data/tcr/AL152017_Maria.pdf

Pascual, Ananda, Marta Marcos, and Damià Gomis. (2008) "Comparing the Sea Level Response to Pressure and Wind Forcing of Two Barotropic Models: Validation with Tide Gauge and Altimetry Data." Journal of Geophysical Research: Oceans 113, no. C7 (July 2008): 2007JC004459. https://doi.org/10.1029/2007JC004459

Volkov, Denis L., Kate Zhang, William E. Johns, Joshua K. Willis, Will Hobbs, Marlos Goes, Hong Zhang, and Dimitris Menemenlis. (2023) "Atlantic Meridional Overturning Circulation Increases Flood Risk along the United States Southeast Coast." Nature Communications 14, no. 1 (August 22, 2023): 5095. https://doi.org/10.1038/s41467-023-40848-z

Widlansky, Matthew J., Xiaoyu Long, and Fabian Schloesser. (2020) "Increase in Sea Level Variability with Ocean Warming Associated with the Nonlinear Thermal Expansion of Seawater." Communications Earth & Environment 1, no. 1 (August 20, 2020): 9. https://doi.org/10.1038/s43247-020-0008-8

Woodworth, Philip L. (2019) "The Global Distribution of the M1 Ocean Tide." Ocean Science 15, no. 2 (April 16, 2019): 431–42. https://doi.org/10.5194/os-15-431-2019

Wunsch, Carl, and Patrick Heimbach. (2007) "Practical Global Oceanic State Estimation." Physica D: Nonlinear Phenomena 230, no. 1–2 (June 2007): 197–208. https://doi.org/10.1016/j.physd.2006.09.040

Zlotnicki, Victor, Zheng Qu, and Joshua Willis. (2019) "MEaSUREs Gridded Sea Surface Height Anomalies Version 1812." NASA Physical Oceanography Distributed Active Archive Center. https://doi.org/10.5067/SLREF-CDRV2

Supplementary Material

Tidal Gauge Precise Time Series

Location name (Station ID)	TG start	Absolute start	Absolute End	TG ends
Isabel Segunda, PR (732)	(2009, 03, 07)	(2009, 03, 07)	(2017, 10, 19)	(2017, 10, 19)
Esperanza, PR (733)	(2005, 08, 16)	(2005, 08, 16)	(2017, 12, 31)	(2019, 12, 31)
Arecibo, PR (735)	(2008, 08, 29)	(2008, 08, 29)	(2017, 12, 31)	(2017, 12, 31)
Mayaguez, PR (736)	(2008, 03, 11)	(2008, 03, 11)	(2017, 12, 31)	(2019, 12, 31)
Fajardo, PR (783b)	(2008, 10, 07)	(2008, 10, 07)	(2017, 12, 31)	(2017, 09, 19)

Notes

1. Meridional ranges in the ECCO model only vastly increase at the -10° to 10° latitude, which is outside of our current range, but still critical mapping information when comparing global ocean state mapping.
2. In order to access ECCO data, one must make an account with a unique username and password to utilize the python code.
3. These TGs include Isabel Segunda, PR, Esperanza, PR, Arecibo, PR, Mayaguez, PR, Fajardo, PR.
4. More details of the time series in used for each tidal gauge is detailed in the supplementary information graph, ⅘ TG were established after ECCO so the time series starts with the establishment of the TG, however, Fajardo began in 1921, but only the data with ECCO is used. So in Fajardo the time series starts on January, 1st 1992.
5. The Pearson's correlation coefficients and P-values are all rounded up to two decimal places.