

Editorial

Editorial for Special Issue “Tropical Cyclones Remote Sensing and Data Assimilation”

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Received: 3 September 2020; Accepted: 6 September 2020; Published: 19 September 2020



Abstract: Tropical cyclones (TCs) are essential for many reasons, including their destruction of human lives and property and their effect on heat and nutrient fluxes between the ocean’s surface and its depths. A better understanding of ocean fluxes is needed to predict the impact of global climate change on the oceans and to quantify how ocean heat content modulates the dynamics of global climate change. Similarly, improved modeling of nutrient fluxes is crucial for maintaining fisheries and preserving crucial marine ecosystems to benefit both humanity and marine life. Numerous remote sensors measure crucial geophysical quantities before, during, and after TCs, including sea surface temperature (SST), ocean color, chlorophyll concentration, ocean surface winds, sea surface height, and significant wave height. In this special issue, an international group of researchers have written articles describing (1) novel techniques and remote sensors for measuring the aforementioned quantities in tropical cyclones, (2) methods for validating and improving the accuracy of those measurements and harmonizing them among different sensors, (3) scientific analyses that investigate the relationships between remote-sensed ocean surface measurements and in situ measurements of vertical profiles of ocean temperature, salinity, and current, and (4) strategies for utilizing remote-sensed measurements to improve operational forecasts in order to provide better tropical cyclone warnings to human populations.

The articles in this issue run the gamut from improvements to data accuracy, timeliness, and availability [1–4], and characterization and removal of biases among existing data sets [5,6], to the utilization of remotely sensed data to improve TC characterization and ocean surge detection and forecasts [7–10], with novel scientific analyses [11–13] that illuminate the relationship between TCs and ocean heat and nutrient fluxes.

Ocean surface wind vectors are an important parameter to measure in TCs because they supply the forcing function that leads to ocean mixing and thus the exchange of cold water at depth and warmer water at the surface across the thermocline [14]. Surface winds, along with storm surge inundation, also provide the destructive force that causes property damage and loss of human life once a TC reaches a populated coastline. Ocean wind scatterometers [15,16] are radars that transmit signals at 30- to 70-degree incidence angles with respect to the ocean’s surface. Operating in low earth orbits, they provide twice-daily near-global measurements of ocean-surface wind vectors derived from the effect of cm-wavelength wind-driven capillary waves on the percent of a radar’s transmitted signal, which bounce back to the antenna from which they were transmitted. Higher winds produce more

small-scale waves, which results in higher backscatter for the incidence angles at which scatterometers operate. Typically, processing algorithms are applied to retrieve wind fields and downlinked radar echo data at computing centers on the ground, but there are delays in downlinking the data, processing it, and then transmitting the data to forecasters. In [1], onboard-spacecraft wind retrieval processing is investigated as a means of reducing the time it takes to put wind fields into forecasters' hands by a couple of important hours. As a TC nears to coastline, accurate prediction of where it makes landfall, its intensity, and any storm surge associated with it are all enhanced by more frequent observation. Toward this end, land-based coastal Doppler radar [17] (e.g., NEXRAD in the United States and CINRAD in China) can be an important resource; however, these radars unfortunately yield ambiguities in their reported speeds. In [2], an ambiguity dealiasing method is developed that makes these measurements more useful in TCs. Aside from timeliness, spaceborne ocean wind scatterometers have three primary shortcomings in TC conditions: rain contamination [18], insufficient measurement resolution to resolve the intensity speeds in the eyewall, and reduced sensitivity at higher wind speeds [19]. In [4], we encounter a glimpse of a short-lived instrument that was capable of overcoming all these issues. The SMAP radar utilized a Synthetic Aperture Radar mode that allowed 1-km resolution. SMAP's transmit frequency was L-band, a lower frequency at which rain contamination is much reduced and sensitivity is good at high wind speeds. Unlike most SAR platforms, SMAP utilized a dual polarization spinning antenna that allowed wind direction and well as speed retrieval. Even though SMAP radar is no longer operating due to transmitter failure, SMAP's passive radiometer is still useful for measuring salinity and extreme wind speeds at 40-km resolution [20,21].

Another important measurement for understanding TCs is significant wave height (SWH). In [3], a method is developed to determine significant wave heights at high spatial resolutions using Sentinel-1 SAR. By extending the regime of accurate SWH from SAR to higher values, one can obtain instantaneous imagery of SWH in storms to supplement the one-dimensional profiles currently available from spaceborne altimetry [22].

In addition to examining improvements in measurement techniques and sensors, it is important to understand and resolve biases between sensor platforms that have been utilized for long periods of time. In [5], infrared [23] and microwave [24] SST climate data records are compared to quantify the differences in cold wake observations of TCs. By understanding and eventually resolving these differences, we can better quantify cold wake development in TCs as a function of storm intensity and other storm parameters in order to model the impact of TCs on ocean heat content dynamics.

Disagreement between different sensor platforms is a common occurrence, especially in extreme regimes like TCs where the data needed to resolve these differences is obtained infrequently, and spatial and temporal collocations must be precise to ensure both sensors measure the same conditions in a rapidly evolving TC. Data from ocean wind scatterometers and step frequency microwave radiometers are an example of the common concern. Step frequency microwave radiometers (SFMR) used in aircraft reconnaissance use dropwindsondes for in situ ground truth while ocean wind scatterometers typically use buoys. Much work is needed to get the four data sets (i.e., dropwindsondes, buoys, scatterometers, and SFMR) to agree in TCs. In [6], residual biases between SFMR and dropwindsondes are resolved as a crucial step in this ongoing process.

After measurements are obtained, one needs to relate those measurements to storm location, intensity (maximum sustained winds), and storm surge parameters that are important for forecasters to predict the impact of storms and issue appropriate warnings to people endangered by them. In [7], a neural network approach is used to relate high altitude multi-spectral cloud imagery to TC maximum-sustained winds. Unlike ocean wind scatterometers, one does not obtain direct measurements of surface winds from cloud imagery. However, cloud-imaging satellites are available in geostationary orbit and thus obtain high-frequency coverage in time [25,26], unlike polar-orbiting scatterometers. Methods like those in [7] allow forecasters to use data that are available at all times to refine their forecasts constantly. In [9], ocean wind scatterometer and microwave radiometer data

are combined empirically to estimate maximum wind intensity, providing estimates that complement those in [7] and are more directly related to winds at the surface.

While improvements in the tracking of TC maximum intensity and location are essential, forecasters have been able to estimate these quantities with some confidence for decades. Storm surge, by contrast, is considerably harder to predict. In [10], a novel approach using land-based seismometers enables the tracking of the origin of TC-induced swells. This breakthrough method could be used to analyze the relationship between TCs and storm surges going back decades using historical seismometer data.

In addition to aiding the operational forecasting of TCs, remotely sensed data are also a useful tool for scientists trying to understand the vertical ocean transport of heat and nutrients, and thus helpful for better understanding ongoing global climate change and its impact on marine ecosystems. In [11], remotely sensed data including surface winds, SST, sea surface height anomaly (SSHA), and ocean color are used in coordination with the in situ measurements of vertical ocean temperature and salinity during the passage of TCs Kalmaegi and Fung-Wong. The resultant experiment illuminates the relationship between the translation speed and intensity of TCs and upwelling-induced ocean cooling and enhanced chlorophyll concentration, demonstrating that a prior TC could affect the track of a subsequent TC.

In [12], cross-calibrated data sets of ocean winds, rainfall, SST, SSHA, and geostrophic currents containing combined data from multiple remote-sensing platforms are collocated with SMAP sea surface salinity data and in situ ocean vertical profiles from buoys and mooring stations during the passage of typhoons Sarika and Haima in 2016. The collocated data are used to determine the relative importance of surface cooling, mixing, and horizontal and vertical advection in determining the final oceanic responses to the two typhoons. The oceanic response is found to be heavily influenced by the relative positions of the typhoons.

In [13], remotely sensed observations along the path of Typhoon Linfa of chlorophyll concentration, SST, and geostrophic currents produced from SSHA are used in conjunction with WHOI models of heat flux and in situ ocean temperature and salinity profiles to show that typhoon-induced eddies are a major contributor to increased phytoplankton growth after a typhoon has passed. Furthermore, the authors develop a model of the interrelationship among and relative importances of Ekman mass transport, Ekman pumping velocity, surface heat flux, mixing, and eddy generation with respect to chlorophyll concentration.

Funding: A portion of the work described in this editorial was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Another portion was carried out in the framework of the Spanish Research and Development Plan under Project L-BAND (ESP2017-89463-C3-1-R).

Acknowledgments: The editors would like to thank all the authors for their hard work and excellent contributions to this issue.

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

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