Promises in air-sea fully-coupled data assimilation for future hurricane prediction

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Abstract

The recent article by Li and Toumi (2018) published in *Geophysical Research Letters* explored the potential for improving tropical cyclone intensity forecasts by assimilating synthetic coastal surface currents from high-frequency radar observations. Although it is an idealized study using simulated observations, this may signal the beginning of a new frontier in future hurricane prediction through ingesting in-situ and remotely-sensed observations of oceanic currents into fully-coupled systems. Assimilation of oceanic observations can improve not only the state estimation of both oceanic and atmospheric variables, it also has the potential to better estimate uncertain model physics' parameters such as the air-sea exchange coefficients.

Hurricane Florence is a perfect reminder that while the position of the storm near landfall in the Carolinas' coast was forecasted to within 100 km of the actual storm 5 days in advance, nearly all operational hurricane models along with the official human forecasters at the National Hurricane Center have difficulty in predicting the intensity even within 36 hours of its landfall (**Figure 1**). Contrary to the forecasted major hurricane strength landfall of a projected category-4 hurricane at landfall, Florence rapidly weakened to an eventual category-1 storm while reaching the coast. The exact reasons for its rapid weakening, as well as the subsequent near-stalled movement near and after landfall that caused catastrophic flooding in the Carolinas, will be investigated by many researchers in the near future but it has been speculated that the underestimated hurricane-induced cooling may be one of the factors causing the overprediction in the NHC official forecast. Strong than predicted air-sea interactions due to stronger intensity, greater size, a shallower mixed layer depth, and a slower translation speed of Harvey may have pumped to the surface enough deep cold ocean water, greatly reducing the energy supply from the ocean needed to sustain a strong hurricane.

The ocean circulations, temperature, and density remain poorly initialized in all operational hurricane intensity forecast models, even those that are fully coupled air-sea systems. Consequently, there are unavoidably large inconsistencies between ocean and air circulations at the air-sea interface. Moreover, it is estimated that there is at least 50% of uncertainty in our current best estimates of the air-sea exchange coefficients of energy, momentum and moisture at high wind speed ranges (Powell et al. 2005; Green and Zhang 2014), a critical factor in the control of hurricane intensity (Emanuel 1995; Emanuel and Rotunno 2011). It has proven difficult to estimate these from basic theory, laboratory experiments, and measurements made in the extraordinary conditions of real hurricanes (Bell et al. 2012).

The recent article by Li and Toumi (2018) explored the potential for improving tropical cyclone intensity forecasts by assimilating synthetic coastal surface currents from simulated High-frequency (HF) radar observations. Although this is an idealized study using simulated observations initialized with a synthetic vortex in a quiescent environment, to the best of our knowledge, this is the first study that explores a new frontier for future hurricane prediction through ingesting remotely sensed oceanic current observations into a fully coupled analysis and prediction system.

With the use of an air-sea-coupled forecast model and an advanced data assimilation technique called an ensemble Kalman filter (EnKF), first proposed by Evensen (1994) and reviewed extensively in Houtekamer and Zhang (2016), this pioneering study by Li and Toumi (2018) demonstrates that assimilation of oceanic current observations not only improves the state estimation of the oceanic state variables including sea surface temperature and winds but also directly and indirectly improves the estimation of unobserved atmospheric state variables, resulting in remarkable improvements in tropical cyclone intensity forecasts.

Since the HF radar can measure surface currents in all conditions, it is also possible that such high-resolution observations can be used to estimate the elusive, uncertain air-sea exchange coefficients, for example, through augmenting such uncertain flux coefficients as part of the state variables in a coupled-model EnKF system that can perform ensemble-based simultaneous state and parameter estimation. The likely strong, flow-dependent correlations between these flux coefficients, especially the drag and the surface ocean currents, will help to better estimate these coefficients and better initialize both the atmosphere and ocean circulations, as demonstrated in Li and Toumi (2018).

The air-sea-coupled modeling and data assimilation system can potentially extend far beyond assimilating the HF radar observations. For example, new technologies such as sensors from unmanned vehicles have been developed to better observe ocean conditions below the water surface (Cione et al. 2016). The assimilation of these into coupled ocean-atmosphere models is currently being explored. Recent studies demonstrate great potential in improving hurricane intensity and structure prediction through assimilating high spatiotemporal resolution, all-sky radiances from the newest-generation geostationary infrared satellites GOES-16 and Himawara-8 (Zhang et al. 2016). Further advances are expected when all-sky microwave radiances are assimilated into the cloud-resolving hurricane prediction models, since many of the microwave sensors/channels can penetrate into the clouds and are not only sensitive to the atmospheric temperature, moisture and hydrometers but also to the sea state of the ocean surface (oceanic sea surface temperature, wind speed, waves and/or surface emissivity) (Sieron et al. 2018). The use of an air-sea fully coupled modeling system in coupled data assimilation will be necessary to fully maximize such potentials, given these observations are responsive to, and thus be able to better update both the atmospheric and ocean state variables simultaneously.

Advanced air-sea-coupled modeling and data assimilation systems can further help us estimate the fundamental limits in hurricane predictability, in particular the predictability of intensity. Hurricane intensity forecasting remains a challenge, despite dramatic track forecast improvement over the past few decades (**Figure 2**). Hurricane intensity not only depends on the track and environmental conditions, which have been better forecasted owing to advances in global numerical weather prediction, but also is critically dependent on the initial vortex structure, intensity and moisture content (Emanuel and Zhang 2017) which are often under-observed by existing measurement systems., Intensity also depends on internal atmospheric dynamics, such as chaotic moist convection (Zhang and Sippel 2009), and complex air-sea interaction processes (Chen et al. 2018) that may have more limited predictability. However, a recent study by Emanuel and Zhang (2016) demonstrated that we are far from the limits of intrinsic predictability for tropical cyclones, with greater potential in better initializing the tropical cyclone vortex. This is consistent with recent studies that have demonstrated the potential for improved prediction by assimilation of high-resolution in-situ and remotely sensed observations from radars and airborne dropsondes (Zhang and Weng 2015; Weng and Zhang 2016).

To further maximize the predictability potential, the air-sea-coupled modeling and data assimilation system may help further identify where to observe, what to observe, and how to design more cost-effective observing systems for both atmospheric and oceanic states (e.g., Lorenz and Emanuel 1998). There are a growing number of studies that explore the progress, potential and challenges of using ensemble-based techniques in the observing network design, and targeted observations for tropical cyclone prediction (Wu et al. 2005; Xie et al. 2013), but to the best of our knowledge, none of the tropical cyclone observing system design and impact studies has yet to use an air-sea fully coupled system. Future studies need to explore the critical needs and potential of both the oceanic and atmospheric state observations for hurricane prediction with a fully coupled analysis and forecast system.

The benefits of air-sea-coupled modeling and data assimilation should extend far beyond hurricane prediction, in particular for forecasts longer than 2 weeks where the impacts from air-sea interactions likely become increasingly larger, from subseasonal phenomena such as the 30-60-day Madden-Julian Oscillations (MJOs), to the interannual variabilities such as the El Nino and South Oscillation (ENSO), to decal oscillations and beyond. At these longer time scales, it will likely be imperative to have the coupled modeling and data assimilation for other components of the earth systems such as the land surface and cryosphere.

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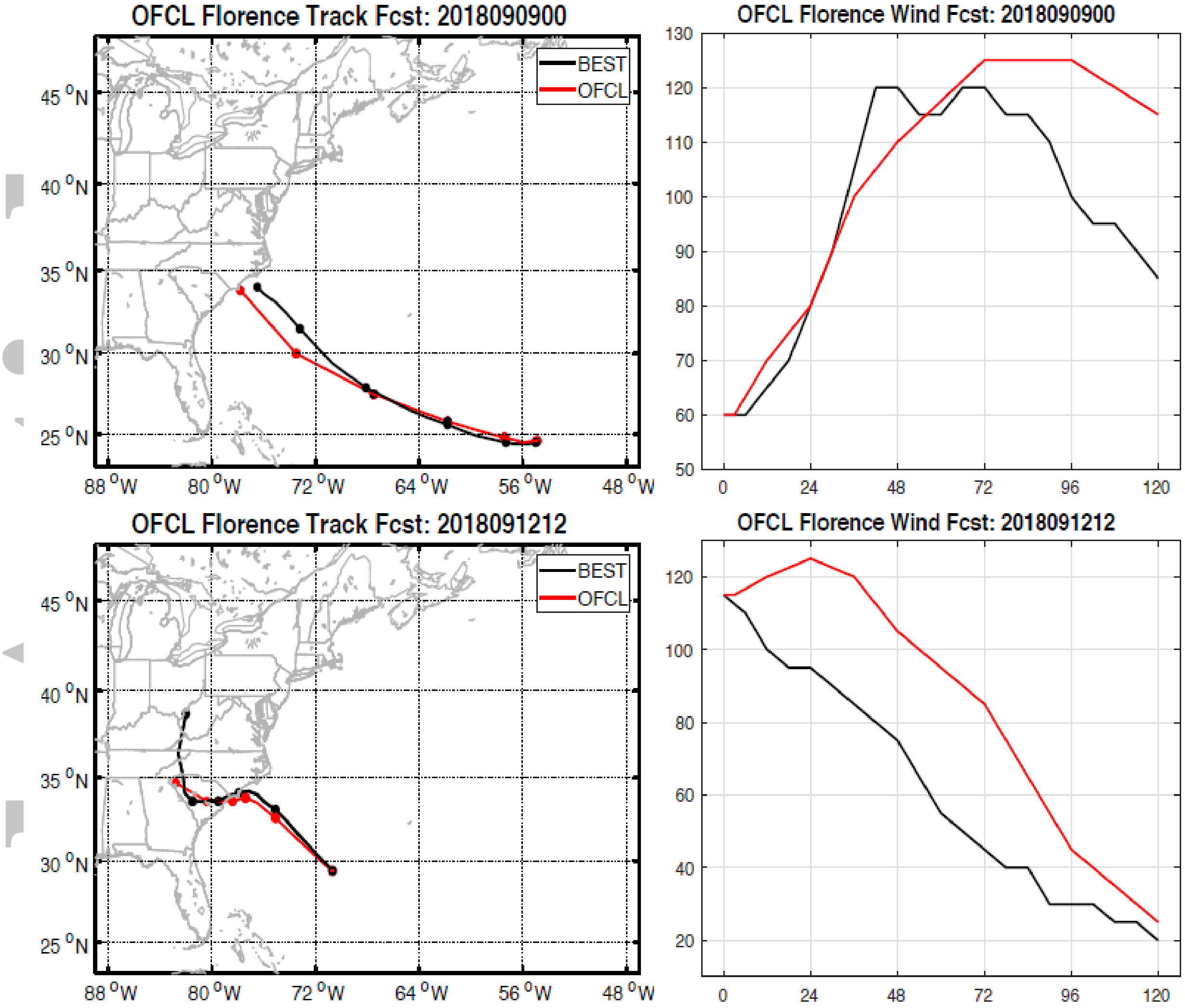

Figure 1. The official 120-hour position (left) and intensity forecasts (knots) of Hurricane Florence issued by the National Hurricane Center at 00Z 9 (top) and 12Z 12 (bottom) September 2018, corresponding respectively to about 5 days and 36 hours before its actual landfall.

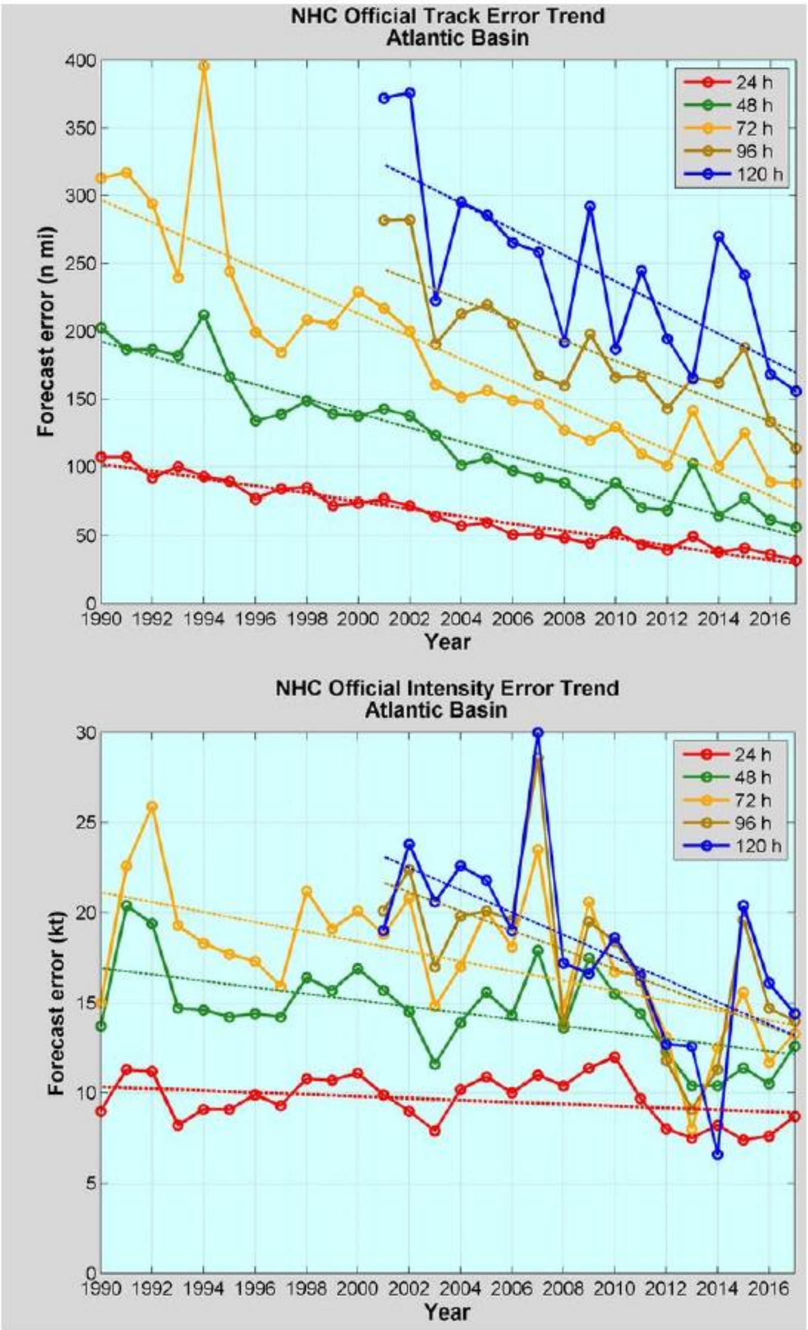

Figure 2. Top: Annual average official track errors by the National Hurricane Center's official forecasts for Atlantic basin tropical cyclones for the period 1989-2017, with least-squares trend lines superimposed. Bottom: The corresponding annual average official intensity errors for Atlantic basin tropical cyclones for the period 1990-2017, with least-squares trend lines superimposed. This figure is downloaded directly from the National Hurricane Center's official website https://www.nhc.noaa.gov/verification/verify5.shtml