Atmosphere-Ocean Coupling in Tropical Cyclones

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1. Introduction

The advent of numerical weather prediction tropical cyclone (TC) models has demonstrably improved the forecasts of TCs over the last decades. But to establish useful warning systems for TCs, it is necessary to accurately predict both storm track and intensity. Whereas TC tracks are determined almost exclusively by their large-scale atmospheric environment, storm intensity is influenced to a greater degree by smaller-scale features in both the atmosphere and ocean. The factors that control the intensity of TCs are still poorly understood, leading to limited reliability in forecasts of TC intensity evolution. Variability in TC intensity originates from two sources: internal variability and environmental interactions. There are three critical aspects of the environmental interactions: 1) the dynamical and microphysical processes near and at the sea surface that influence the turbulent exchange of heat and momentum between the ocean and atmosphere, 2) vertical and horizontal transport of momentum and heat in the atmospheric boundary layer and 3) the turbulent entrainment of relatively cold water through the seasonal thermocline, which affects the sea surface temperature and thereby influences storm intensity. Three-dimensional, coupled atmosphere-ocean research and operational models have been developed to simulate and predict the mutual response of a TC and the ocean (Bender and Ginis 2000, Bao et al., 2000, Bender et al., 2007, Chen et al., 2007, Surgi 2007). One such coupled model, the GFDL/URI hurricane-ocean prediction system, has been used operationally at the NOAA's National Centers for Environmental Prediction (NCEP) since 2001. The GFDL/URI model has demonstrated steady improvements in TC intensity prediction over the last several years (Bender et al. 2007). Another fully coupled model, the Hurricane Weather Research and Forecast (HWRF) model became operational at NCEP in 2007 (Surgi 2007).

Expert reports commissioned by NOAA, the U.S. National Science Board and the American Geophysical Union have concluded that further advances in TC intensity forecasts and impacts projection require novel theoretical concepts and the next generation very high resolution coupled atmosphere-wave-ocean numerical models with improved boundary layer and surface flux parameterizations, tested against high-quality observations.

Below I briefly summarize the results of the most recent efforts of our research group at URI and our collaborators to advance our understanding and parameterization of air-sea fluxes in tropical cyclone conditions and improving the ocean model initialization as a route toward skillful prediction of tropical cyclone intensity and structure.

2. Role of surface waves in air-sea momentum fluxes under tropical cyclones

Recent observations from the Coupled Boundary Layer and Air-Sea Transfer (CBLAST) field program that was sponsored by the U.S. Office of Naval Research (Black et al., 2007) and the analysis of GPS drop sondes by Powell et al. (2003, 2007) have shown that the drag coefficient varies widely under TCs. However, even though this was one of the main foci of the CBLAST program, it was a daunting task to measure surface fluxes in wind speeds exceeding 30 m s^{-1}. Very few measurements exist for higher wind speeds and this remains an area of significant uncertainty. Our approach to this problem is based on improving our understanding of the physical processes at and near the air-sea interface and a developing numerical framework to explicitly resolve key processes that are responsible for the wide variability of air-sea fluxes. We have particularly been focusing so far on the momentum and kinetic energy fluxes in high wind and tropical cyclone conditions.

2.1. Sea state dependence

Proper evaluation of the sea state dependence of air-sea fluxes requires modeling the wave boundary layer (lower part of the atmospheric boundary layer that is affected by surface waves) and the equilibrium range of wave spectra. We developed a new wave boundary layer model based on the conservation of momentum and energy by explicitly resolving the form drag due to non-breaking waves. Moon et al. (2004a,b,c) have coupled the NOAA's wave model (WAVEWATCH III or WW3) and the equilibrium wave spectrum model of Hara and Belcher (2004) to predict the air-sea momentum fluxes over any given surface wave fields, including those under TCs. Fan et al. (2008a,b) extended this model to examine the momentum and kinetic energy fluxes under growing seas and TCs.

Moon et al. (2004a,b,c) results have shown that the drag coefficient is spatially variable and is generally reduced at very high wind speeds under TCs, being consistent with the field observations. Another important finding is that the drag coefficient mainly depends on two parameters – wind speed and input wave age – regardless of the complexity of the wave field (even under TCs). Here, the input wave age is one of the standard output parameters of WW3 and is a measure of the development stage of locally wind forced waves, excluding the effects of long swell and waves that are misaligned with the local wind. Based on this finding Moon et al. (2007) have developed a simplified parameterization of the drag coefficient in terms of the local wind speed and the local input wave age. This parameterization has been implemented into the GFDL and HWRF operational coupled hurricane-wave models at NCEP (Bender et al., 2007) and the WAVEWATCH III wave model (Moon et al., 2008).

We have developed a new coupled wind and wave (CWW) model that includes the enhanced form drag of breaking waves. Breaking and non-breaking waves induce air-side fluxes of momentum and energy in a thin layer above the air-sea interface within the constant flux layer (the wave boundary layer). By imposing momentum and energy conservation in the wave boundary layer and wave energy conservation, Kukulka and Hara (2008a,b) have derived coupled nonlinear advance-delay differential equations governing the wind speed, turbulent wind stress, wave height spectrum, and the length distribution of breaking wave crests. The system of equations is closed by introducing a relation between wave dissipation (due to breaking waves) and the wave height spectrum. The improved CWW model was first applied for fully-grown seas and then was applied for a wide range of wind wave conditions from laboratories to the open ocean. Kukulka and Hara (2008a,b) investigated the effect of air flow separation due to breaking waves on the air-sea momentum flux and concluded that the contribution of breaking waves is increasingly important for younger seas under higher wind speeds. The model results of the Charnock coefficient are similar to the results of non-breaking model (Hara and Belcher 2004, Moon et al., 2004a) for grown seas, but approach the breaking model results (Kukulka et al., 2007) for very young seas, highlighting the significant contribution of breaking waves under strongly forced conditions typical in tropical cyclones.

2.2. Air-sea flux budget

Traditionally, the momentum and kinetic energy fluxes from wind to waves are assumed to be identical to the fluxes into subsurface currents due to wave breaking based on the assumption that no net momentum (or kinetic energy) is gained (or lost) by surface waves. This assumption, however, is invalid when the surface wave field is not fully developed. Especially under TC conditions, the surface wave field is complex and fast varying in space and time and may significantly affect the air-sea flux budget. Fan et al. (2008a,b) investigated the effect of surface gravity waves on the momentum and kinetic energy transfer budget across the air-sea interface under growing seas and TC conditions. They found that the momentum and energy fluxes into ocean currents may be significantly less than the fluxes from air when the wave field is growing and extracting momentum and kinetic energy. The spatial variation of the TC-induced surface waves plays an important role in reducing the momentum and kinetic energy fluxes into subsurface currents in the rear-right quadrant of the TC. In an idealized Category 3 TC moving with a forward speed of 5 ms^{-1}, this reduction is up to 7-8% for the momentum flux and 10% for the kinetic energy flux on the right side of the storm. This difference highlights the significance of the air-sea flux budget analysis in coupled models.

2.3. Wind-wave-current interaction

Fan et al. (2008c) investigated the wind-wave-current interaction mechanisms in tropical cyclones and their effect on the surface wave and ocean responses in a set of numerical experiments. They found that the time and spatial variations in the surface wave field, as well as the wave-current interaction significantly reduce momentum flux into the currents. This reduction is the largest in the rear-right quadrant of the TC. In an idealized Category 3 TC moving with a forward speed of 5 ms^{-1}, wind-wave-current interaction can reduce the momentum flux into currents up to 10% relative to the flux from wind. The reduction in momentum flux into the ocean consequently reduces the magnitude of subsurface current and SST cooling to the right of the storm track and lessens mixed layer deepening in the wake of a TC. During wind-wave-current interaction, the momentum flux into the ocean is mainly affected by reducing the wind speed relative to currents, while the wave field is mostly affected by refraction due to the spatially varying currents. In the area where the current speed (in the wave propagation direction) has local maximum, the wave spectrum of longer waves is reduced, the peak frequency is shifted to a higher frequency, and the angular distribution of the wave energy is widened.

2.4. Improving momentum flux parameterization in wave model

It has been known that the NCEP operational WAVEWATCH III (WW3) wave model overestimates the significant wave height under very high wind conditions in strong hurricanes (Tolman et al. 2005). Moon et al. (2008) have implemented the Moon et al. (2007) drag coefficient formulation with the reduced drag at high winds into the WW3 model. The results show significant improvements in the WW3 wave forecast during hurricanes. Fan et al. (2008d) continued this work and investigated the effects of wind-wave-current interaction on the wave predictions during Hurricane Ivan (2004) by coupling WW3 with the Princeton Ocean Model. The model results were compared with field observations of the surface wave spectra from a scanning radar altimeter (SAR), NDBC time series and satellite altimeter measurements. The results suggest that the WW3 model with the original drag coefficient parameterization tends to overestimate the significant wave height and the dominant wave length, and produces a wave spectrum that is higher in wave energy and narrower in directional spreading. When the improved drag parameterization of Moon et al. (2007) is introduced and the wave-current interaction is included, the model yields improved forecast of significant wave height and wave spectral energy. When the hurricane moves over pre-existing mesoscale ocean features (warm- and cold-core ring, Loop current), the short-term current response can be significantly modulated by the non-linear interaction of the storm-induced and pre-existing strong currents in the mixed layer. This modulation also affects surface gravity wave prediction.

3. Importance of accurate ocean initialization of mesoscale features in coupled TC-ocean models

One major challenge for proper ocean initialization in a coupled TC–ocean model is accurate representation of mesoscale oceanic features that do not follow an annual (or even a regular) cycle, such as the penetration of the Loop Current (LC) into the Gulf of Mexico (GoM) and the shedding (and perhaps reattachment) of Loop Current eddies (LCEs). For these features, neither a monthly climatology nor a set of historical observations is sufficient. Using a feature-based (F-B) modeling approach that assimilates satellite-derived altimeter, sea surface temperature, and in situ data in the GoM, a new ocean initialization has been developed for the operational GFDL and HWRF coupled hurricane–ocean models (Yablonsky and Ginis, 2008). This new procedure is designed to account for real-time spatial and temporal variability of mesoscale oceanic features to produce a more realistic three-dimensional temperature field valid at the model initialization time. Yablonsky and Ginis (2008) compared vertical profiles from the F-B data assimilated temperature fields to 18 GoM AXBT temperature profiles on 15 September 2005, the ocean climatology, and an alternative data-assimilated product (RSMAS HYCOM) to determine the relative accuracy of the initialization procedure. It was shown that the F-B ocean initialization creates a significantly improved three-dimensional temperature

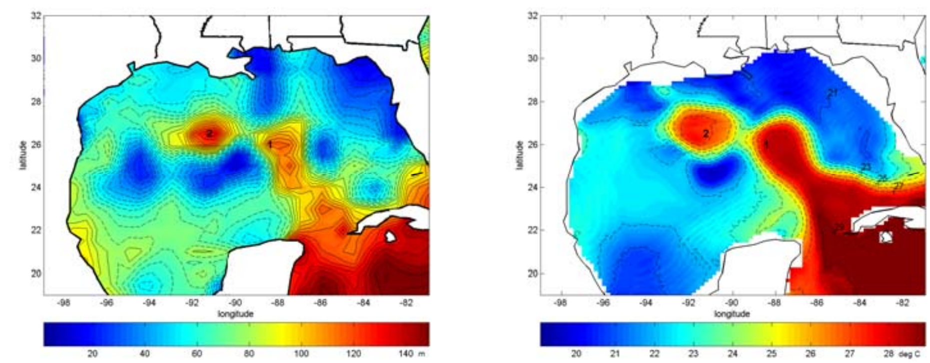

Figure 1: Adopted from Yablonsky and Ginis (2008). Depth(meters) of the 26^{o}C isotherm on September 15, 2005, derived from satellite altimeter data (courtesy of Michelle Mainelli) (left) compared to the temperature (^{o}C) at 75-m depth after the F-B ocean model initialization (right). The numbers indicate the location of AXBT temperature profiles.

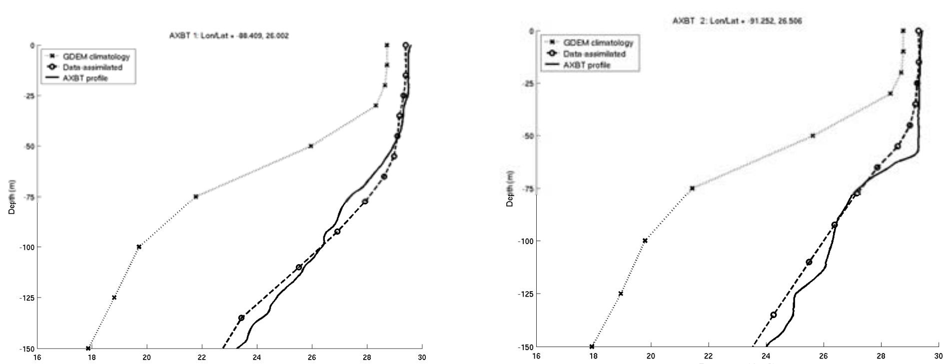

Figure 2: Adopted from Yablonsky and Ginis (2008). AXBT #1 (left) and #2 (right) temperature profiles (black solid), GDEM September climatology (dotted with "x" markers), and model profiles after the F-B ocean model initialization (dashed with circle markers). AXBT positions are shown in the top labels and the position relative to the rest of the Gulf of Mexico basin is indicated in Fig. 1.

field over climatology. Also, when evaluating ocean mixed layer temperature, depth and upper thermocline temperature against AXBT profiles, the F-B initialization technique is more accurate than those obtained from the RSMAS HYCOM. Fig. 1 compares depth of the 26^{o}C isotherm on September 15, 2005, derived from satellite altimeter data and the temperature at 75-m depth after the F-B ocean model initialization. Climatological, AXBT and model temperature profiles in two locations, indicated in Fig. 1, are shown in Fig. 2.

We conducted sensitivity experiments for selected hurricanes with the GFDL coupled hurricane-ocean model to evaluate the impact of assimilating mesoscale oceanic features on both the SST cooling under the storm and the subsequent intensity change with and without altimeter data assimilation. The results of two simulations for Hurricane Katrina (2005) are shown in Fig. 3 and Fig. 4. In the CTRL case, the Loop Current and a warm core ring are assimilated using real-time altimetry to accurately represent these features (Figure 3a). In the CLIM case, the Loop Current is initialized instead in its climatological position, and no warm core ring is assimilated (Figure 3b). The presence of the Loop Current and warm-core eddy reduced the SST cooling along the hurricane track in the CTRL case (not shown) and allowed the storm to become more intense (Figure 4). In fact, in the CTRL case the GFDL intensity forecast of the actual storm is much improved compared to the CLIM case.

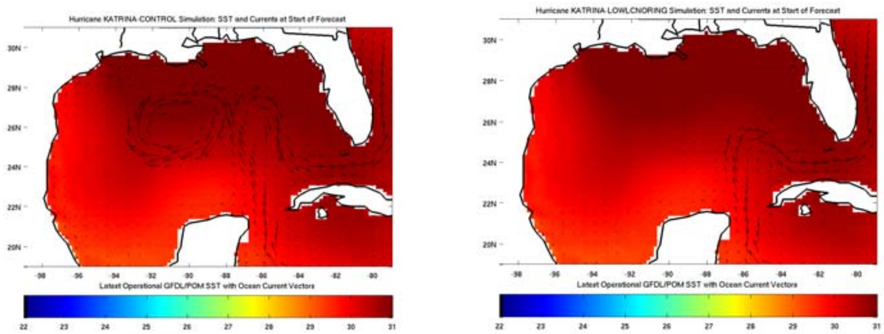

Figure 3: SST and surface currents for Hurricane Katrina coupled GFDL model forecasts with the Loop Current and a warm core ring initialized based on altimetry to represent the actual location as of 26 August 2005 (left panel) and a modified Hurricane Katrina coupled GFDL model forecast in which the Loop Current is initialized in its climatological position, and no warm core ring is assimilated (right panel).

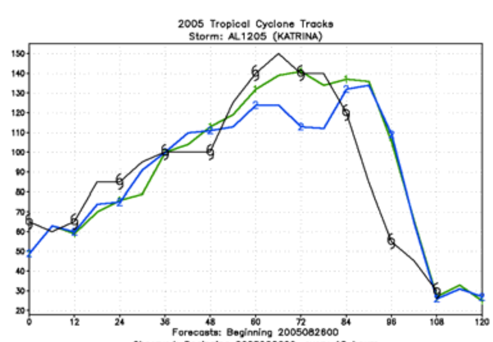

Figure 4: Hurricane Katrina maximum wind speed (kt) for CTRL (green line; "1" symbols), CLIM (blue line; "2" symbols), and observations (black line; hurricane symbols).

4. Inadequacy of one-dimensional ocean model for coupled TC-ocean forecasts

It has become well-established that SST cooling under the TC is primarily caused by shear-induced mixing of the upper ocean and entrainment of cooler water into the upper oceanic mixed layer (OML) from below. Since this shear-induced mixing is a one-dimensional (1D) process, some recent studies suggest that coupling a 1D ocean model to a TC model may be sufficient for capturing the storm-induced SST cooling in the region providing heat energy to the TC (Emanuel et al. 2004; Lin et al. 2005, 2008; Bender et al. 2007; Davis et al. 2008). If in fact a 1D model is sufficient, valuable computational resources can be saved as compared to coupled models that employ a fully three-dimensional (3D) ocean component.

Yablonsky and Ginis (2008b) have recently evaluated the difference in the SST response to TC wind forcing underneath the storm core using both a 1D and a 3D version of the same ocean model. Specifically, this study investigates the potential impact of upwelling, which can only be captured with a 3D ocean model. Upwelling decreases the OML depth, thereby allowing for enhanced shear-induced mixing and subsequent SST cooling under the storm core if the storm is translating slowly enough to be impacted by the upwelled region. Advection via background surface currents, as in ocean fronts or eddies, may also limit the ability of a 1D ocean model to properly capture the SST response, but here the focus is simply to address the differences in an initially horizontally-homogeneous ocean without background currents.

The 3D experiments in this study are performed using a version of the Princeton Ocean Model (POM; Mellor 2004) that is similar to the version used in the operational GFDL coupled hurricane-ocean prediction system (Bender et al. 2007). The 1D experiments use the same version of POM, except the advection and pressure gradient terms are removed so that at each grid point, there is no interaction amongst surrounding grid points in the horizontal.[1] This 1D simplification is consistent with the 1D version currently used in the GFDL model for the eastern Pacific basin (Bender et al. 2007). In all experiments, the ocean is initialized with a horizontally-homogeneous temperature (T) and salinity (S) profile. Two T profiles are tested: in the "GCW" experiments, the T profile is based on the GDEM climatological profile in the Gulf of Mexico Common Water during the month of September, while in the "CRB" experiments, the T profile is based on the September GDEM climatological profile in the Caribbean Sea, except the OML temperature, and hence sea surface temperature, is adjusted slightly to match the OML temperature in the GCW experiments (Fig. 5).

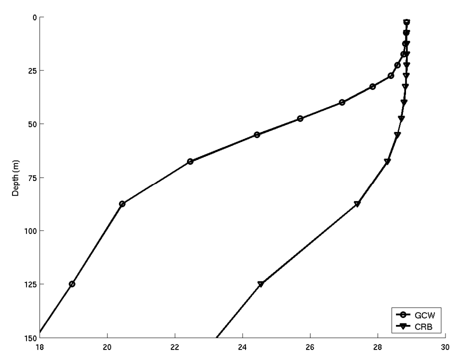

Figure 5: Upper 150-m of GCW ("o" markers) and CRB (triangle markers) initial ocean temperature profiles. Markers are located at the POM half-sigma levels.

[1] For simplicity, horizontal diffusion terms are not removed, but tests show the impact of these terms is negligible.

The wind stress distribution is based on the wind field derived from an analytic model of the wind and pressure profiles in hurricanes (Holland 1980). In all experiments, this wind stress field translates westward with a prescribed speed, and model integration continues until the average SST cooling under the storm core reaches quasi-steady state (≤ 5 days). Translation speeds from 0.2 to 2° latitude per 6 hr (~1 to 10 m s^{-1}) [with an increment of 0.1° latitude per 6 hr (~0.5 m s^{-1})] are tested so the impact of translation speed on the difference in storm-induced SST cooling between the 1D and 3D versions of the model can be determined.

To quantify the magnitude of SST cooling within the region providing most of the heat energy to the storm, the average SST cooling is calculated within a 60-km radius and 200-km radius around the storm center. The average SST cooling for all experiments after quasi-steady state is reached is shown in Fig. 6. The most striking aspect of this result is the large difference in SST cooling between the 3D and 1D simulations with translation speeds < ~5 m s^{-1} (< ~3.5 m s^{-1}) in the GCW (CRB) experiments. For the slowest translation speed tested, ~1 m s^{-1}, the 3D simulation for the GCW (CRB) experiment yields average SST cooling of > 10°C (~4.5°C) within the 60-km radius, while the 1D simulation for the GCW (CRB) experiment yields SST cooling of only ~2.5°C (~0.5°C) within the 60-km radius. Even for storms translating at ~2 m s^{-1}, the 3D simulation produces double the cooling of the 1D simulation.

Significant differences in average SST cooling within the storm core between the 1D and 3D simulations for slower-moving storms implies the increased importance of upwelling relative to vertical mixing alone. It is illustrated in Fig. 7 which focuses on the experiments with the GCW initial profile with 2.4 and 4.8 m s^{-1} translation speed. For the 2.4 m s^{-1} experiments the difference between 1D and 3D is striking. In the 1D experiment, the OML depth steadily increases from an initial depth of ~35 m at > 200 km ahead of the storm center to ~60 m at > 80 km behind the storm center. As the OML depth increases, the OML (and hence sea surface) temperature steadily decreases. In the 3D experiment, upwelling begins to impact the OML temperature even > 100 km ahead of the storm center. Significant cooling OML cooling occurs from front to back through the storm core, and the first upwelling maximum occurs ~70 to 150 km behind the storm. For the 4.8 m s^{-1} experiments, the difference between 1D and 3D is still significant, but it is less dramatic than the difference for the 2.4 m s^{-1} experiments.

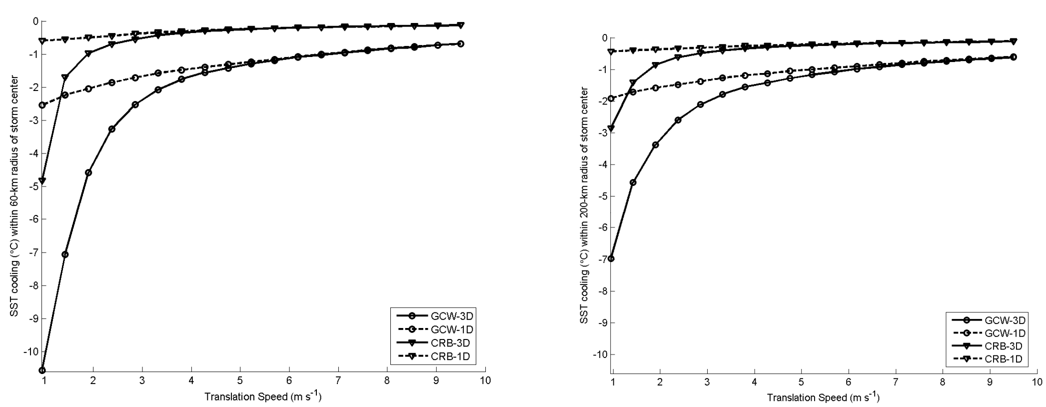

Figure 6: Average SST cooling as a function of storm translation speed within a radius of (a) 60-km and (b) 200-km of the storm center for: GCW-3D (solid line, "o" marker), GCW-1D (dashed line, circle markers), CRB-3D (solid line, triangle markers), and CRB-1D (dashed line, triangle markers). Markers are located at each translation speed tested.

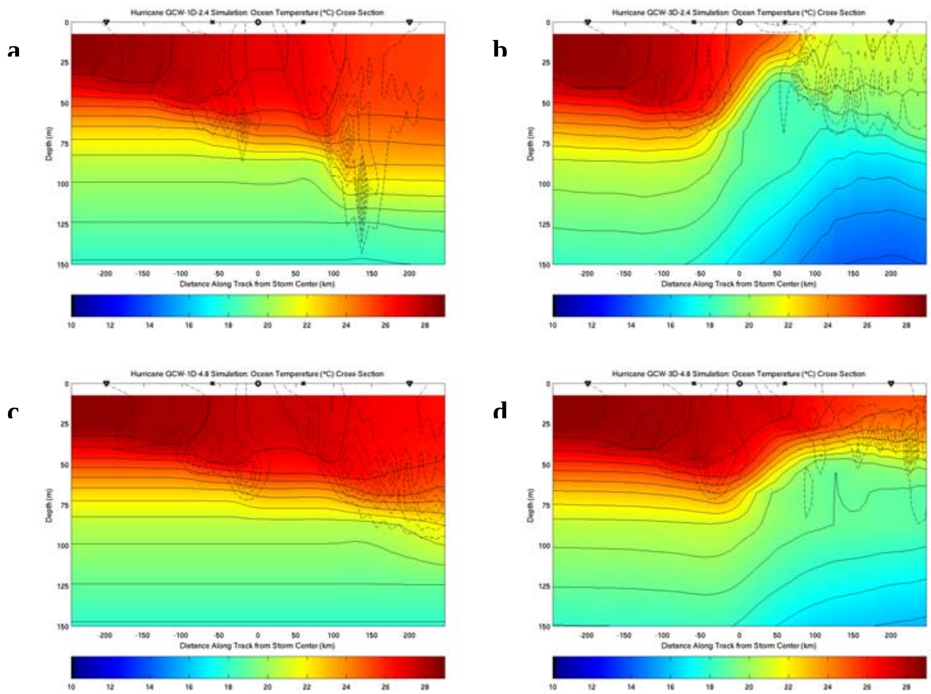

Figure 7: Along-track, quasi-steady state ocean temperature cross-sections for the GCW-1D (a, c) and GCW-3D (b, d) experiments with translation speeds of 2.4 m s^{-1} (a, b), 4.8 m s^{-1} (c, d). Temperature is solid-contoured every 1°C, and TKE is dash-contoured every 0.01 m^2 s^{-2}.

These experiments clearly indicate that by neglecting upwelling, 1D ocean models miss an important mechanism for hurricane-induced SST cooling, and for storms translating at 3.5-5 m s^{-1} or less (depending on the initial upper-ocean temperature profile), this upwelling-enhanced SST cooling can occur within the storm core where heat flux from the ocean to the atmosphere can impact hurricane intensity. According to the Atlantic basin hurricane database (HURDAT; Atlantic Oceanographic and Meteorological Laboratory 2008), hurricanes in the Gulf of Mexico (18-31°N; 98-81°W) have historically translated at < 5 m s^{-1} 73% of the time and < 2 m s^{-1} 16% of the time, while hurricanes in the entire western tropical North Atlantic (10-31°N; 98-50°W) have historically translated at < 5 m s^{-1} 62% of the time and < 2 m s^{-1} 12% of the time. It is therefore clear that 1D ocean models are inadequate for coupled hurricane-ocean model forecasting.

5. Future strategies for coupled TC-wave-ocean modeling

During TC conditions, large amount of sea spray is produced by bursting air bubbles in whitecaps and by tearing spume from the wave crests. Consequently, both turbulence and sea spray provide routes by which moisture, heat and momentum cross the air-sea interface. Although the question as to whether or how sea spray affects the evolution of TCs has been around for a long time, the answer has remained elusive. All the modeling attempts to study the impact of sea spray evaporation on TCs have so far relied on simplified bulk parameterizations of the spray-mediated fluxes. They produced a wide range of contradictory effects on TC intensity, suggesting no impact (Wang et al., 1999), increased intensity (Andreas and Emanuel, 2001; Bao et al., 2000), and reduced intensity (Lighthill et al., 1994; Henderson-Sellers et al., 1998).

There are several complex and not well understood aspects of sea spray dynamics in TC conditions. One aspect is associated with spray generation processes. In nature, sea spray is the product of wave breaking. At present, all the spray-mediated flux schemes utilize very simple diagnostic relations to provide the wavecharacteristic information based on the wind information only. In the current NOAA/ESRL air-sea heat flux parameterization scheme (Fairall et al., 2008) sea spray generation explicitly depends on two key wave parameters, namely, the total energy dissipation rate due to surface wave breaking, and the height of the droplet sources (i.e., the height of dominant breaking wave crests). These wave parameters are uniquely related to the wind speed if wave fields are fully developed. However, with young and complex wave fields under TCs these parameters are highly variable in space and time (e.g., Fan et al., 2008b). Therefore, a fully coupled TC-wave model is required to accurately simulate the sea spray generation and its impacts on TC forecasts.

Another aspect of sea spray is its direct effect on the surface stress where turbulence theory shows that surface drag can be reduced by heavy spray production. Theoretically, the concentration of sea spray droplets in the marine surface boundary layer can reach the level at which its associated air-flow density stratification will tend to suppress turbulence, reducing wind stress at the ocean surface and thus increase the surface wind speed (Kudryavtsev, 2006). However, in nature this process is much more complicated because this same turbulence is also responsible for maintaining the thermal air-fluxes. Reduction in wind stress will lead to reduction in thermal fluxes which in turn reduces the energy supply to the TC and ultimately limits the surface wind speed. It is important in the future to address the issue of how the stress reduction effect can be properly parameterized and incorporated into the TC model's physics at extreme high wind regimes.

In summary, improved predictions of TC intensity, structure, and motion will require fully coupled ocean-wave-atmospheric models that explicitly resolve the effects of sea state on air-sea fluxes and spray generation. Future TC models should include the following coupled modeling strategies: 1) in the TC model, the parameterizations of the air-sea heat and momentum fluxes and the spray source functions explicitly include the sea state dependence, ocean currents and SST; 2) the wave model is forced by the sea-state dependent momentum flux and includes the sea spray and ocean current effects; 3) the ocean model is forced by the sea-state dependent momentum and kinetic energy fluxes that account for the air-sea flux budget.

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