Upper Ocean Response to Tropical Cyclone Wind Asymmetries

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Introduction

The most apparent effect of a tropical cyclone on the upper ocean is the marked cooling of sea surface temperature (SST) that is clearly seen in Advanced Very High Resolution Radiometer (AVHRR) images of SST. As a storm intensifies, the increasing wind speed may increase evaporation and supply the storm with the necessary source of heat for further intensification. However, the significant SST reduction induced by the increasing wind speed leads to reduced air-sea fluxes thus decreasing the storm intensity. In the context of extra tropical transition, the scales of upper ocean thermal and momentum response due to the passage of tropical cyclones is reviewed and the ocean response is simulated using a numerical ocean model for symmetric and asymmetric components of the wind field of hurricane Gilbert (1988) in the Gulf of Mexico.

Background

Relevant fields for coupled air-sea interactions in the Oceanic Planetary Boundary Layer (OPBL) and the upper ocean heat content are SSTs, Mixed Layer Depths (MLDs), mixed layer and thermocline currents and density structure over scales of atmospheric forcing. OPBL response due to the passage of a storm depends on the forced current structure in the upper ocean and can be classified into near-field and far-field response. In addition to SST (OPBL temperature) decrease, near-field response includes storm surge due to a combination of wind driven currents, inverse barometric effect, astronomical tides, and surface waves. Cyclonically rotating hurricane winds cause the oceanic mixed layer currents to diverge from the storm track starting within one-quarter of an inertial wave length behind the eye, where the inertial wave length (λ) is defined as the product of the storm translation speed (U_h) and the inertial period (IP=$\frac{12}{sin\phi}$ hr) at that latitude (ϕ). SST decreases in this directly forced regime are due to surface fluxes of latent and sensible heat to the atmosphere (∼20%) and vertical mixing at the base of the oceanic mixed layer (∼80%) induced by wind stress and strong vertical shears. Over the next half inertial cycle (i.e. up to 0.75λ), mixed layer currents converge toward the storm track, causing an increase in the mixed layer depth. This alternating cycle of upwelling and downwelling occurs over distances of λ or inertial periods and establish a horizontal pressure gradient that excites baroclinic near-inertial motions in the thermocline.

Black (1983) stratified extensive Airborne eXpendable Bathythermograph (AXBT) survey during 18 hurricanes found that the maximum upper ocean cooling was about 1 to 6°C with mixed layer deepening of 20 to 50 m for fast, moderate and slow moving storms. These values set the limits for observational, analytical, diagnostic and numerical studies of OPBL response in the directly forced regime. However, it should be noted that the definition of SST differs within various communities. While satellite based estimates of SST represent the skin temperature of the ocean, ship and *insitu* measurements lie within 1

Parameter	Frederic	Norbert	Josephine	Gloria	Gilbert	Opal
Radius of maximum winds, RMW (km)	30	34	52	46	60	25
Maximum wind stress, τ_{max} (Nm^{-2})	3.3	4.4	3.4	3.4	4.2	23.9
Speed of the hurricane, U_h (ms^{-1})	6.5	3.7	4.2	6.8	5.6	8.5
First mode phase speed, c_1 (ms^{-1})	3.0	2.1	3.0	3.0	2.8	3.0
Froude number, U_h/c_1	2.1	1.4	1.4	2.3	2.0	2.8
Inertial Period, IP (day)	1.0	1.6	1.0	1.0	1.25	1.14
Coriolis Parameter, $f \times 10^4$ (s^{-1})	0.7	0.5	0.7	0.7	0.58	0.64
Prestorm Mixed layer depth, h (m)	30	40	55	45	35	NA

Table 1: Air-Sea Parameters and nondimensional scales in tropical cyclones Frederic (79), Norbert (84), Josephine (84), Gloria (85), Gilbert (88) and Opal (95). Prestorm mixed layer depth is not known for Opal as ocean measurements were not made.

to 10 m depth. In contrast, climatological estimates are smoothed from several observations and therefore represent an average temperature in that region. Due to high wind speeds in a hurricane, a 10 m layer in the OPBL is mixed with layers below before the arrival of outer winds of 17 ms^{-1} (34 kt) and therefore the oceanic mixed layer temperatures are more appropriate in a coupled hurricane-ocean system for hurricane intensity.

Upper Ocean Response Scales

Ocean response due to the passage of hurricanes depend upon the speed of translation of the storm, radius of maximum wind (RMW), maximum wind stress, wind profile etc. Air-sea parameters for hurricanes Frederic (1979), Norbert (1984), Josephine (1984), Gloria (1985), Gilbert (1988) and Opal (1995) are shown in Table 1. Froude numbers estimated by the ratio of storm translation speed (U_h) and the first baroclinic mode phase speed (c_1) in the ocean indicate that these storms are moderate to fast movers and therefore the oceanic response is expected to be predominantly baroclinic associated with upwelling and downwelling of isopycnals in spreading 3-dimensional wakes. Smaller Radii of Maximum Wind for hurricanes Frederic, Norbert and Opal suggest a well defined eye with clear wind maxima, whereas Josephine, Gloria and Gilbert had a very broad wind field. In particular, Gilbert wind field contained a secondary wind maxima due to an outer eyewall located around 90 km from the center. These parameters set the temporal and spatial scales of ocean response and the expected magnitudes of the response could be estimated. For a non-recurving storm it is convenient to use a coordinate system centered in the eye with Inertial Periods and RMW as along-track and cross-track coordinates, respectively.

Hurricane Gilbert

Hurricane Gilbert was one of the strongest storms in the Atlantic basin in recent history. Over the warm waters of Western Caribbean sea, the storm explosively strengthened to category 5 with a minimum central pressure of a record 888 mb and flight-level winds exceeding 80 ms^{-1} at a radius of about 15 km from the center prior to crossing the Mexican islands of Cancun and Cozumel. The storm translated at a speed of 7 ms^{-1} and winds greater than 32 ms^{-1} extended beyond 100 km from the eye. After crossing the Yucatan peninsula, the translation speed decreased to 5.6 ms^{-1} and Gilbert was weakened as it entered Gulf of Mexico. The aircraft acquired wind and thermodynamic measurements at flight-level of 850 mb that indicated a maximum 10-min sustained winds of about 53 ms^{-1}. These flight-level winds are reduced to 10 m standard height using the boundary layer model of Powell (1980). Reduced flight-level winds are combined with the European Center for Medium-range Weather Forecasting (ECMWF) model-generated 10 m wind field and buoy measurements, and objectively analyzed by a method in which cubic B-splines minimize the deviations between the input observations and analysis output (Powell and Houston 1996) to obtain boundary layer winds over the Gulf of Mexico. The analyzed wind field is broad with wind speeds up to 30 ms^{-1} extending out to 160 km from the eye, and the maximum sustained 10-min wind is about 42 ms^{-1}. Winds at the secondary R_{max} exceeded the primary wind maximum and this secondary eyewall convection is also apparent in the airborne radar data as well as Special Sensor Microwave/Imager (SSM/I) data.

As part of an Office of Naval Research (ONR)- NOAA upper ocean response experiment, 76 AXCPs (Airborne eXpendable Current Profilers) and 51 AXBTs were successfully deployed in the western Gulf of Mexico, from NOAA WP-3D aircraft to investigate the evolving three-dimensional ocean response (Shay *et al.* 1992). This experiment improved upon the previous observations by acquiring data prior, during and subsequent to the passage of hurricane Gilbert in the Gulf of Mexico from 14 to 19 Sept 1988. Details of this experiment are found in Shay *et al.* (1992). These measurements revealed the presence of an anticyclonic warm core eddy and associated geostrophic velocities of up to 1 ms^{-1} about 200 to 250 km to the right of the storm track (Shay *et al.* 1998). Shay *et al.* (1992) used the objective analysis (OA) technique of Mariano and Brown (1992) to derive the pre-storm, storm, wake 1 and wake 2 SST and MLD (Mixed Layer Depth) fields from data distribution. The SSTs here are defined as the temperature of the well mixed layer and the depth of the layer is the depth at which temperature decreases by more than 0.2° C. On 14 Sept 1988, the prestorm SST was fairly uniform with significant cooling in the wake of the storm. On 16 Sept, during the passage of the storm, SST started decreasing ahead of the storm with a maximum decrease of 3.5 to 4°C on the right rear quadrant. On 17 Sept, one day after storm passage, a pool of water with a temperature decrease of 4° C was located about 1 to 2 RMW to the right of the storm. On 19 Sept, this cooler water is displaced from its position on the 16th. The mixed layer depths (MLD) between prior to, during, one and three days following the storm passage indicate a mixed layer deepening of 30 to 35 m with a relative maximum at about 1 to 3 RMW to the right of the storm track. AXCP observed storm induced velocities were of the order of 1.2 ms^{-1} in the mixed layer and the anticyclonically rotating velocities in the eddy were about 1 ms^{-1}. Near the storm track there was significant vertical shear at the mixed layer base that continued to cool the SST even a day after the passage of the storm. To isolate the storm-induced response, this background variability associated with the eddy had to be removed from the measured currents. The mixed layer heat budget is also modulated by the pre-existing current structure (Jacob *et al.* 1999).

Upper Ocean Response to Wind Asymmetries

The Miami Isopycnic Coordinate Ocean Model (MICOM) is used to investigate the ocean response due to the symmetric and total wind field. In this model, the ocean is represented as a stack of layers, each with constant density and governed by equations resembling shallow-water equations. Layered models such as this, reduce the vertical truncation error, by concentrating coordinate surfaces in regions characterized by large vertical and horizontal gradients compared to conventional cartesian coordinate models. Specific advantages of using MICOM in this study are: an explicit mixed layer physics, and realistic eddy shedding events from the western boundary current in the North Atlantic and Gulf of Mexico. The model has a resolution of 0.07° in the domain that extends from 80 to 98° W and from 14 to 31° N and invokes Kraus-Turner (1967) entrainment formulation (Bleck *et al.* 1989). The model is set up with quiescent, climatological and realistic initial conditions and the response due to changes in forcing structure is investigated using the analyzed and parametric model winds.

The analyzed wind field is decomposed into symmetric and asymmetric components. The average translation speed of the storm is 5.6 ms^{-1} in the Gulf with a maximum symmetric wind component of 30 to 32 ms^{-1}. Maximum wind speeds due to higher order asymmetries range from 5 to 8 ms^{-1} in the domain. With the ocean model initial conditions being the same, symmetric (by symmetric here we mean the vector sum of storm centered symmetric component and the translation speed) and total winds are used to force the model and the results are compared with observations. While the thermal response for the realistic oceanic initial condition compares well with the AXCP data for both total and symmetric wind fields, the area averaged surface fluxes in the directly forced region increase by about 20 to 30 % for the total wind forcing. A similar increase in fluxes are also seen by using realistic initialization of the ocean model with the eddy in the domain with a marked decrease of 0.8 to 1.1 ° C in the rms differences between simulated and observed temperatures.

Summary

Numerical simulation of the Gilbert case indicates the need to represent higher order wind asymmetries for more accurate flux estimates. This is particularly relevant for transitioning tropical cyclones where the asymmetries will be more pronounced with expanding RMW. Realistic initialization of the ocean model significantly improves the model-data comparisons. The TOPEX-POSEIDON satellite altimeter measures the Sea surface Height Anomalies (SHA) with respect to a mean geoid and provides valuable information on the oceanic mesoscale activity that significantly modulates the climatological initial conditions (Shay *et al.* 1999). SHA derived from TOPEX data in conjunction with the AVHRR SST images are now used to monitor the upper ocean heat content in real time in the Gulf of Mexico and along the eastern seaboard that could be extended to other areas. Due to hostile environmental conditions in a tropical cyclone (strong winds and high seas) aircraft is the only viable platform for making simultaneous measurements in the atmospheric and oceanic planetary boundary layers because of the strong winds and waves. To quantify the APBL/

OPBL fluxes, an integrated experimental approach is being developed with a suite of oceanographic and atmospheric components that includes expendables that measure the upper ocean density and velocity structures (AXCPs, AXBTs and AXCTDs), radome gust probe for quantifying heat, momentum and moisture fluxes, Airborne InfraRed Thermometer for SSTs, SFMR/C-SCAT for surface stress fields, Surface Contour Radar for directional wave spectra, GPS sondes for APBL profiles and Floats for currents. The satellite data provides a large scale context for these in situ observations. As models are being developed at a rapid rate, more high quality observations are needed to evaluate and validate them and a balanced approach is required to understand this interaction problem.

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