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Project Title: Improving the Hurricane WRF-Wave-Ocean Coupled System for Transition to Operations
Recipient Name: The University of Rhode Island
Investigator: Isaac Ginis
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Reporting Period: 08/01/2008 - 12/31/2008

Work Accomplishments:

1. Tasks scheduled for Year 2:

a) Implementing and testing the effects of waves on the near-surface ocean currents and wave-current interaction in the HWRF coupled model.
b) Improving heat flux parameterization in the HWRF.
c) Including the effect of breaking waves in the momentum flux parameterization in the HWRF.

2. Tasks accomplished this period

a) Implementing and testing the effects of waves on the near-surface ocean currents and wave-current interaction in the HWRF model.

During this time period, we transitioned to NCEP/EMC (Dr. Hendrik Tolman) the URI air-sea interface model (ASIM) for implementation into the WAVEWATCH III (WW3) wave model, which is currently being coupled with the HWRF model. The key elements of ASIM have been described in the previous JHT reports and peer-reviewed publications (Moon et al., 2004a, b and Fan et al., 2008 a, b, c). We are assisting the EMC group in testing the code and evaluating the impact of ASIM on the wave predictions and air-sea fluxes in hurricane conditions. In the second half of Year 2, the ASIM will be imbedded into the HWRF hurricane-wave-ocean coupled model and will calculate all the flux boundary conditions for the atmospheric, wave, and ocean models.

We continued to work on assessing the effects of wave-current interaction on air-sea momentum fluxes and wave predictions in hurricanes. Particularly, we investigated the role of pre-existent currents due to mesoscale ocean features on wave predictions. Hurricane Ivan in 2004 crossed the Loop Current and a warm-core ring (WCR) in the Gulf of Mexico. Fortunately, during that time, detailed SRA wave spectra measurements were collected by NASA through a joint effort between the NASA/Goddard Space Flight Center and NOAA/HRD. These observations are used in this study to investigate whether inclusion of the effect of pre-existent currents may improve the wave predictions using WW3.

For this study, we utilized the altimetry data from the Colorado Center for Astrodynamics Research (CCAR) Real-Time Altimetry Project through their website: (http://argo.colorado.edu/~realtime/welcome/). The CCAR altimetry map on September

12, 2004, shown in Figure 1a, is used to initialize the position and structure of the LC and the warm-core ring in the Gulf of Mexico, shown in Figure 1b, in the ocean model. The feature-based modeling procedure of Yablonsky and Ginis (2008) is used to assimilate the altimetry observations. This ocean initialization procedure is the same as the one used in the operational HWRF and GFDL coupled models.

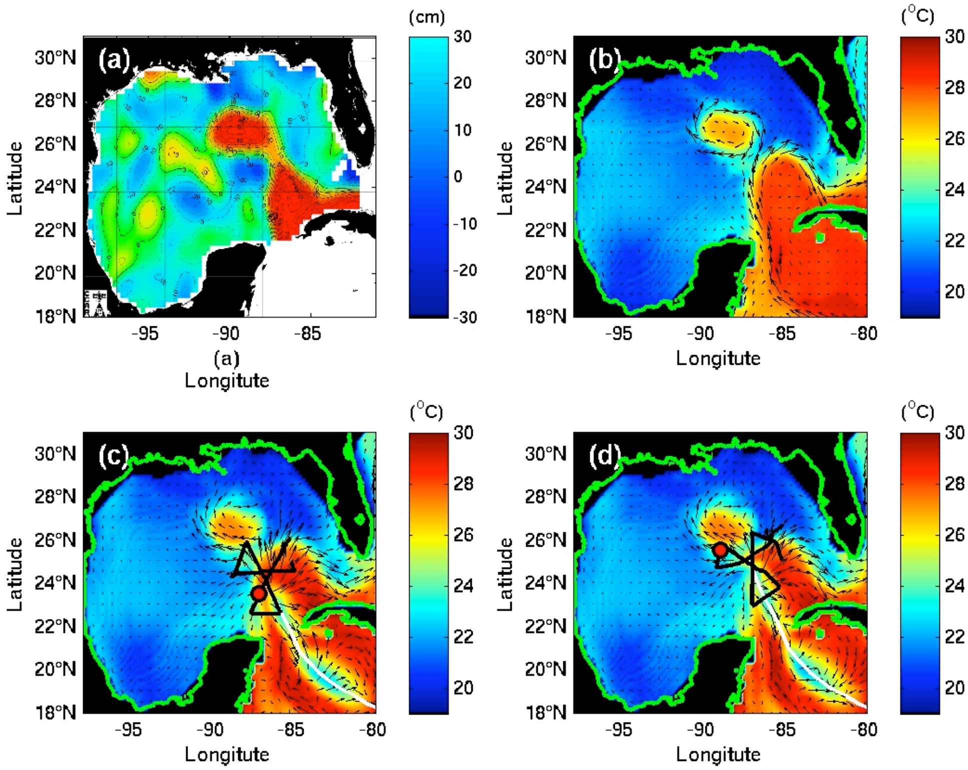

Figure 1. *Satellite altimetry map in the Gulf of Mexico on September 12, 2004 (a), and ocean temperature at 70 m depth with current vectors at L/4π depth in the ocean model at 12 UTC on September 12 (b), 21 UTC on September 14 (c), and 2:40 UTC on September 15 (d). On figure (c) and (d), the black line is flight track, the white line is hurricane track, the red dot shows the location of the SRA measurements at this time.*

To investigate the effect of pre-existent currents, we compare two wave model simulations with and without the Loop Current and WCR. Figure 2c shows significant wave height (H_s) comparison between the two simulations along the September 14th – 15th flight. The SRA measurements are also shown for reference. The H_s difference between the two experiments is clearly seen along some of the flight sections. Let us examine two such periods highlighted by the gray areas in Figure 2c).

At 21:00 UTC on September 14, H_s is significantly larger with the LC initialization. The spatial snapshot of the H_s difference with and without the LC initialization is shown at the corresponding time in Figure 2a. Figure 1c shows the spatial distribution of the ocean temperature and current field at 70 m depth. At this time, the aircraft is over the edge of the LC, where a strong northward current is added due to the LC initialization (Figure 3a). The wave field at the same time (Figure 3b) indicates that the dominant waves are propagating southward at this location. If we consider the evolution history of these dominant waves (along the pink arrows in Figures 3a and 3b), it is evident that a strong opposing current persisted (i.e., the packet propagation was slower) throughout the wave evolution, such that the overall wave spectrum was enhanced. This wave spectrum enhancement explains why the predicted H_s at this location is increased when the Loop Current initialization is included.

At 02:40 UTC on September 15, the predicted H_s is significantly smaller with the Loop Current initialization (Figure 1c). Figure 2d shows that the flight is passing through the southern edge of the warm core ring at this time. Due to the initialization of the warm core ring, a strong westward current is added at that location (Figure 2c). The wave field at the same time (Figure 3d) shows that the dominant waves are propagating westward. The evolution history of these dominant waves (along the pink arrows in Figures 3c and 3d) is such that a strong positive (aligned) current accelerated the wave packet propagation and reduced the spectral level throughout the wave evolution.

These two examples clearly demonstrate that strong currents due to pre-existing mesoscale oceanic features may significantly modify the wave field prediction, mainly because such currents accelerate or decelerate the wave propagation.

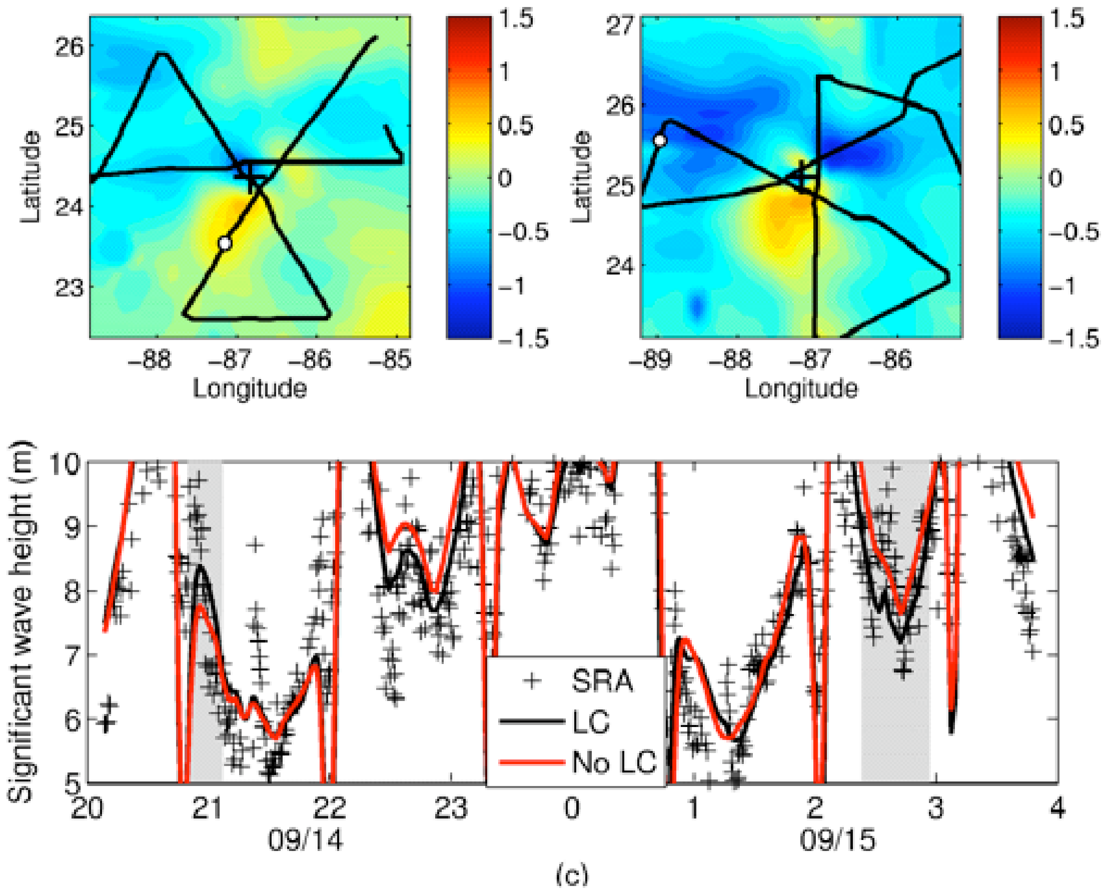

Figure 2. *WW3 significant wave height (H_s) in the experiment with Loop Current initialization in the ocean model minus the H_s without Loop Current initialization at (a) 21 UTC on September 14, and (b) 2:40 UTC on September 15. (c) H_s with Loop Current (black line) and without Loop*

Current (red line) initialization in the ocean model compared with SRA observations (black cross).

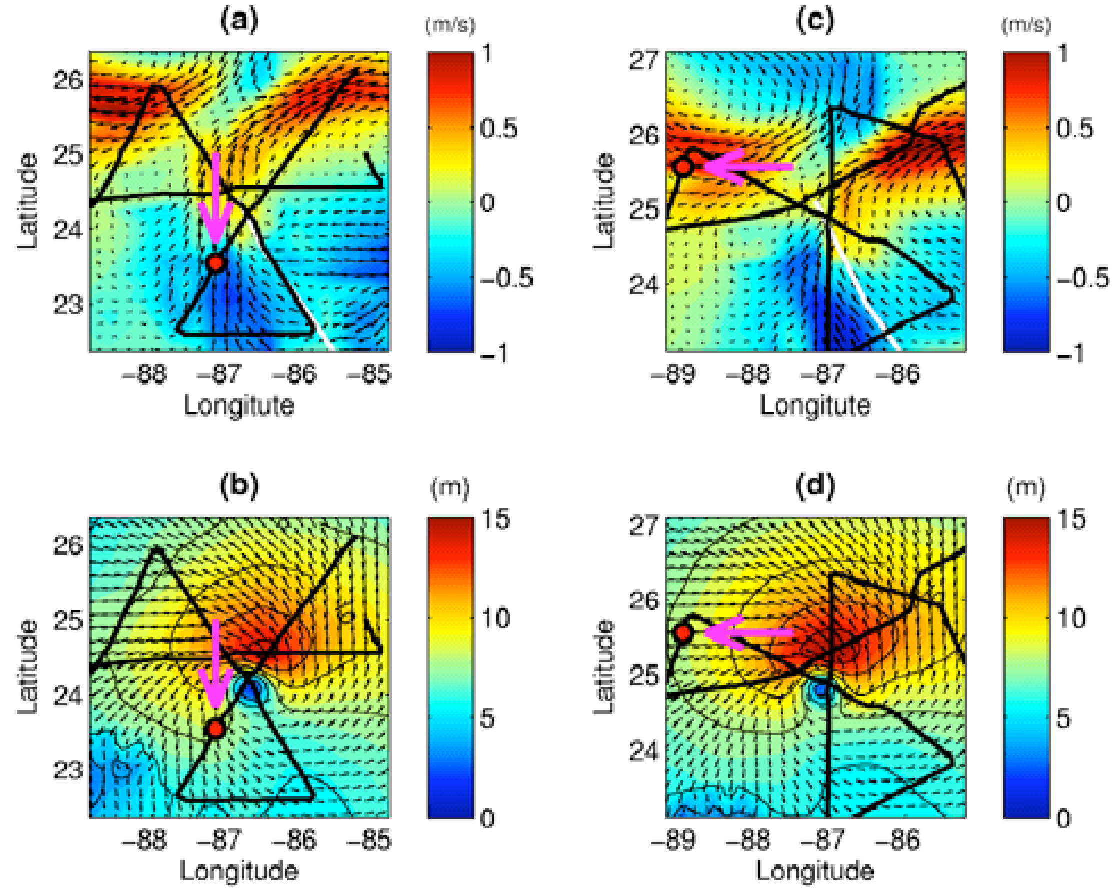

Figure 3. *(a) Ocean current difference between the experiments with and without the Loop Current initialization at 21:00 UTC on September 14. (b) Significant wave height (H_s) in color and dominant wave length and direction in black arrows at 21:00 UTC on September 14. (c) Ocean current difference between the experiments with and without the Loop Current initialization at 2:40 UTC on September 15. (d) Significant wave height (H_s) in color and dominant wave length and direction in black arrows at 2:40 UTC on September 15. The black line shows the flight track and the red dots show the location of the flight at the time that the current and wave field are shown. The pink arrow shows the wave propagation path.*

b) Improving heat flux parameterization in the HWRF

Our approach to improving the air-sea heat flux parameterization in HWRF is to explicitly predict spray generation and spray effects on sensible/latent heat fluxes, in collaboration with NOAA/ESRL scientists Drs. Chris Fairall and Jian-Wen Bao. We are working on implementing the ESRL sea spray model into the URI ASIM.

The parameterization of sea spray effects involves five critical components: (1) droplet source strength as a function of wind and wave parameters, (2) the characteristic height of the droplet sources, (3) vertical diffusion of droplets, (4) droplet evaporation microphysics, and (5) feedback effects (subgrid scale modification by the droplets of their own evaporation environment). The existing ESRL parameterization accounts for all of these processes and explicitly calculates the spray-enhanced sensible and latent heat fluxes. In the latest version of the ESRL parameterization, the spray flux terms are parameterized based on the droplet source function, the droplet evaporation response time, the droplet thermal response time, and the suspension time $\tau_f = h / v_f$, where h is the effective droplet source height and v_f is the size-dependent mean fall velocity. The source function is parameterized in terms of energy lost to the wave-breaking process, EF_c, which is simply related to the wind speed. The source height h is related to the significant wave height.

Within the framework of the URI ASIM, which includes explicit coupling with the WW3 model, this spray effect parameterization is implemented by estimating the two key parameters, EF_c and h, that are needed as input to the spray model. The total energy lost to breaking EF_c is accurately estimated based on ASIM, which explicitly accounts for the sea state dependence and the air-sea flux budget. The effective droplet source height is determined not from the significant wave height but from the input wave age (wave age of the wind forced part of the spectrum) and the wind stress. This modification is important under tropical cyclones because the dominant scale of breaking waves is related to the scale of the actively wind-forced waves, not to the scale of swell generated elsewhere.

The URI ASIM code has been transferred to the ESRL group for embedding the ESRL sea spray model. Once this task is completed, we will proceed with testing and evaluating the effect of sea spray on the air-sea fluxes within a framework of a fully-coupled hurricane-wave-ocean system.

c) Evaluation of impact of warm ocean eddies on hurricane-induced surface cooling.

Although this task is not explicitly mentioned in the Year 2 work plan, we continued to work with Dr. Carlos Lozano and his ocean modeling group at NCEP/EMC on the development and testing of the coupled HWRF-HYCOM model. This is a continued effort that began in Year 1 of this project. During this time period, we investigated the impact of warm ocean eddies on hurricane-induced surface cooling. In recent years, it has become widely accepted that the upper oceanic heat content (OHC) in advance of a hurricane is generally superior to pre-storm sea surface temperature (SST) for indicating favorable regions for hurricane intensification and maintenance. The OHC is important because a hurricane's surface winds mix the upper ocean and entrain cooler water into the oceanic mixed layer from below, subsequently cooling the sea surface in the region providing heat energy to the storm. For a given initial SST, increased OHC typically decreases the wind-induced sea surface cooling, and a warm ocean eddy has a higher OHC than its surroundings, so the argument is often made that conditions become more favorable for a hurricane to intensify when the storm's core encounters a warm ocean eddy.

When considering hurricane intensity, one often neglected aspect of a warm ocean eddy (also known as a warm core ring (WCR)) is the anticyclonic circulation in the eddy that exists due to the geostrophic adjustment of the density and velocity fields. The primary goal of this study is to assess whether or not advection due to a WCR can play a significant role in storm-core SST cooling; if so, a WCR could potentially have the opposite effect on storm-core SST cooling and subsequent hurricane intensity change than would be predicted by OHC alone. In addition, a WCR's circulation may contribute to enhanced surface current divergence, thereby increasing the magnitude of upwelling.

In a series of idealized numerical experiments, a WCR is assimilated into the otherwise horizontally-homogeneous ocean using the feature-based methodology of Yablonsky and Ginis (2008). This WCR is nearly circular in shape, with a radius of 1.2° (i.e. 133 km along the north-south axis and 123 km along the east-west axis), which is typical of WCRs in the Gulf of Mexico. The hurricane wind stress field translates due westward towards and then past a WCR centered at 85.7°W. Experiments are performed with the WCR located in the center of the storm track (WCRC), to the south (i.e. left) of the storm track (WCRL), and to the north (i.e. right) of the storm track (WCRR) (Fig. 4). The results are compared with the control experiment (CTRL) in which there is no WCR specified.

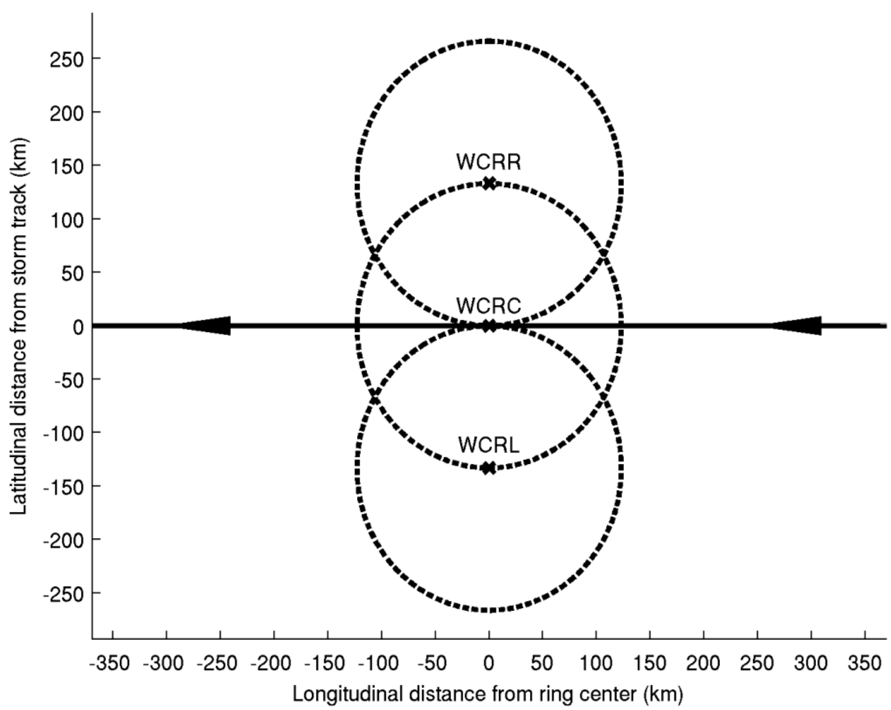

Figure 4. *Schematic indicating the WCR position when located in the center of the storm track (WCRC), to the south (i.e. left) of the storm track (WCRL), and to the north (i.e. right) of the storm track (WCRR). Storm track and direction are indicated by the horizontal line with embedded, westward-pointing arrows.*

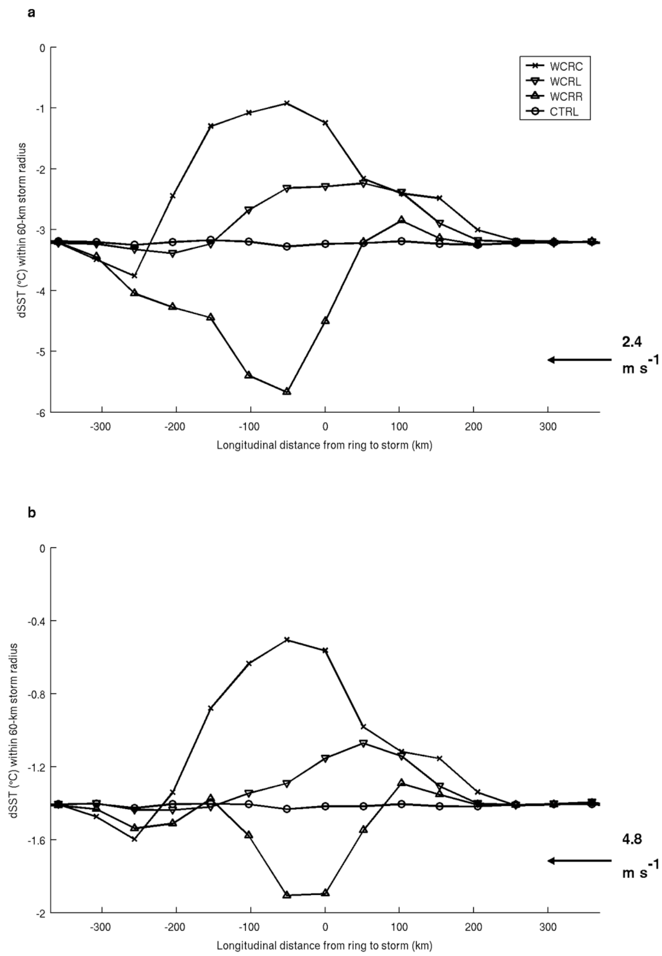

***Figure 5**. Average SST cooling within a 60-km radius of the storm center (dSST-60) for the experiments with translation speeds of 2.4 m s^{-1} (a) and 4.8 m s^{-1}. Each panel includes WCRC ("x"), WCRL (downward triangle), WCRR (upward triangle), and CTRL ("o") experiments.*

Since the goal of this study is to quantify the magnitude of SST cooling only within the region providing most of the heat energy to the storm, the average SST cooling is calculated within a 60-km radius around the storm center (hereafter dSST-60) while the storm-induced cooling is being influenced by the WCR (when present). In the WCRC and WCRL experiments, the magnitude of dSST-60 generally decreases as the storm approaches the WCR and then increases towards its original value as the storm passes the WCR. This trend is consistent with the purely thermodynamic view of a WCR, whereby the deeper mixed layer within the WCR restricts the ability of the storm to entrain a significant quantity of cooler water into the upper oceanic mixed layer via shear-induced mixing. The most significant and perhaps unexpected result occurs in the WCRR experiment. The magnitude of the dSST-60 in this experiment increases dramatically as the storm passes the WCR (Fig. 5). It turns out that this increase in the magnitude of the dSST-60 is caused by the WCR's anticyclonic circulation, which advects the storm's cold wake horizontally in the direction of the storm track, thereby increasing the SST cooling underneath the storm core. This effect is clearly seen in Fig. 6, which shows the SST and current vector difference field between WCRR and CTRL when the storm center is ~50 km and ~250-km past the WCR's center longitude. The results of this study are summarized in Yablonsky and Ginis (2009) submitted for publication in *Mon. Wea. Rev*.

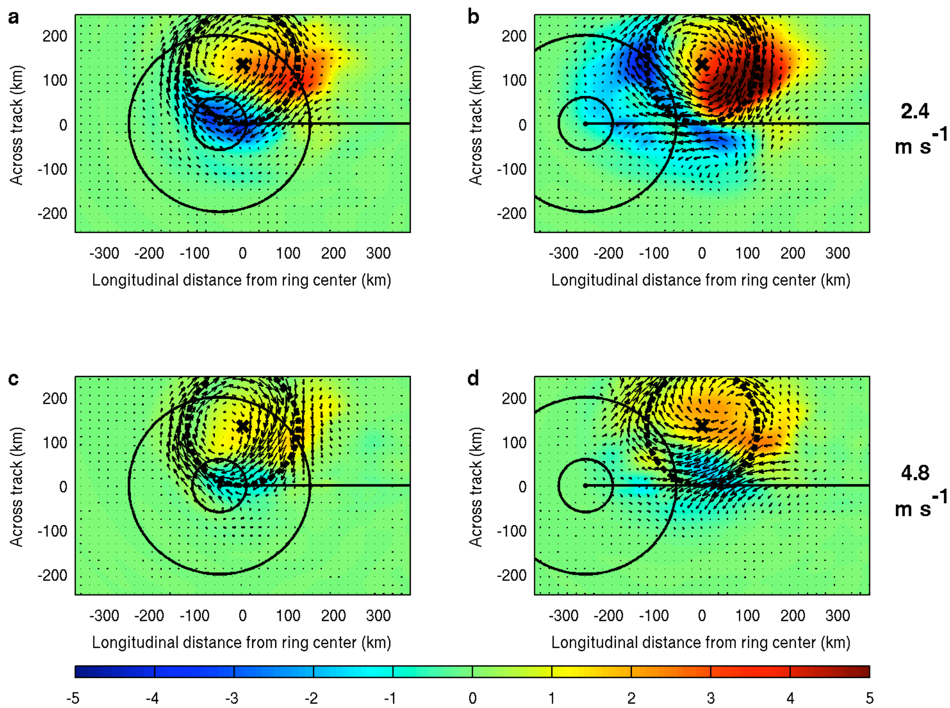

Figure 6. *WCRR – CTRL SST (°C) and surface current vector difference field when storm center is ~50 km (a, c) and ~250 km (b, d) past the WCR's center longitude for 2.4 m/s, and 4.8 m/s experiments. Thin solid circles indicate 60-km and 200-km radii from the storm center; thick dashed circle indicates the WCR's perimeter.*

<u>References</u>

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