14D.1 OCEAN MIXED LAYER THERMAL CHANGES INDUCED BY MOVING TROPICAL CYCLONES, PART I: ANALYSES OF INNER CORE OBSERVATIONS OBTAINED BY RESEARCH AIRCRAFT

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1. INTRODUCTION

This paper reviews one part of Black (1983), a Ph.D. thesis that describes the inner core sea surface temperature (SST) response to tropical cyclone (TC) forcing. He analyzed the SST fields in the TC inner core obtained with airborne expendable bathythermographs dropped from aircraft at pre-selected locations and remotely sensed observations that were continuously recorded from low flight levels in 19 TCs. His analysis revealed the presence of an inner core, crescent-shaped pattern of SSTs that are cool relative to nearby pre-storm SSTs and are largely confined to the right-rear quadrant (relative to storm motion in the NH) of TCs in ocean areas with shallow mixed layer depths (MLD) <70 m (Fig. 1). Only small TC-related SST changes occur in ocean areas with MLD >70 m. The coolest SSTs, up to 5°C cooler than the pre-storm values, occur at radii of one to more than three times the radius of maximum wind (RMAX).

The Hurricane Research Division of NOAA is conducting a field program to investigate possible SST changes caused by the surface wind field of the TCs. It began in the late 1960s with U.S. Navy aircraft and has continued from 1975 until the present, with NOAA research aircraft. They simultaneously measure the TC atmospheric structure, upper ocean structural changes that the TC low-level wind forcing may induce, and any effects that upper ocean changes may have on the heat and moisture fluxes from the ocean to the atmospheric boundary layer (ABL). The field program has investigated a wide range of TCs in various parts of the tropical and subtropical oceans.

2. SCHEMATIC OF SST CHANGES INDUCED BY TCs WITH FORWARD MOTION (U) > 3.5 M S^{-1}

The schematic in Fig. 1 shows the primary characteristics of the crescent-shaped SST pattern plotted as a function of direction of storm motion and RMAX. For those TCs with U >3.5 m s^{-1}, the schematic illustrates the concentration of cooler SSTs, in the right-rear quadrant, with little evidence of their occurrence in the left-front quadrant. The maximum SST change of >-3°C is located near 2.5 RMAX.

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3. OCCURRENCE OF COOLEST SST IN A TC AS A FUNCTION OF U AND MAXIMUM HORIZONTAL WIND SPEED (VMAX)

Figure 2 shows a plot of the SST change induced by TCs as a function of U. For U in the range of 3-10 m s^{-1}, the coolest SSTs in a TC become slightly cooler in a linear manner as U decreases. When U <2-3 m s^{-1}, the coolest SSTs become cooler more rapidly as U decreases and approach -5 °C for a nearly stationary TC.

Figure 3 shows the maximum SST change during each of the flights relative to VMAX for TCs with U >3.5 m s^{-1}. The largest SST change of ~-4°C was observed with VMAX of 35-40 m s^{-1} after a linear increase from zero cooling for VMAX ~20 m s^{-1}. The lower values of peak SST cooling for VMAX >35 m s^{-1} may be the result of a few intense storms almost always being observed in ocean regions with deep mixed layers where little SST cooling occurs.

4. COMPARISON OF SST AND NEAR-SURFACE AIR TEMPERATURE IN A SLOW-MOVING TC

The finding of relatively cool water just outside the eyewall implies that air flowing over this water into the eyewall can inhibit TC strengthening, or even cause weakening, by reducing parcel buoyancy and enthalpy fluxes.

The surface air temperature can equal or even exceed the SST in regions of the largest ocean cooling and in areas downwind from the cooled SSTs. The relatively warm surface air temperatures can inhibit or even reverse fluxes of heat from the ocean to the ABL. As shown in Fig. 4, Black and Holland (1995) determined that the surface heat fluxes were **downward** throughout most of the inner 200 km of Kerry, a slowly moving TC (1-2 ms^{-1}).

5. CONCLUSIONS

Black's (1983) thesis demonstrates that, in ocean areas with MLD <70 m, the inner core SSTs observed in the right-rear quadrant of a TC are cooler than the SSTs in advance of the TC. The cooler inner core SSTs are likely to reduce the heat and moisture transfer from the ocean to the ABL and affect TC intensity. We estimate that in an average TC the sensible heat flux is ~15% of the enthalpy flux, but that 15% may be critical in determining the potential of a TC to intensify or weaken.

Furthermore, these observations imply that intense TCs (Saffir-Simpson categories 3, 4 or 5) are most likely to occur only in oceanic regions where the MLD is >70 m, and the sensible heat and moisture fluxes into the ABL of a TC are both positive. The validation of cooler, inner core SSTs is in progress. A goal is to represent this cooling effect in terms of basic, operationally available quantities, such as U and VMAX. It will be interesting to see if the parameterization of this cooling pattern in numerical models can help to improve TC intensity forecasts.

6. REFERENCES

Black, P. G., 1983: Ocean temperature changes induced by tropical cyclones. Ph.D. Thesis, Dept. of Meteorology, Pennsylvania State University, 278 pp.

Black, P. G. and G. J. Holland, 1995: the boundary layer of Tropical Cyclone Kerry (1979), *Mon. Wea. Rev.*, **123**, 2007-2028.

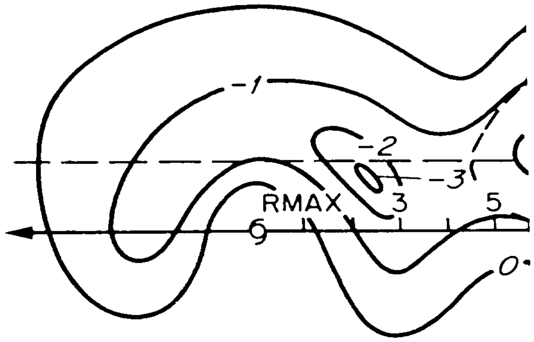

Figure 1. Schematic of SST changes induced by those TCs with storm motion >5 m s^{-1}. The schematic illustrates the crescent-shaped pattern of SSTs concentrated in the right-rear quadrant and the coldest SSTs near 2.5 RMAX.

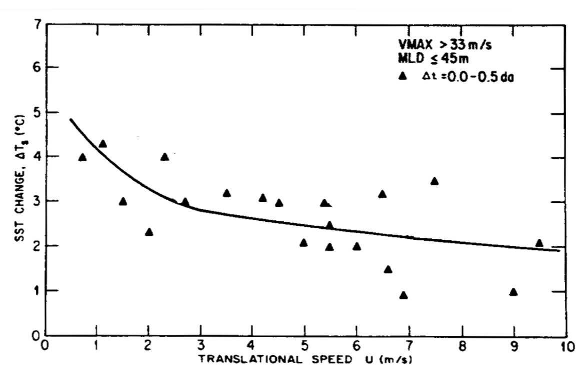

Figure 2. Coldest inner core SSTs as a function of U for TCs with MLD < 45 m, adapted from Black (1983).

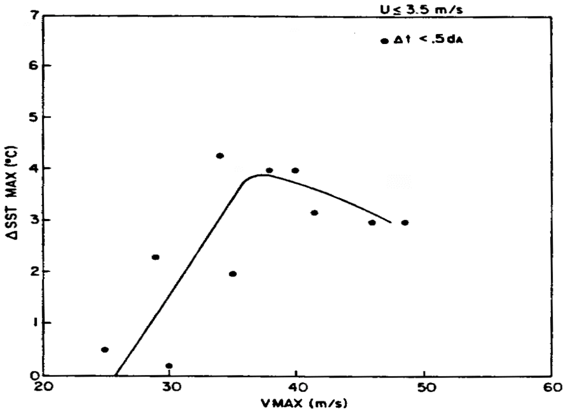

Figure 3. Coldest SST as a function of VMAX, adapted from Black (1983).

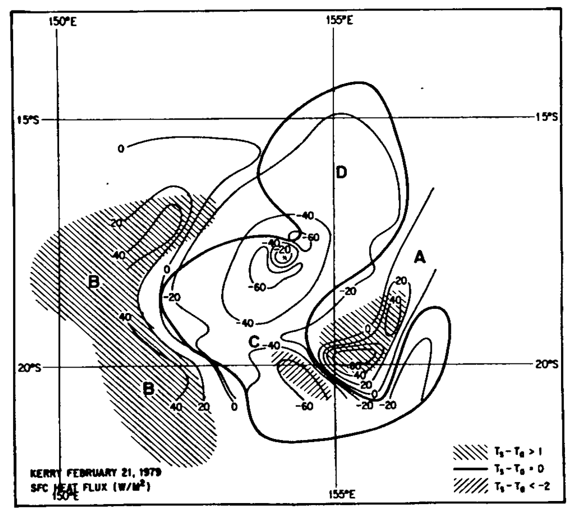

Figure 4. Plot of surface sensible heat flux from Cyclone Kerry (1979), showing regions of significant downward heat flux (regions C & D) within the thick, solid line of zero air-sea temperature difference and the regions of significant upward heat flux (regions A & B, cross-hatched backward), from Black and Holland (1995).