OCEAN-INTERACTION EFFECTS ON TROPICAL CYCLONES

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1. INTRODUCTION

The dramatic effect of hurricane-force winds on the ocean surface is well known by mariners and coastal residents unfortunate enough to have been in the path of tropical cyclones. Less well known is the control that the ocean surface and mixed layer exerts on tropical cyclones. Our collective ignorance of this control is reflected in our almost total lack of skill in forecasting hurricane intensity change. My purpose here is to make the case that two fundamental advances will be necessary before we can forecast hurricane intensity change with appreciable skill: high-resolution, coupled ocean-atmosphere forecast models, and much-improved understanding of sea-air exchange at extraordinary wind speeds.

2. HURRICANE FORECAST SKILL

Because of the extreme loss of life and damage wrought by hurricanes, much effort has been made to improve forecasts of their tracks and intensities, particularly in the U.S. Over the past 30 years, considerable improvements have been made in track forecasts (Figure 1), but there has been little gain in the accuracy of intensity forecasts (DeMaria and Kaplan, 1997). Part of this lack of improvement may be owing to the high resolution required to simulate numerically the core of tropical cyclones. Experiments by Rotunno and Emanuel (1987) and Bister and Emanuel (1997) indicate that numerical convergence of tropical cyclone intensity does not occur until a resolution of roughly 7 km has been achieved, at least in axisymmetric models. (Apparently, such high resolutions are not required for accurate track forecasts, given the substantial improvement in their accuracy over the past few decades. This may be because the feedback of tropical cyclones onto the large-scale steering currents is exercised primarily through the outer circulation (Chan and Williams, 1987), not through the region of high winds.)

Although insufficient resolution can be blamed for lack of model performance in predicting hurricane intensity change, it is more difficult to explain why experienced forecasters have been so singularly unsuccessful. Much attention has been paid to the interaction between hurricanes and synoptic-scale environmental features such as short-wave troughs (Riehl, 1954; Sadler, 1976), but the increasing awareness of the importance of such features coupled with the improved prediction of them by forecast models has not translated into much improved forecasts. Besides lack of model resolution, part of the blame may be laid on internal variability (Willoughby and Black, 1996), though high-resolution

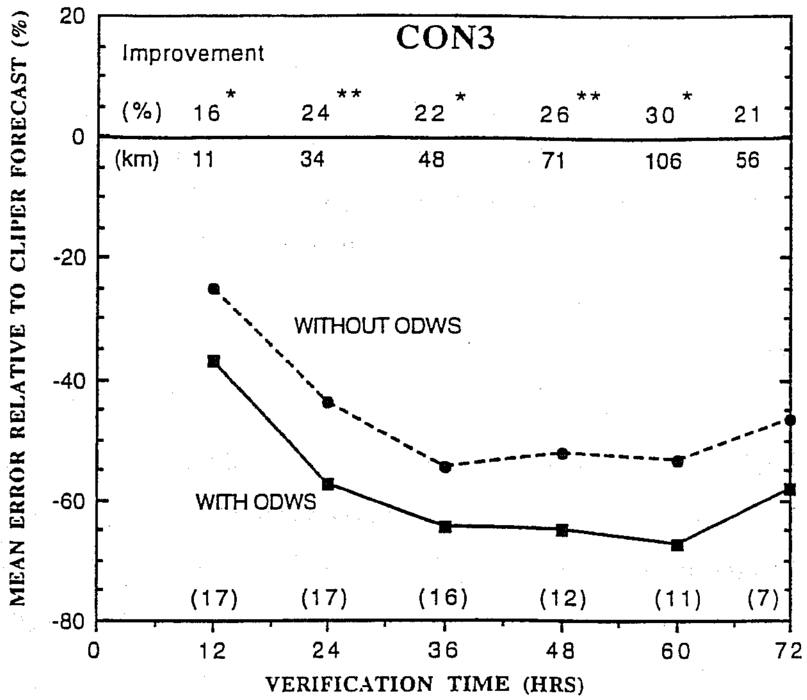

Fig. 1 The average relative errors (in percent) of the numerical forecasts with and without omega dropwindsondes (ODWs). The numbers just above the zero-skill line are the percentages of improvement of the forecast tracks with ODWs, relative to those without ODWs, where the single- and double-asterisk superscripts indicate significance of this improvement at the 95° and 99° significance level, respectively. Numbers just below the zero-skill line are the average track improvements in kilometers, and those in parentheses at the bottom are the number of cases for each forecast interval. From Burpee et al., 1996.

models (e.g., Bister and Emanuel, 1997) usually fail to show substantial intensity fluctuations arising from internal variability alone. (One drawback of such models is their axisymmetry; perhaps three-dimensional models would exhibit more internal variability. On the other hand, the primary physical phenomenon thought to be responsible for internal intensity fluctuations is the concentric eyewall cycle (Willoughby et al., 1982), which is largely axisymmetric in character.)

Until comparatively recently, forecasters have been reluctant to take into account the role of the ocean in controlling hurricane intensity. For example, a forecaster's handbook published only a few years ago (WMO, 1993) makes only a passing reference to ocean effects on hurricane intensity. This reluctance stems in part from an incomplete understanding of the physics of hurricane-ocean interaction and in part from a failure to absorb the significance of recent work on coupled air-sea dynamics in hurricanes. Surmounting these obstacles may prove essential to better intensity forecasts.

3. SURFACE EFFECTS ON TROPICAL CYCLONE INTENSITY

The basic physical process that causes and sustains hurricanes is the transfer of latent heat from ocean to atmosphere, primarily in the high-wind region of the storm. Likewise, virtually all of the dissipation that absorbs the input energy takes place at or near the sea-air interface. Thus it is not surprising that hurricane intensity should prove sensitive to the physics of heat and momentum transfer at the ocean surface. The physics of the hurricane heat engine have been described elsewhere (e.g., Bister and Emanuel, 1997), but it is useful to review the main elements for the purpose of delineating the role of the ocean.

Consider a control volume bounded by two streamlines near the eyewall of a steady-state hurricane, illustrated in Figure 2. The volume is also bounded below by the sea surface and, at large radius from the center, by a surface of constant temperature, T_0. As shown by Bister and Emanuel, the basic energy balance in this control volume may be written descriptively as

$$\epsilon_1 \text{ (enthalpy flux) } + \epsilon_2 \text{ (dissipative heating) } = \text{ total dissipation,} \tag{1}$$

where ϵ_1 and ϵ_2 are thermodynamic efficiencies of the basic form

$$\epsilon = \frac{T_{\text{in}} - T_{\text{out}}}{T_{\text{in}}}.$$

Here T_{in} and T_{out} are the entropy-weighted average temperatures at which heat is put into the system and at which heat is ultimately exported.

In the steady state, the only enthalpy flux into the volume is from the sea surface, assuming that there is no systematic turbulent enthalpy flux through the sides of the control volume. (In the developing stages, a turbulent convective downdraft enthalpy flux into the volume can be strong enough to offset the surface enthalpy flux; see Emanuel, 1989.) Dissipative heating, usually neglected in atmospheric thermodynamics and in virtually all atmospheric models, proves to make an important contribution to hurricane thermodynamics. As shown in Bister and Emanuel (1997), virtually all the dissipative heating occurs in the *atmospheric* surface layer. This is because the height-integrated dissipation rate is proportional to the surface stress multiplied by a mean flow velocity. The surface stress in the ocean and atmosphere have the same magnitude, but the atmospheric velocity scale is much large than that of the ocean. We can assume that both the surface enthalpy flux and the dissipative heating occur at the local surface temperature T_s. All the heat is exported from the system at a temperature T_0. Thus

$$\epsilon_1 = \epsilon_2 \equiv \epsilon = \frac{T_s - T_0}{T_s}. \tag{2}$$

Using bulk aerodynamic formulae, the surface enthalpy flux and surface dissipation rate may be expressed, respectively, by

$$\text{enthalpy flux } = \rho C_k |\mathbf{V_s}| (h_s^* - h) \tag{3}$$

and

$$\text{dissipation rate } = \text{ dissipative heating } = \rho C_D |\mathbf{V_s}|^3, \tag{4}$$

where ρ is the air density at the surface, $|\mathbf{V_s}|$ is a characteristic surface wind speed, C_k and C_D are exchange coefficients for enthalpy and momentum, respectively, and the specific enthalpy, h, is defined

$$h \equiv C_p T + L_v q, \tag{5}$$

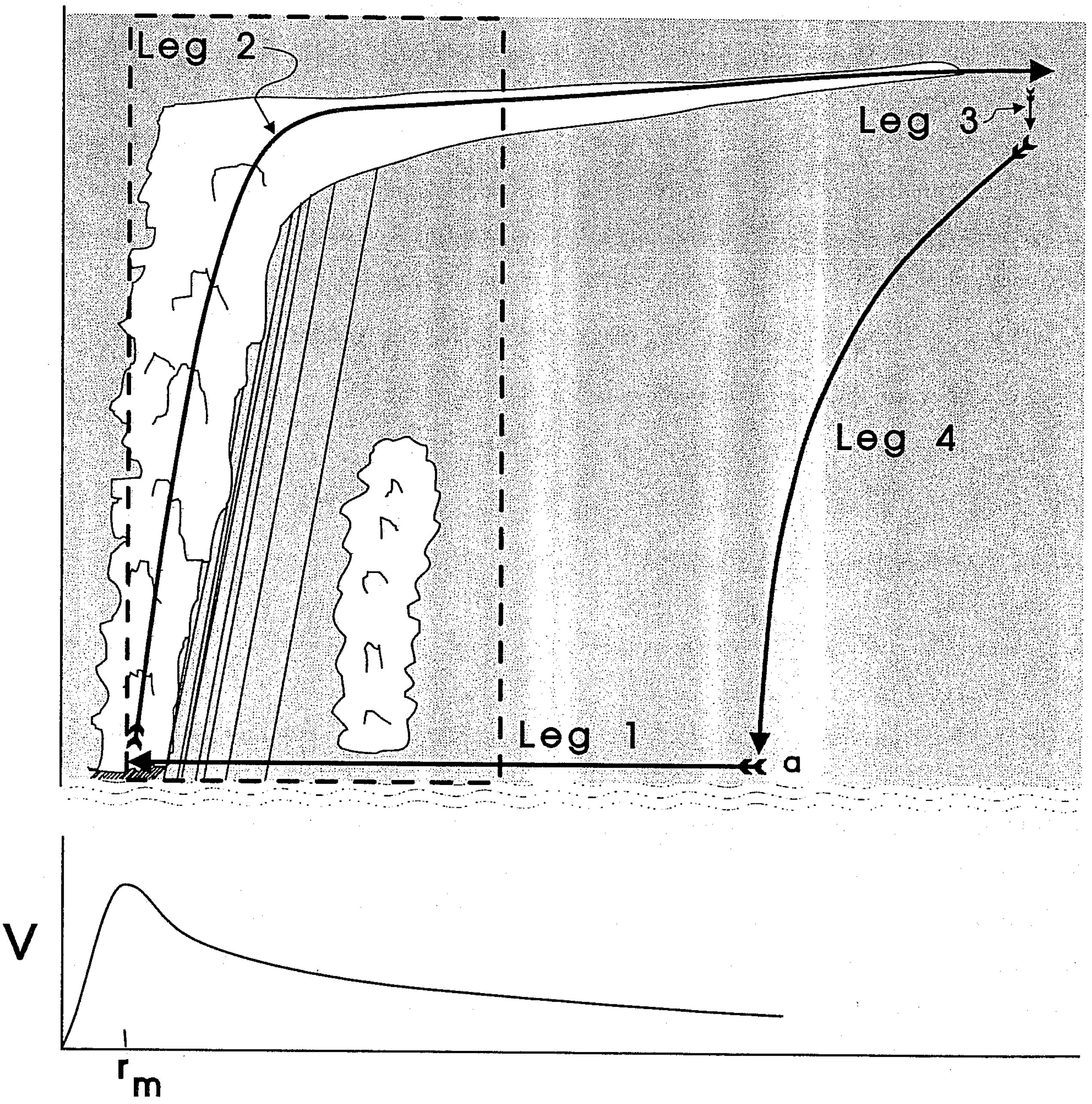

Fig. 2 Control volume (dashed box) for energy budget. Radial profile of azimuthal wind is at bottom.

where C_p is the heat capacity at constant pressure, L_v is the latent heat of vaporization, and q is the specific humidity. In (3), h_s^* is the enthalpy of air that is saturated at sea surface temperature and pressure.

Using (2), (3), and (4), the energy equation (1) can be written

$$|\mathbf{V_s}|^2 = \epsilon' \frac{C_k}{C_D}(h_s^* - h), \tag{6}$$

with

$$\epsilon' = \frac{T_s - T_0}{T_0}. \tag{7}$$

(Note that without dissipative heating, ϵ' would equal ϵ.) Leaving aside, for the moment, what exactly determines the value of h in the eyewall region of a hurricane, (6) immediately yields a *characteristic* velocity scale for a hurricane, which is a function of the degree of air-sea thermodynamic disequilibrium (given by $h_s^* - h$), the surface and outflow temperatures, *and the surface exchange coefficients.* As hurricanes are subcritical vortices (Emanuel, 1986), the outflow streamlines asymptote to an altitude at which the eyewall air is neutrally buoyant with respect to the unperturbed environment. Thus, with the important exception of the exchange coefficients, all of the variables in (6) are well determined by the ocean temperature and the environmental sounding.

It should also be noticed that h_s^* in (6) depends on the local surface pressure, because of the dependence of q^* and q on pressure at constant temperature. Pressure in turn depends on the vortex strength, so (6) must be solved iteratively.

In numerical models, C_D and C_k are specified (often as functions of wind speed) and so the predictions of (6) can be compared directly to numerical output. Figure 3 compares the output of two numerical simulation models with (6) for a given ocean temperature and environmental sounding. Clearly, the prediction is very good.

While (6) is an excellent predictor of model hurricane intensity, it fails rather miserably to predict the intensities of actual storms, as shown in Figure 4. Here a rather crucial and indefensible assumption has been made: that $C_k = C_D$. Figure 4 shows that (6), with this assumption, gives a rather good upper bound but a poor prediction in general.

Why does (6) fail to predict individual hurricane intensity while being an excellent predictor of model storm intensity? The usual culprits cited in the literature are three-dimensional interactions between hurricanes and environmental flow anomalies. There can be little doubt, from forecasting experience, that such features as environmental vertical shear are at least partially responsible for lowering the average intensity of storms well below the prediction by (6). On the other hand, if all the blame rests with the atmosphere, how is it that experienced meteorologists are not systematically able to forecast intensity?

Another suspect is cooling of the ocean surface owing to turbulent entrainment of cold water through the seasonal thermocline, about which more in section 4. Here we may rely on experience in the western North Pacific, where the ocean mixed layer is so deep as to almost preclude any substantial effects of thermocline entrainment on the time scale of hurricanes. Even so, there is much variability in western North Pacific typhoon intensity.

Could it be that the failure of (6) to predict the intensities of real storms stems in part from poor specification of C_k and C_D? To the author's knowledge, this idea has never been subject to real scrutiny.

It must be admitted that we know next to nothing about air-sea exchange coefficients at the extraordinary wind speeds of hurricanes. The general impression of authorities on the subject (e.g.,

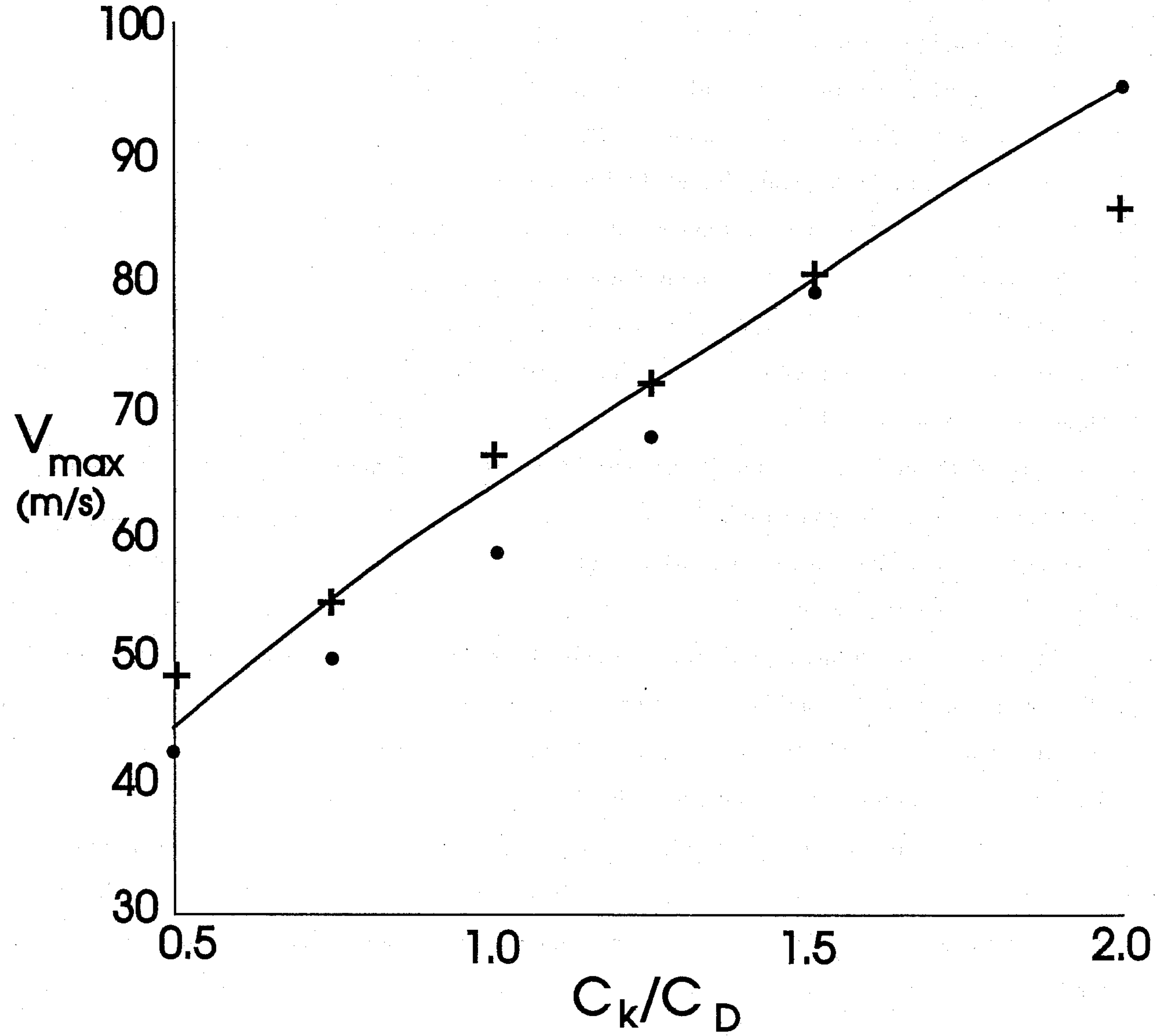

Fig. 3 Dependence of maximum wind speed on ratio of enthalpy and momentum exchange coefficients. Solid line is from Eq. 6, +'s denote results of numerical simulations using the model of Rotunno and Emanuel (1987), and dots represent simulations using the model of Emanuel (1995b).

Greenaert et al., 1987) is the C_D increases faster than C_k with wind speed because of wave drag. Inferences by Shay (1997) show C_D rising to a value of nearly 4 times C_k at large wind speeds. But if these inferences can be applied to the hurricane core, then intense hurricanes would be impossible, and *no* storms would approach the limit given by (6) with $C_k - C_D$.

Sea spray effects have been cited as a possible mitigating factor in hurricane intensity (Lighthill et al., 1994). But as pointed out by the author (Emanuel, 1996), the evaporation of sea spray leaves enthalpy unchanged and so cannot directly alter estimates made using (6). (Owing to the cooling of the air, there may be a reduction of ϵ but this would be very slight.) Numerical experiments by George Craig (personal communication) confirm that evaporation of spray has little effect on storm intensity.

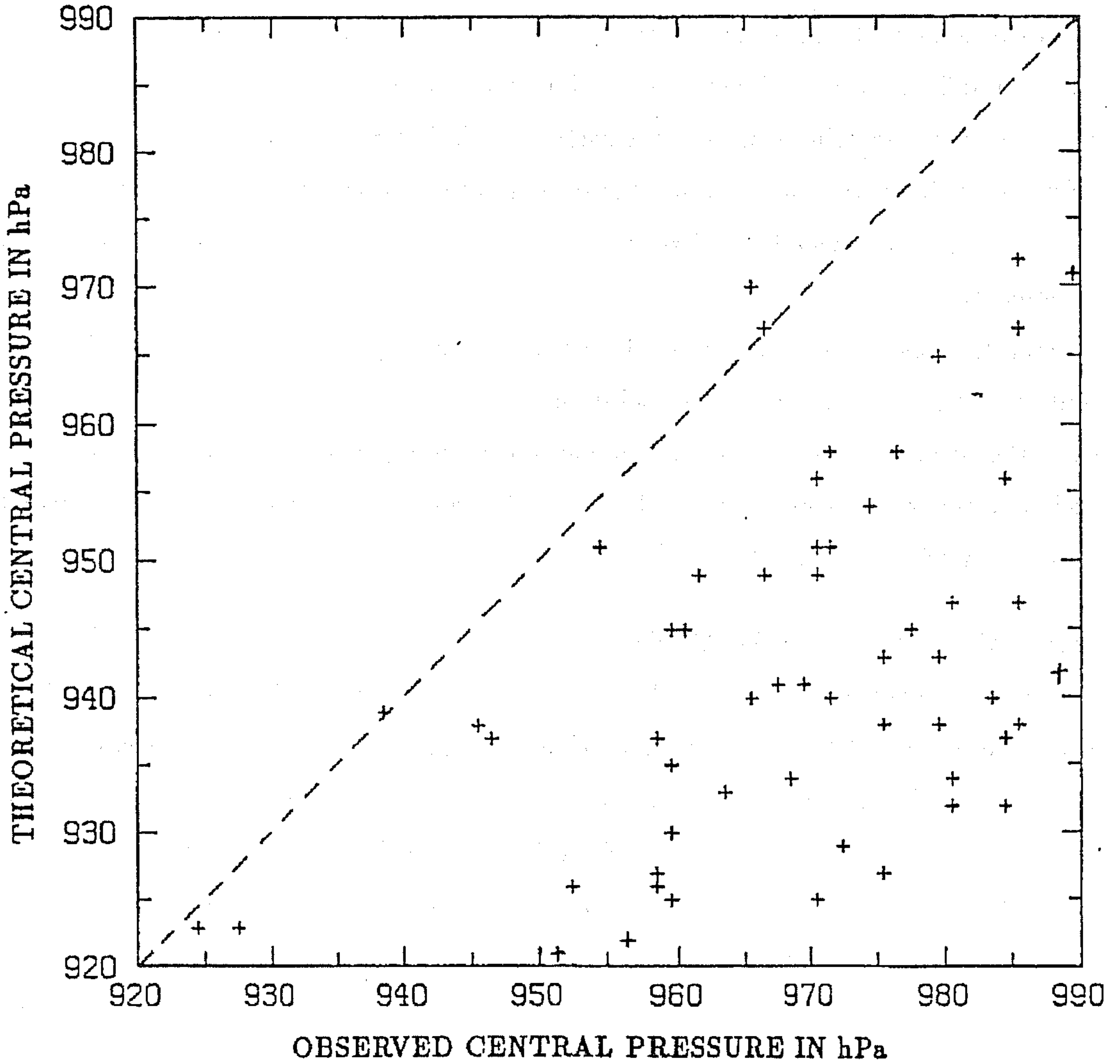

Fig. 4 Observations of the central pressures of Atlantic tropical cyclones, versus potential intensity estimated from climatological conditions. From Schade (1994).

Even so, it would be surprising if the physics of air-sea interaction were not dramatically altered in hurricane-force winds. The sea surface is by no means self-similar, because surface tension and viscosity always enter as important parameters, so there are several nondimensional parameters that must be used to describe the sea state, even if it is in statistical equilibrium. (It is always possible to estimate wind speed from aerial photographs of the sea, even if the altitude of the aircraft is unknown (Black and Adams, 1983). This observation, by itself, rules out self-similarity.) The sea surface appears to become an emulsion at very high wind speeds (Black and Adams, 1983), so that in a real sense, there is no surface at all. It is not inconceivable that emulsions might even reduce the drag coefficient.

An effect that has not heretofore been considered in heat exchange at the sea surface is bubbling. (Bubbles are known, however, to play a crucial role in gas exchange.) If a bubble that has percolated up through water consists of air in thermodynamic equilibrium with water, and if we neglect the horizontal speed of the bubbles, then it is easily shown that the enthalpy and momentum exchange coefficients associated with the bubbles are equal. Perhaps sea-air heat and momentum exchange become strongly influenced by bubbles at very high winds speeds.

Other intriguing possibilities present themselves. Bubble formation is sensitive to the surfactant content of water, which varies substantially because of natural processes, including organic processes. Could it be that natural variability of surfactant levels explains part of the natural variability of hurricane intensity?

In general, the possibly different dependencies of C_k and C_D on wind speed and sea state opens the possibility that (6) may have multiple solutions.

Clearly, the behavior of enthalpy and momentum exchange across the sea surface at very high wind speed is an unsolved problem that will have to be resolved before one can make predictions of hurricane intensity with any confidence.

4. THERMOCLINE ENTRAINMENT

Hurricanes are extremely sensitive to small, local reductions of sea surface temperature (SST) near the eyewall, where most of the entropy increase in the inflow occurs. To get a feeling for this, we may ask the question: What decrease of sea surface temperature is necessary to offset the increase of entropy by evaporation? Or, to put it differently, how much decrease in surface temperature is necessary to bring the ocean surface into thermodynamic equilibrium with the unperturbed surface air stream? This condition is given by

$$q^* = q_a = \mathcal{H}_a q_0^*, \tag{8}$$

where q_0^* is the specific humidity of air saturated at the unperturbed SST and $\mathcal{H}_a$ is the ambient near-surface relative humidity. Using the Clausius-Clapeyron equation,

$$q^* = q_0^* + \frac{L_v q_0^*}{R_v T_0^2}(T - T_0), \tag{9}$$

where T_0 is the original SST, L_v is the latent heat of vaporization, and R_v is the gas constant for water vapor. This is valid for small $T - T_0$. Substituting (8) into (9) gives

$$T - T_0 = -\frac{R_v T_0^2}{L_v}(1 - \mathcal{H}_a). \tag{10}$$

Using $T_0 = 300$ K and $\mathcal{H}_a = 0.8$, it is seen that an SST depression of only about 3 C is necessary to eliminate altogether the thermodynamic disequilibrium that sustains hurricanes. Therefore, a 1 C SST depression should have a strong effect on hurricane intensity.

Some confusion about this elementary point exists, because it is not observed that hurricanes occurring over SST's of, say, 28°C are systematically less intense than those occurring over SST's of

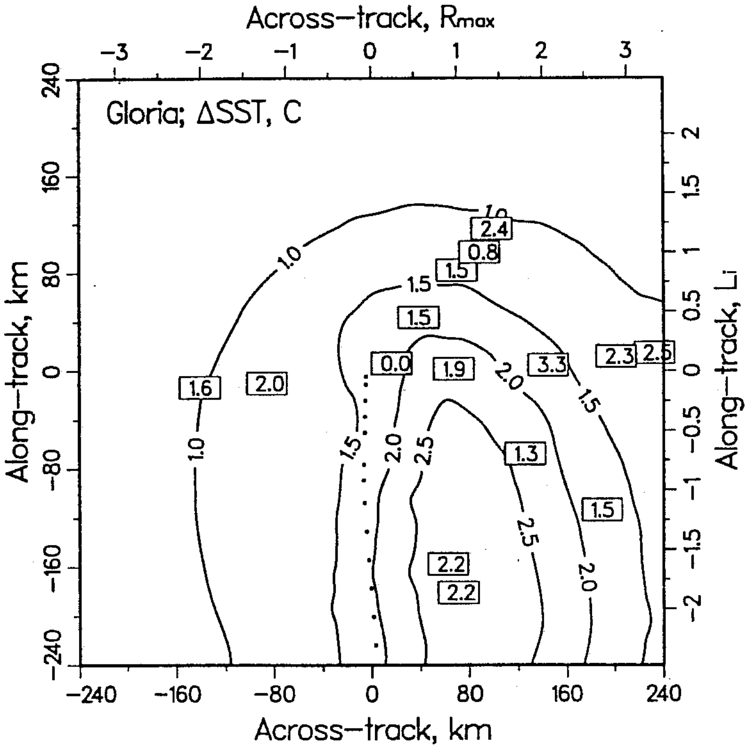

Fig. 5 Distribution of sea surface temperature anomaly around Hurricane Gloria, 1995. Numbers in boxes are from observations, while contours are based on model output. From Price et al. (1994).

29°. But on the large scale, atmospheric and oceanic temperatures change in concert, whereas here we are talking about a strictly *local* SST reduction.

Hurricanes excite a great deal of turbulence in the ocean mixed layer. When the turbulence penetrates into the seasonal thermocline, colder water from beneath the thermocline is mixed upward, cooling the ocean surface. Figure 5 shows the reduction of SST caused by Hurricane Gloria. Note that most of the reduction occurs behind and to the right of the hurricane's track, although the reduction is still appreciable near the center of the storm. Why is the SST reduction strongest to the right of the storm's motion?

There are two sources of turbulence in the thermocline: downward penetrating turbulence generated at the sea surface by wind, and local turbulence caused by shear across the thermocline. This shear is a by-product of wind-driven currents in the mixed layer. The strongest currents occur to the right of the storm's track (in the northern hemisphere) because there the veering of the winds as the storm passes resonates with inertial oscillations in the sea. It is generally believed that thermocline entrainment is dominated by shear-induced turbulence; this would explain why the greatest cooling is to the right of the track.

Numerical simulations with coupled air-sea models have by now demonstrated beyond reasonable doubt that cooling of the upper ocean surface by storm-induced entrainment can have a profound effect on the intensity of hurricanes. These simulations have been performed by Sutyrin et al. (1984), Bender et al. (1993), and Khain and Ginis (1991), among others. Using a very high resolution

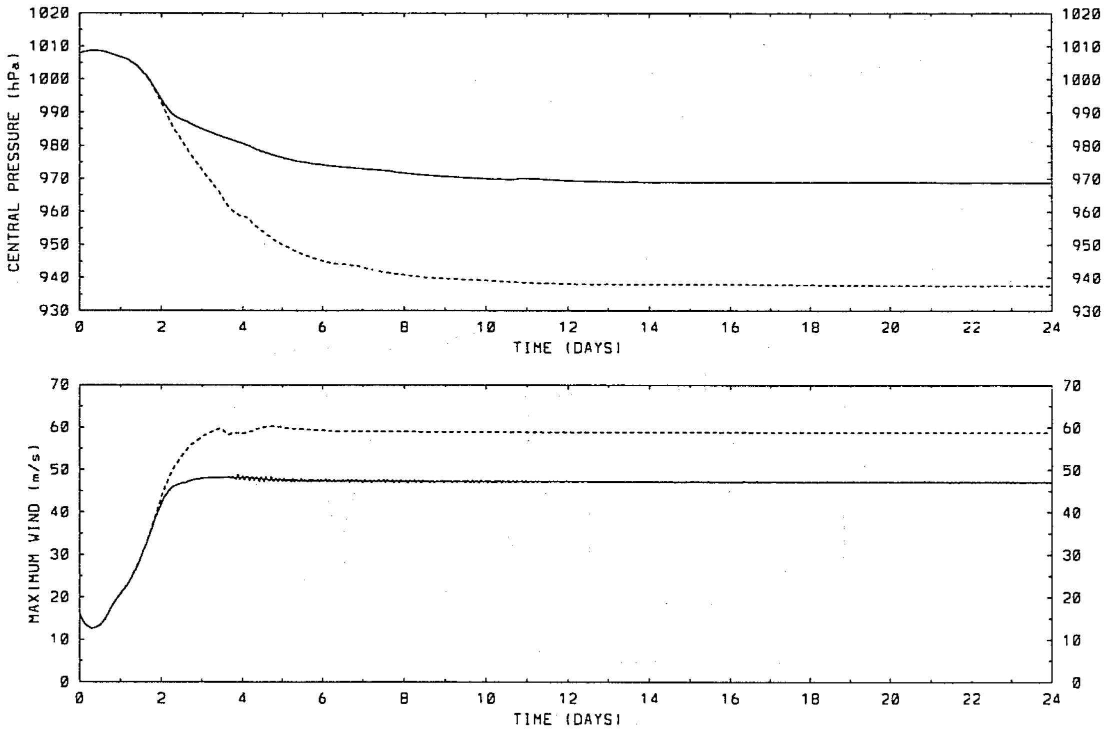

Fig. 6 Time series of the central pressure (top) and of the maximum azimuthal wind (bottom). The solid line marks the coupled default experiment; the dotted line is from an identical experiment with fixed SST. From Schade (1994).

axisymmetric hurricane model coupled to a three-dimensional ocean model, Schade (1994) was able to perform a very large number of simulations to explore the full range of parameter space. An example comparing a coupled to an uncoupled model run is shown in Figure 6. Later, Schade (1997) was able to demonstrate that so far as the feedback on storm intensity is concerned, the excitation of inertial oscillations is largely irrelevant, as it affects the SST mostly in the wake of the storm, whereas the important feedback effect occurs near the eyewall. He was able to develop an analytic expression for the intensity reduction owing to thermocline entrainment, as a function of nominal storm intensity, size, translation speed, and unperturbed ocean mixed-layer depth. This expression predicts very well the results of the numerical simulations.

These results show that the intensity of hurricanes is often reduced quite substantial by thermocline entrainment. But all of these results depend on parameterizations of entrainment rates that may fail under the extraordinary conditions near the hurricane core. For example, at very high wind speeds, significant wave heights become comparable to mixed-layer depths, and wind-induced turbulence may contribute to thermocline entrainment. Experimental verification of thermocline entrainment in hurricanes is needed.

5. SUMMARY

Hurricane intensity depends strongly on microscale processes governing enthalpy and momentum flux across the sea surface at extreme wind speeds, and entrainment of cold water across the thermocline.

These processes are poorly understood, particularly under hurricane conditions. Meteorologists have focused largely on atmospheric dynamics in trying to explain and forecast hurricane intensity change. While there is no doubt that atmospheric dynamical processes play an important role in hurricane intensity change, attempts to account for these have not led to significant forecast skill. The time has come to focus on ocean control of hurricane intensity.

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