Thermodynamic control of hurricane intensity

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To establish useful warning systems for hurricanes, it is necessary to accurately predict both hurricane intensity and track. But although the forecasting of hurricane tracks has improved over the past 30 years, the factors that control the intensity of hurricanes are still poorly understood, leading to almost no reliability in forecasts of hurricane intensity evolution. Efforts to improve intensity forecasts have focused almost exclusively on characterizing the dynamical interactions between hurricanes and their atmospheric environment. Here I use a simple numerical model to demonstrate that, in most cases, the evolution of hurricane intensity depends mainly on three factors: the storm's initial intensity, the thermodynamic state of the atmosphere through which it moves, and the heat exchange with the upper layer of the ocean under the core of the hurricane. Such a limited number of controlling factors offers hope that, given an accurate forecast of a hurricane's track, its intensity can be reliably forecast using very simple models.

Forecasts of the tracks of hurricanes have improved steadily over the past three decades[1], owing to a combination of better observations and much improved numerical models. These improvements, coupled with advances in warning systems and preparedness for emergencies, have brought about a significant decline in loss of life in the USA in spite of a near doubling of the coastal population during this period. At the same time, the economic vulnerability to hurricanes has increased dramatically. It has been estimated[2] that a repeat of the Miami hurricane of 1926 would incur $75 billion in insured loss, compromising the entire US insurance industry. Among the many costs associated with hurricanes is the expense of evacuation. In practice, many more people are evacuated than was necessary in hindsight, owing to uncertainties in the forecast of both the track and intensity of the storm. Evacuation in the face of a marginal hurricane is usually unnecessary, but is often carried out because hurricanes can intensify rapidly and unexpectedly.

In contrast to the improvement in track forecasts, there has been comparatively little advance in predictions of intensity[1] (as measured, for example, by maximum surface wind speed), in spite of the application of sophisticated numerical models. The best intensity forecasts today are statistically based[3]. Most of the research literature on hurricane intensity focuses on the pre-storm sea surface temperature and certain properties of the atmospheric environment, such as the vertical shear of the horizontal wind and dynamical features such as disturbances in the upper troposphere[4]. This remains so, even though it is well known that hurricanes alter the surface temperature of the ocean over which they pass[5] and that a mere 2.5 K decrease in ocean surface temperature near the core of the storm would suffice to shut down energy production entirely[6]. Simulations with coupled atmosphere–ocean models[6–8] confirm that interaction with the ocean is a strong negative feedback on storm intensity. During the Atlantic hurricane season of 1998, guidance based on coupled-model simulations was provided to forecasters for the first time.

Although there is much hope that three-dimensional coupled models will lead to better understanding of the factors that control hurricane intensity and to increased reliability ('skill') of hurricane intensity forecasts, the present generation of models may not have enough horizontal resolution to capture the full intensity of extreme storms. (Fortunately, it is probably not necessary to capture full storm intensity in order to achieve a good track forecast.)

Here I show that an accurate account of the evolution of storm intensity can be achieved using a very simple coupled ocean–atmosphere model in which the atmospheric component is cast in a transformed radial coordinate that greatly increases horizontal resolution in the critical region around the eyewall, the ring of intense convection that surrounds the eye of the storm. This is so even though the atmospheric component is axisymmetric and therefore excludes interactions with vertical wind shear and dynamical features of the atmospheric environment. This demonstrates that, once storm genesis has occurred, much of the evolution of storm intensity is controlled by its initial intensity together with the thermodynamic properties of the atmosphere and upper ocean along the storm track.

The model

The atmospheric model assumes that the storm is axisymmetric, and that the airflow is never very far from a state in which the horizontal and vertical pressure gradient accelerations are balanced by centrifugal and gravitational accelerations, respectively. It also assumes that the vortex is always close to a state of neutral stability to a combination of gravitational and centrifugal convection ("slantwise convection"[9]). These constraints place very strong restrictions on the structure of the vortex so that, with the exception of the water-vapour distribution, the vertical structure is determined by a very limited set of variables. Moist convection is represented by one-dimensional plumes whose mass flux is determined in such a way as to ensure approximate entropy equilibrium of the boundary layer. The model variables are cast in "potential radius" coordinates[10]. Potential radius (R) is proportional to the square root of the absolute angular momentum per unit mass about the storm centre and is defined by $fR^2 = 2rV + fr^2$, where V is the velocity of air flowing around the storm, r is the physical radius and f is the Coriolis parameter, which is twice the local vertical component of the Earth's angular velocity.

In the runs presented here, there are 50 nodes that span 1,000 km, giving an average resolution of 20 km; however, the resolution is substantially finer than this in regions of high vorticity, such as the eyewall. A complete description of the model is given elsewhere[11]. When run with a fixed sea surface temperature and a fixed atmospheric environmental temperature profile, and provided that the vortex specified at the start of the model integration is strong enough, the model vortex amplifies over a period of 4–5 days right up to its potential intensity (see upper curve in Fig. 1a). The potential intensity is the maximum steady intensity a storm can achieve based on its energy cycle, in which the heat input by evaporation from the ocean, multiplied by a thermodynamic efficiency, is balanced by mechanical dissipation in the storm's atmospheric boundary layer[12]. It is given by

$$V^2 = \frac{C_k}{C_D}\frac{T_s - T_o}{T_o}(k_s - k_a) \qquad (1)$$

where V is the maximum wind speed, C_k and C_D are dimensionless exchange coefficients for enthalpy and momentum, T_s and T_o are the absolute temperatures of the sea surface and storm top, and k_s and k_a are the specific enthalpies of the air at saturation at the ocean surface and ambient boundary layer air, respectively. (That the outflow rather than inflow temperature appears in the denominator of equation (1) is due to the fact that the dissipative heating in the storm's boundary layer recycles some of what would otherwise be waste heat back into the thermodynamic cycle of the storm[13].

Whereas model storms usually spin up to their potential intensity and remain at that intensity indefinitely, real hurricanes seldom behave that way; in fact most hurricanes experience a sharp decline shortly after achieving their peak intensity[14]. Moreover, very few real storms ever achieve the potential intensity given by equation (1). From records of previous storms together with the climatology of potential intensity, there is a nearly uniform probability that a given hurricane will achieve any intensity between marginal hurricane force and the potential intensity[14].

The axisymmetric hurricane model is coupled to a one-dimensional ocean model in a unique way. First, it is assumed that the hurricane responds principally to sea surface temperature changes under its eyewall, and that these can be closely approximated by sea surface temperature changes under that part of the eyewall that lies along the storm track. Second, the evolution of sea surface temperature along the storm track up until the time that the centre of the storm arrives can be approximated as arising entirely from one-dimensional stirring of each vertical column, with no influence from its neighbours. (The horizontal exchange of enthalpy between oceanic columns is ignored.) Finally, the mixing is approximated by assuming that a bulk Richardson number, relating the velocity of the ocean's mixed layer to the jump in temperature across the base of that layer, remains constant[15] as the ocean mixed layer is accelerated by the wind stress imposed from the passing storm. Thus the ocean model consists merely of a set of one-dimensional ocean columns along the storm track, whose temperature is changed only through vertical mixing in each column. The temperature stratification

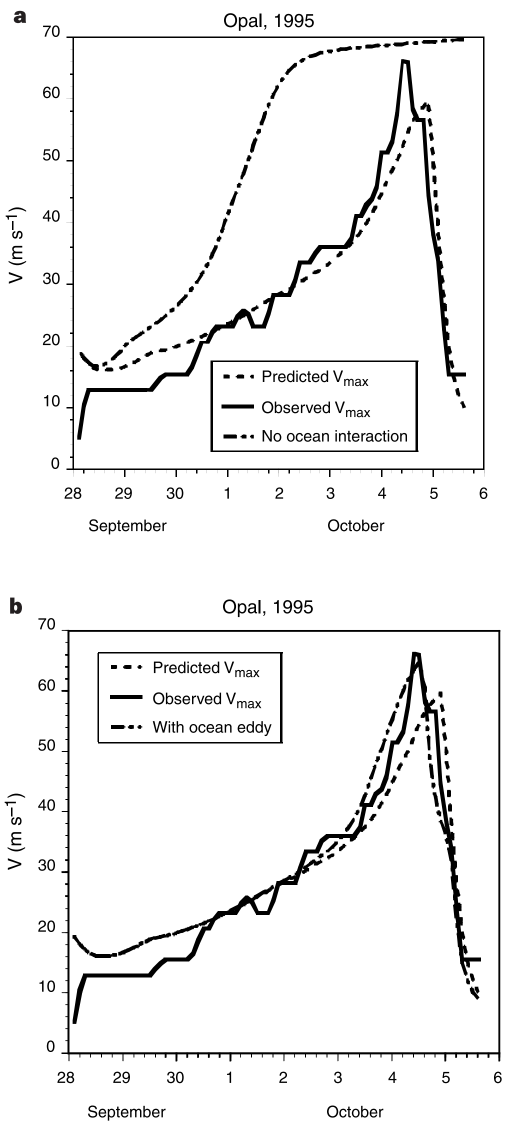

Figure 1 Evolution of the maximum wind speed in Hurricane Opal. In **a**, the solid line shows the observed evolution, the dashed line shows the modelled evolution, and the dash-dot line shows evolution modelled without ocean interaction. In **b**, the dash-dot line shows evolution modelled in the presence of a warm ocean eddy.

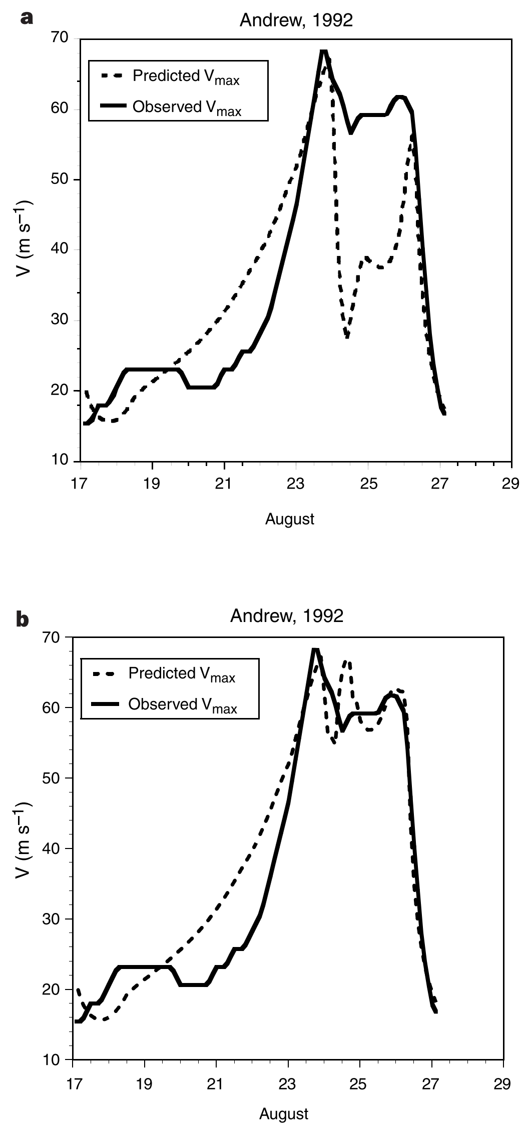

Figure 2 Evolution of the maximum wind speed in Hurricane Andrew. Solid lines are observations and dashed lines are modelled values. The nominal model run is shown in **a**, while the run in **b** takes into account the swamp in southern Florida and the shallow continental shelf to its west (see text for details).

below the mixed layer is set to a constant in the runs described here. This very simple formulation has been shown to lead to a storm intensity evolution that is virtually indistinguishable from that of the same hurricane model coupled to a three-dimensional ocean model, in the case of a steadily moving storm[16].

For each event, the model is initialized using a synthetic warm-core vortex. In each of the cases discussed below, the geometry of the vortex is identical, though in principle it can be varied according to the size of the real system. The maximum wind speed of this initial vortex is matched to the observed wind speed at the beginning of the initial period of intensification of the observed system. Also, the initial degree of saturation of the inner storm core is specified so as to achieve the observed, initial rate of intensification. These are crucial steps, as the subsequent evolution is quite sensitive to the initial state. Apart from this initial matching of the model and observed maximum wind speeds, no adjustment of the model vortex towards observations is made.

Two properties of the storm's environment along its observed track are specified from monthly mean climatology: the potential maximum wind speed[17] and the ocean mixed-layer depth[18]. The former is interpolated from the 2.5° grid on which it was supplied to the observed storm position; the latter was similarly interpolated from a 1° grid to the observed storm position. Both data sets were also linearly interpolated to the actual date, assigning the monthly mean climatology to the 15th day of each month. These monthly climatologies were formed using many years of data; no year-to-year variations are accounted for. A third data set, on a 1° grid, was also used to specify ocean depths along the observed storm track. This was used to detect landfall, and also to reveal those situations when the ocean mixed layer extends right to the ocean floor, so that surface cooling by mixing cannot occur. The landfall algorithm is one of maximum simplicity: when the centre of the storm passes over land, the coefficient of surface enthalpy flux is set to zero everywhere. Although this is unrealistic, in practice the strongest effects are under the eyewall, whose passage over land occurs nearly at the same time that the storm centre makes landfall. (The small differences in timing are comparable to the six-hour temporal resolution of the observational data.)

In each of the cases presented below, the evolution of maximum surface wind speed in the model is compared to the observed evolution; no attempt has been made to compare the evolutions of model and observed storm structure, as the latter is not available in any convenient form. It should be borne in mind that not all of the reported wind speeds are directly measured by aircraft or radar; some are partially subjective estimates based on satellite imagery. (Here again, the readily available data archive does not document

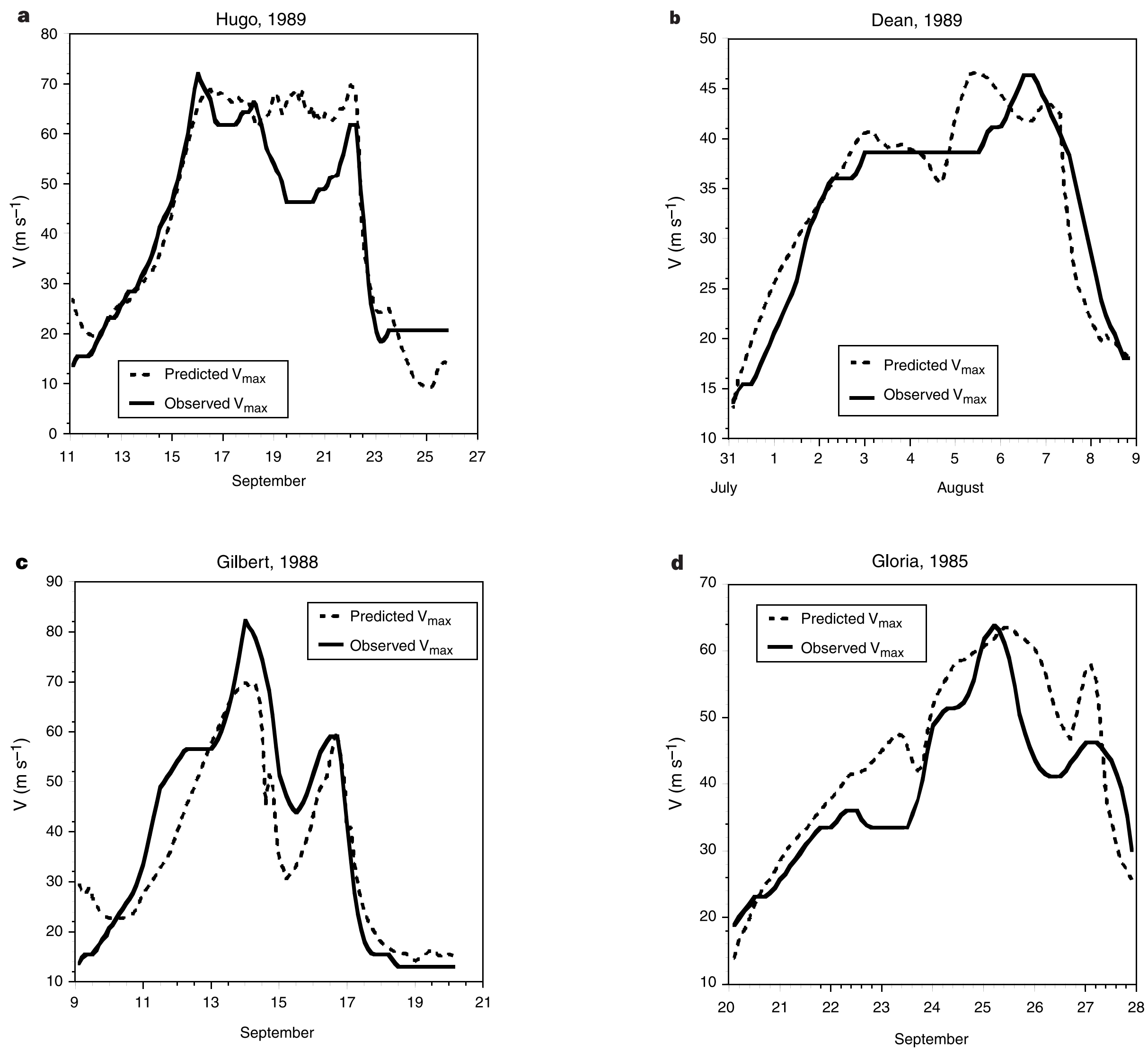

Figure 3 Evolution of maximum wind speed in several hurricanes. **a**, Hurricane Hugo; **b**, Hurricane Dean; **c**, Hurricane Gilbert; and **d**, Hurricane Gloria. In all cases the predicted and the observed maximum wind speeds are shown by dashed and solid lines, respectively.

the source of the data, but it is safe to assume that most reported wind speeds in storms within one day of landfall in the USA are based on reliable *in situ* or radar measurements within six hours of the reporting time.)

Model skill

Some well simulated examples. Figure 1 shows the observed and modelled evolution of Hurricane Opal, which moved through the Gulf of Mexico in October, 1995, making landfall in northwestern Florida. Also shown in Fig. 1a (but not in subsequent figures) is the evolution that would have occurred had the ocean temperature remained fixed in time, demonstrating the crucial role of ocean interaction. Previous studies of this event have emphasized the role of an approaching upper-tropospheric disturbance[4] or the observed presence of a warm ocean eddy at about the time of maximum intensification, but Fig. 1a shows that most of the evolution can be accounted for without these effects (I. Ginis, personal communication). The main influence of the approaching upper-tropospheric disturbance was to accelerate the forward motion of the storm, thereby decreasing the ocean cooling. Insertion into the model of a warm ocean eddy of about the dimensions and magnitude of that observed did result in a small but noticeable increase in the peak intensity of the storm, as shown in Fig. 1b.

Hurricane Andrew developed east of the Bahamas in August, 1992, and then moved westward across the southern tip of Florida, into the Gulf of Mexico, and then northwestward, making landfall again in Louisiana. It was the most expensive natural disaster in US history, incurring more than $28 billion in damage. The evolution of Hurricane Andrew's intensity is shown in Fig. 2a. Here the modelled evolution departs noticeably from the observed in several respects. In its early stages, the model storm intensifies while the observed storm in fact weakens. Operational forecasters at the time attributed this weakening to the presence of substantial vertical wind shear, an effect not accounted for in this model. More spectacularly, the model intensity declines far more rapidly than observed after making landfall in southern Florida. Two important model deficiencies may come into play here: first, the southern tip of Florida is not dry land but rather a swamp, so that the assumption of vanishing surface heat flux may be extreme. Second, the resolution of the ocean depth data set was not high enough to account accurately for the presence of a shallow shelf extending westward from the southern tip of Florida. In reality, the ocean mixed layer over which Hurricane Andrew moved probably extended right to the sea floor for the first ten hours or so after the storm left Florida. In Fig. 2b, the model has been modified to account for the actual depth of the sea floor along the storm track, and the surface enthalpy exchange coefficient has been reduced by only one-half while the storm is over southern Florida. This illustrates how very sensitive hurricane intensity is to the nature of the underlying surface.

Hurricane Hugo moved through the northern Caribbean and then up over the Sargasso Sea, making landfall in South Carolina in September, 1989. Figure 3a compares the actual and modelled storm evolution. The simulation is quite good, except when the storm is over the Sargasso Sea, in which case the model overestimates its actual intensity. There is considerable evidence that Hugo was affected by vertical wind shear during this time.

Hurricane Dean moved westward over the tropical North Atlantic to just north of the Virgin Islands, then turned north, moving over open waters until it struck southeastern Newfoundland in early August, 1989. It never exceeded marginal hurricane intensity. Figure 3b compares the predicted and modelled intensities of that storm.

Hurricane Gilbert, in September 1988, was the most intense hurricane ever recorded in the Atlantic region. It moved westward over the Caribbean Sea, striking Jamaica and the Yucatan peninsula before passing into the Gulf of Mexico. Figure 3c shows that whereas

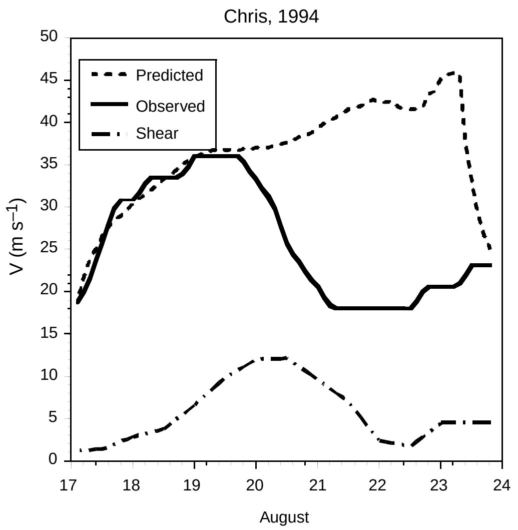

Figure 4 Evolution of the maximum wind speed in Hurricane Chris. The solid line shows observations, and the dashed lines are modelled values; the dash-dot line shows an estimate of the magnitude of the environmental vertical wind shear at the storm centre.

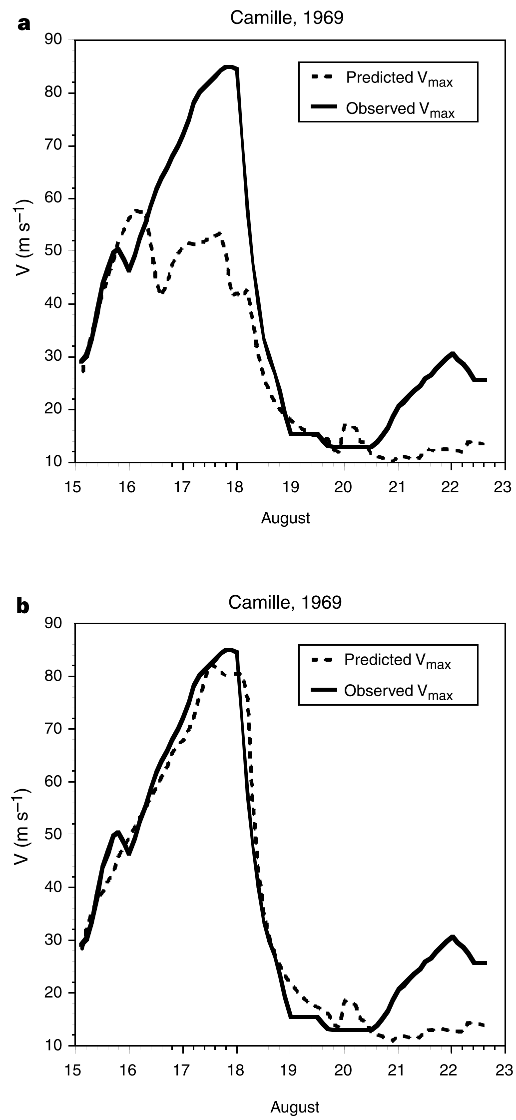

Figure 5 Evolution of the maximum wind speed in Hurricane Camille. Solid lines are observations, and dashed lines are modelled values. The nominal model run is shown in **a**, while in **b** the ocean interaction is omitted.

the character of the storm's intensity evolution was well simulated, the peak intensity was substantially underestimated.

Hurricane Gloria formed off Africa, and affected the US east coast in late September, 1985. Figure 3d shows that the evolution of its intensity was well simulated in most respects.

Some notable failures. Especially in their early stages of development, tropical cyclones are susceptible to suppression through the effects of vertical wind shear, or enhancement by dynamical interactions with other weather systems in the high troposphere. These effects have been emphasized in many previous investigations. We have found several examples in which the skill of the present model is significantly compromised by such effects. An example of the first effect is demonstrated by Fig. 4, which shows the model prediction of the wind-speed evolution of marginal hurricane Chris in 1994, together with an estimate of the magnitude of the observed environmental vertical wind shear at the storm centre (J. Kaplan, personal communication). This hurricane appears to have been severely limited by the shear, which reaches its peak intensity just as the hurricane goes into decline. We have also found several cases in which the present model underpredicts the intensity of events that were apparently affected by dynamical interactions with their environment. We emphasize, however, that such effects are significant in only a small fraction of the cases that we have examined.

Figure 5a shows the predicted and observed evolutions of Hurricane Camille of 1969, the only category 5 hurricane to strike the US mainland in the 100-year period of record, making landfall near Biloxi, Mississippi. The intensity of the storm is very badly underpredicted. Figure 5b shows that if the sea surface temperature is held fixed, the simulation is quite good. One of the interesting features of the Gulf of Mexico is the Loop Current, an extension of the Gulf Stream that loops up towards the coast of Alabama and Mississippi but whose exact position is somewhat variable. No manifestation of this current was evident in the climatological ocean data interpolated to the observed positions of Camille. There is some evidence that Camille moved right along the axis of the Loop Current, which has a locally deep, warm mixed layer[19]. It has been suggested[20] that most of the very severe hurricanes that affect the Gulf coast move along the Loop Current.

Discussion

The simulations presented here suggest that, once tropical cyclones reach tropical-storm strength, their intensity evolution is controlled mostly by their initial intensity together with the thermodynamic profile of the atmosphere and upper ocean through which they move. Factors such as vertical wind shear and dynamical interactions with the environment, emphasized in previous work, appear to be strongly influential mostly during the formative stages, when the storms are comparatively weak. Storm intensity is particularly sensitive to the thermodynamic structure of the upper ocean, and it is evident that in at least some cases (for example, Hurricane Camille) the climatological specification of the ocean thermal structure is insufficient. Accurate prediction of hurricane intensity in these cases probably requires accurate measurement of the upper-ocean thermal structure ahead of the storm. The simulations presented here offer hope that even with a very simple model, hurricane intensity can be predicted with useful skill as far in advance as an accurate track prediction can be made. Such track predictions require three-dimensional models able to account for the full range of interactions between the storm and its environment. □

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