The Ocean's Effect on the Intensity of Tropical Cyclones: Results from a Simple Coupled Atmosphere–Ocean Model

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ABSTRACT

A coupled hurricane–ocean model was constructed from an axisymmetric hurricane model and a three-layer ocean model. If the hurricane moves at constant speed across the ocean a statistically steady state (in a reference frame moving with the storm) is reached after a few days of simulation time. The steady-state intensity of the hurricane is strongly affected by the interaction with the ocean. This interaction with the ocean can be described as a negative feedback effect on the hurricane's intensity and is called ''SST feedback.'' A large set of numerical experiments was performed with the coupled model to deduce systematically the dependence of the amplitude of the SST feedback effect on a set of model parameters.

In the coupled model the SST feedback effect can reduce the hurricane's intensity by more than 50%. Only in cases of rapidly moving storms over deep oceanic mixed layers is the SST feedback effect of minor importance. These results cast a new light on the role of the ocean in limiting hurricane intensity.

1. Introduction

Hurricanes[1] form exclusively over the tropical oceans and rapidly disintegrate when they make landfall. This is primarily due to the much-reduced surface heat fluxes over land. Since the surface fluxes peak sharply just outside and under the eyewall, a hurricane effectively ''feels'' the land when the eye of the storm moves onshore even though a large part of the storm's circulation may have been over land much earlier. This becomes most striking when a hurricane moves parallel to the shore line in close vicinity to land, as often happens with recurving storms along the U.S. east coast (e.g., Hurricanes Emily, 1993 and Danny, 1997).

The fundamental role of the surface heat fluxes (foremost that of latent heat) as the energy source of hurricanes has been recognized for a long time (e.g., Riehl 1950; Kleinschmidt 1951). It has also been known since the 1960s that hurricanes leave a wake of cold surface water behind them (e.g., Leipper 1967) that results from rapid turbulent entrainment of cold water into the oceanic mixed layer. Nevertheless, the effect of this cooling on the intensity of hurricanes has received surprisingly little attention. In numerical hurricane models, the ocean was typically treated as a constant sea surface temperature (SST) boundary condition and the effect of the chosen SST field on hurricane intensity was investigated (e.g., Ooyama 1969). Similarly, in numerical ocean models, the hurricane wind field was specified and the oceanic response to the specified hurricane forcing was investigated (e.g., Price 1981). In both approaches one part of the coupled atmosphere–ocean system is treated as active and the other part as passive, such that any feedback effects are excluded a priori.

The first numerical simulations of the coupled hurricane–ocean system were performed with axisymmetric hurricane and ocean models neglecting the hurricane movement. Very limited computer power dictated a coarse horizontal resolution resulting in only weak model storms. From such model simulations Chang and Anthes (1979) concluded that ''appreciable weakening of a hurricane due to the cooling of the oceanic surface will not occur if it is translating at typical speed.'' The fact that their model storm was only very little affected by a rather strong oceanic cooling is likely due to a combination of several problems including their convective parameterization (based on moisture conver-

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[1] The term ''hurricane'' is used loosely in this paper to refer to tropical cyclones in general.

gence), the short integration period of only 24 h, and the aforementioned problems of coarse resolution and thus weak storms. Sutyrin et al. (1979) performed simulations with a coupled model of the oceanic and atmospheric boundary layers and concluded that the ''interaction is so strong that the integral heat and moisture fluxes from the ocean into the atmosphere may change significantly within a few hours and influence the intensity of the tropical cyclone.'' Sutyrin and Khain (1984) coupled an axisymmetric hurricane model to a 3D ocean model and were the first to simulate the effect of the storm movement on the intensity of the storm. They showed that smaller storm translation speeds and smaller initial oceanic mixed layer depths lead to a stronger negative feedback effect of the ocean on the intensity of the hurricane. A fully three-dimensional coupled model was presented by Khain and Ginis (1991) and used to study the effect of the interaction with the ocean on the storm track. Bender et al. (1993) published results from simulations with a very high resolution fully three-dimensional coupled hurricane–ocean model confirming many of the earlier results. While these coupled model simulations have revealed some of the basic aspects of the oceanic feedback effect on hurricane intensity, this feedback has not yet been investigated systematically. Many scientists and forecasters therefore believe that the SST feedback need not be considered to first order, much in the spirit of the early results of Chang and Anthes. How commonplace this belief still is can be seen in a recent portrait of the state of tropical cyclone research by the World Meteorological Organization (Foley et al. 1995). In this paper we hope to suggest a new and different perspective on the effect of the ocean on hurricane intensity.

2. Goal and approach

The goal of this investigation is to understand and quantify the effect of the ocean on the intensity of tropical cyclones. The effects can be categorized into two classes: noninteractive effects in which the ocean is passive, and interactive or feedback effects. The first class of effects can be investigated by quantifying the sensitivity of a hurricane model to its lower boundary condition, a constant SST field. Physically, these effects are primarily caused by the dependence of the surface fluxes on the saturation vapor pressure at the SST. In contrast, investigation of the second class of effects requires a coupled hurricane–ocean model. Ocean dynamics now come into play in addition to the thermodynamics at the atmosphere–ocean interface.

The foci of this paper are the interactive effects of the ocean on hurricane intensity. The noninteractive effects are only briefly addressed in section 3b(1). A quantitative measure of the ocean's interactive effects on a hurricane's intensity is the SST feedback factor F_{SST}:

$$F_{\mathrm{SST}} = \frac{\Delta p}{\Delta p|_{\mathrm{SST}}} - 1, \tag{1}$$

where Δp is the pressure depression in the eye of the storm, that is, the difference between the background surface pressure far away from the storm and the minimum central pressure in the eye. Here Δp serves as a measure of storm intensity. The subscript SST refers to the pressure depression realized with a fixed sea surface temperature, that is, without any feedback. The factor F_{SST} is always negative because a reduction of the SST due to the storm diminishes the storm's intensity; F_{SST} therefore must be in the range $[-1; 0]$. An SST feedback factor of $F_{\mathrm{SST}} = -0.3$, for example, means that the storm's intensity as described by the pressure depression is reduced by 30% due to the SST feedback effect. The central question of this paper is, *How does the SST feedback factor depend on the parameters of the coupled hurricane–ocean system?*

In a complex natural setting, F_{SST} depends not only on a number of environmental parameters but also on the history of the storm. To exclude such a dependence on time only mature storms shall be considered; that is, it is assumed that the coupled hurricane–ocean system has had enough time to settle into an equilibrium state. This state is characterized by a statistical steadiness of all variables in a frame of reference moving with the storm. The SST feedback factor of the mature hurricane–ocean system no longer depends on time but only on the environment of the hurricane–ocean system.

To investigate the parameter dependence of F_{SST}, a coupled hurricane–ocean model was constructed from the axisymmetric hurricane model of Emanuel (1989) and the 3D ocean model of Cooper and Thompson (1989). This choice of models was made to make possible a large number of simulations and thus to allow for a systematic exploration of the parameter space. The coupled model is a process model rather than a forecast model. Its main limitations are the lack of detailed cloud microphysics and the restriction of axisymmetry in the atmosphere. Nevertheless, it is expected that the basic features of the SST feedback effect are reasonably well represented in this simple coupled model.

The approach can be summarized as follows. First, comprehensive sensitivity tests with the uncoupled hurricane model were performed to select a set of environmental parameters that are hypothesized to be relevant to the SST feedback effect. In the range of observed values of these parameters the parameter space was then sampled systematically with the coupled model. Finally, a statistical regression was performed to deduce an analytical expression for the dependence of the SST feedback factor on the environmental parameters.

3. Models

A coupled hurricane–ocean model was constructed from two independently developed and tested models, namely, the axisymmetric hurricane model of Emanuel (1989) and the four-layer ocean model of Cooper and Thompson (1989). As both models have been described in detail elsewhere, the model equations are not derived here again. Instead, both models are briefly introduced from a physical perspective describing the principal physical processes and balances in the models. Those readers interested in the technical details are referred to the original publications. While the original hurricane model is expressed in dimensionless variables, an analogous set of dimensional equations was used to ease the coupling to the dimensional ocean model. The derivation of this set of dimensional model equations is given in Schade (1994). Finally, the coupling procedure by which information is exchanged between the two submodels is described at the end of this section.

a. Hurricane model

The hurricane model is an axisymmetric model in gradient-wind and hydrostatic balance. It thus belongs to the ''models of the first phase'' as defined by Ooyama (1982). Since the present application is restricted to the mature stage of tropical cyclones, the use of a balanced model is justified. The model atmosphere consists of three layers: a boundary layer and two tropospheric layers. In the radial direction, the model uses angular momentum coordinates. Two main advantages arise from this choice of coordinate system. First, the radial resolution in physical space is high in regions where the radial gradient of angular momentum is large. Thus a domain of 2000-km radius can be represented with only 48 radial nodes and yet achieve a resolution of 3–10 km grid spacing in the region of main interest under the eyewall. Second, the slantwise convection in the eyewall of a tropical cyclone, which is typically tilted at an angle of 30°–60°, becomes upright in the framework of angular momentum coordinates and thus easy to represent. At this resolution a time stop of 1 min is required for numerical stability.

The turbulent exchange of momentum between atmosphere and ocean is parameterized using the bulk aerodynamic drag law with a wind speed–dependent drag coefficient. Aside from the effect of radial diffusion, angular momentum is strictly conserved in the interior of the model atmosphere. Since the air flowing in toward the eye at low levels rotates cyclonically, surface friction constantly removes cyclonic angular momentum from the model atmosphere. The angular momentum budget of the model can therefore never settle into a true steady state. Nevertheless, a steady state can be reached at low levels if the radial advection of high angular momentum is balanced by the frictional loss to the lower boundary. The permanent transfer of angular momentum to the ocean is reflected in the evergrowing anticyclone in the upper-atmospheric layer. In angular momentum coordinates, this simply means that the coordinate surfaces are advected outward by the mean radial flow to ever larger radii. While this is clearly unrealistic, it is an artifact of the axisymmetry that does not allow for a mean vertical shear in the troposphere and thus for a flow through the upper anticyclone. In nature, such shear causes a ventilation of the upper-tropospheric anticyclone and a downstream wake of air with low potential vorticity (e.g., Wu and Emanuel 1993). Since there is no vertical diffusion of momentum in the model a steady state can be reached in the lower troposphere in spite of the ever-growing anticyclone aloft.

Similar to momentum, heat is transfered turbulently between atmosphere and ocean and again the bulk aerodynamic drag law is used to parameterize this transfer. In the interior of the atmosphere, two nonconservative processes are included in the model. First, the release of latent heat due to phase changes of water is treated implicitly by using moist entropy as a combined temperature and humidity variable. Second, radiative cooling is crudely parameterized as a Newtonian relaxation back to the initial convectively neutral sounding. Unlike momentum, the moist entropy in the different layers is strongly coupled through convection. As soon as surface fluxes or radiative cooling render the stratification at a grid point unstable, a convective mass flux is triggered that acts to return the profile back to neutrality. In the steady state, surface fluxes, radiation, and convection balance advection of moist entropy. Though radiation plays a minor role for short integration periods and is often neglected in hurricane models, it is a fundamental part of the overall heat balance and a prerequisite for reaching a steady state.

The model is initialized with a marginal tropical storm and a convectively neutral stratification. The constraint of convective neutrality implies that the initial atmospheric sounding is a function of the initial SST and of the initial relative humidity in the boundary layer ($\mathcal{H}$). Physically this initial condition corresponds to a situation where the unperturbed atmosphere has had enough time to adjust to the ocean surface below it. Typically, the initial vortex first spins down slightly owing to friction and convective downdrafts, before the core becomes saturated and intensification begins. The storm then rapidly develops over the next 2–4 days and finally settles into a statistically steady state. Such a typical development is shown in Fig. 1.

b. Sensitivity tests

Many parameters need to be set for a numerical model even if it is as simple as the hurricane model used here. Few of these parameters have a direct physical meaning and can be considered known. The majority of the parameters, such as the bulk drag coefficient, is only known to fall into a certain range of values. Again, other parameters have no direct physical meaning, for example, the length of the time step in the model, but nevertheless may have a strong influence on the model

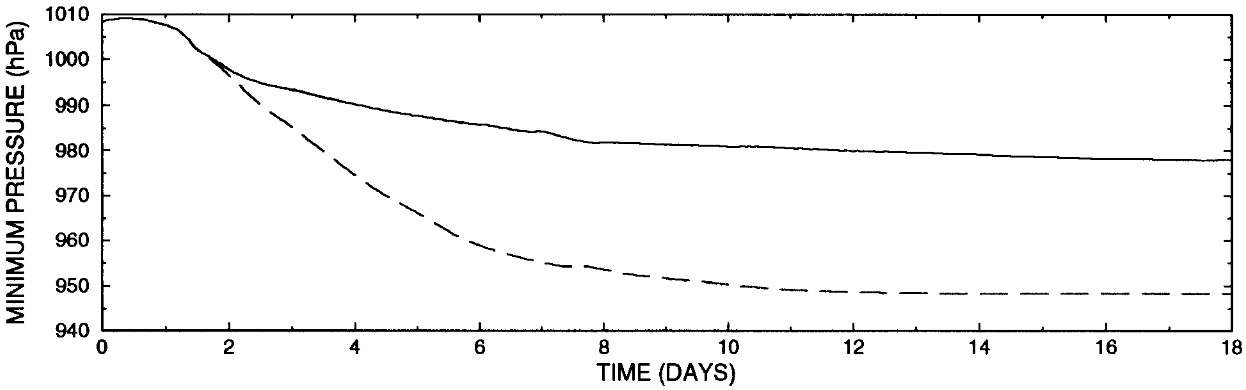

FIG. 1. Time series of the minimum central pressure. The solid line marks the results of a coupled integration while the dashed line is from an identical integration with constant SST. The following dimensional parameters were used: h_o = 40 m, u_T = 6 m s^{-1}, $\Delta p|_{\rm SST}$ = 65 hPa, η = 0.8, f_o = 5 × 10^{-5} s^{-1}, Γ = 8 × 10^{-2} °C m^{-1}, and $\mathcal{H}$ = 84%. The value of $\Delta p|_{\rm SST}$ results from SST = 29°C and $T_{\rm top}$ = −68°C (and $\mathcal{H}$ = 84%).

results. Therefore the sensitivity of the model results to *all* input parameters was tested to discover physical sensitivities of interest and erroneous sensitivities of concern. For sake of conciseness only those results of the sensitivity tests are reported here that are of physical interest or that highlight weaknesses of the model. Put differently, the model results are insensitive to all parameters not mentioned below.

In each set of sensitivity experiments, the sensitivity of the steady-state central pressure to changes in only a single parameter was tested over a range of values considered realistic. All the other parameters were held fixed at their default values. It should be noted, though, that changes in SST and changes in $\mathcal{H}$ imply changes in the initial atmospheric temperature because the atmosphere is assumed to be convectively neutral at the initial time.

1) Sea surface temperature

When the hurricane model is run uncoupled, the SST is constant in time and horizontally uniform. Higher SSTs lead to more intense storms as expected and predicted, for example, by the Carnot theory for hurricanes (Emanuel 1988). A sensitivity of about −6 hPa/K was found (Fig. 2). The default SST is 29°C.

This sensitivity constitutes the noninteractive effect of the ocean on the hurricane's intensity.

2) Relative humidity

In the initial unperturbed model atmosphere, the relative humidity in the boundary layer must be specified. Lower relative humidity leads to stronger storms. While it may seem counterintuitive that a dryer boundary layer gives rise to a more intense moist convective storm the reason for this behavior is quite simple: a dryer boundary layer features a stronger thermodynamic disequilibrium at the sea surface. This becomes most apparent in the extreme scenario of $\mathcal{H}$ = 100% in which the latent heat flux goes to zero. The sensitivity is about 4 hPa/% as shown in Fig. 3. The default relative humidity is 80%.

3) Initial conditions

The final steady state is insensitive to the specification of the initial vortex. Such a lack of sensitivity is gen-

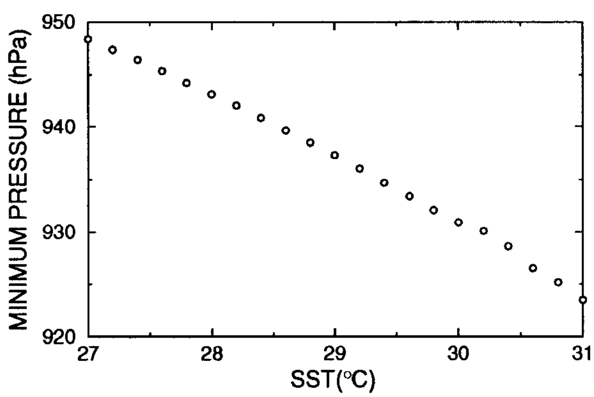

FIG. 2. Sensitivity of the steady-state central pressure to the SST.

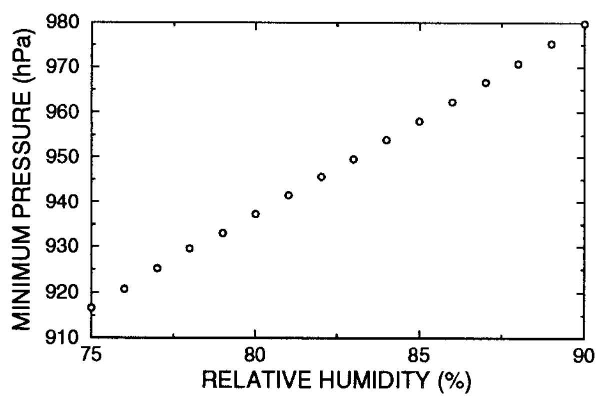

FIG. 3. Sensitivity of the steady-state central pressure to the relative humidity.

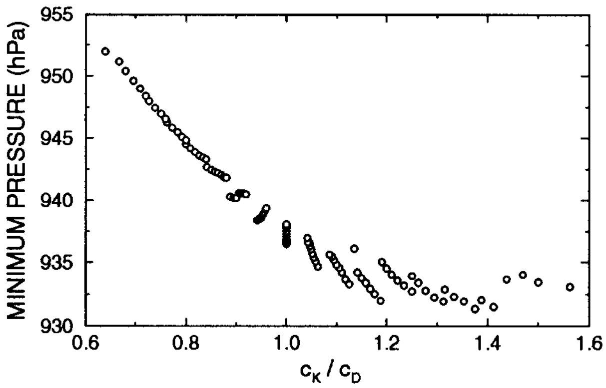

FIG. 4. Sensitivity of the steady-state central pressure to the ratio of the transfer coefficient of heat to that of momentum.

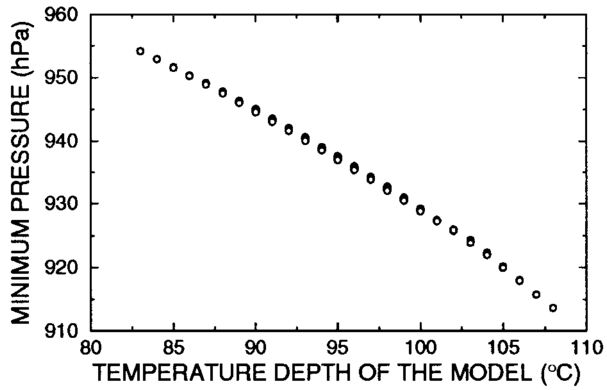

FIG. 5. Sensitivity of the steady-state central pressure to the total temperature depth of the model.

erally very desirable in models that are run to an equilibrium state. Yet in nature, hurricanes of very different sizes have been observed and it is important to investigate how the feedback effect in the coupled model changes with storm size. Our expectation that the final size of the model storm depends on the size of the initial vortex turned out to be wrong and the storm size had to be specified rather artificially in the coupled experiments as described in section 3d.

The default storm has maximum winds of 52 m s^{-1} at a radius of 40 km. Gale force winds extend to a radius of 150 km.

4) TRANSFER COEFFICIENTS

In the default experiment, the transfer coefficients for momentum and heat in the bulk aerodynamical formulas are identical and the storm intensity is insensitive to the choice of value. But a strong dependence on the ratio of the transfer coefficient for heat to that for momentum was found and is displayed in Fig. 4. Ooyama (1969) had already qualitatively described this effect and it is discussed in detail in Emanuel (1995). It is mentioned here because the physics and parameterization of the heat and momentum transfer at high wind speeds are still not well understood and are difficult to measure, and thus they are the source of considerable uncertainty in hurricane models.

The ratio was kept at unity in all coupled experiments for lack of better knowledge.

5) TROPOPAUSE TEMPERATURE

The Carnot theory of hurricanes (Emanuel 1988) predicts a strong sensitivity to the temperature in the outflow region, where heat is lost to space by radiation. The equivalent parameter in our model is the sum of the temperature differences between the top and bottom of each layer, that is, the total ‘‘temperature depth’’ of the model. The larger this temperature depth, the stronger the storm. Figure 5 shows the results of a set of experiments around the default value of 95°C with a slope of a little less than −2 hPa/K.

c. Ocean model

The oceanic response to a moving hurricane has been investigated in great detail and even simple mixed layer models were found to reproduce the main characteristics of this response rather well (e.g., Price 1981, 1983; Price et al. 1994). Therefore the ‘‘Price-type’’ model due to Cooper and Thompson (1989) was chosen, as it has been tested carefully by the original authors and could be used without modifications for our purpose.

The ocean model is run with three active layers: a thin well-mixed layer on top of a strongly stratified layer and a deep abyssal layer. Momentum is turbulently exchanged at the interface with the atmosphere. In the interior of the ocean, vertical exchange of mass and heat is allowed only between the topmost layer representing the oceanic mixed layer and the next lower layer, called the upper thermocline. This exchange represents a turbulent mixing process referred to as entrainment. The Richardson number formulation of Price (1983) is used to parameterize the entrainment. This formulation effectively keeps a bulk Richardson number close to critical under wind forcing. The heat budget of the mixed layer is dominated by the entrainment heat flux through the base of the mixed layer. The exchange of heat between atmosphere and ocean is negligible by comparison (e.g., Bender et al. 1993) and is therefore not included in the model. Besides these turbulent processes gravity wave dynamics govern the ocean’s behavior.

The horizontal resolution of the ocean model ranges from 10 to 25 km depending on the size of the hurricane as given by the size parameter η (see below for details). The time step depends on the chosen resolution and ranges from 5 to 12 min.

The characteristic features of the observed SST changes in the wake of tropical cyclones is reproduced by the model. A strong bias to the poleward side of the track can be seen with maximum SST reductions of typically 2°–6°C behind the storm. The SST reduction under the eye of the storm is much smaller with typical values between 0.5° and 1.5°C.

d. Coupling procedure

Coupling the two models effectively means specifying the exchange of information between the models. As already mentioned above, the turbulent exchange of heat and momentum is parameterized using the bulk aerodynamic drag formula with a wind speed–dependent drag coefficient. The surface pressure field sets up a barotropic flow within the ocean. This effect is neglected because the resulting flow is very weak and does not affect the entrainment process. Also neglected is the effect of the oceanic surface currents on the drag between atmosphere and ocean because the currents are extremely slow compared to the wind speeds in the atmosphere close to the surface. In contrast, the translation velocity of the hurricane relative to the ocean can reach a significant fraction of the wind speed 10 m above ground and therefore is included in the calculation of the turbulent exchange between the two models.

Additional complications arise from the different geometries of the models. Since the hurricane model is axisymmetric it does not ''know'' about horizontal directions other than radial distance from its central axis. Therefore the translation velocity at which the storm moves across the ocean must be specified externally. At the surface the radial nodes of the hurricane model are points in the radial direction and concentric circles in a horizontal plane. The SST felt by the hurricane model at a specific radial node therefore must be calculated as the average SST along a node circle. This amounts to an approximation that is reasonably close to the storm center where the rapid rotation causes rather effective homogenization along node circles. Far away from the storm center, this approximation must break down. Fortunately, the fractional part of anomalous SSTs along a node circle rapidly becomes smaller with increasing distance from the storm center such that the approximation becomes good again for large radii and, moreover, the storm intensity is not very sensitive to SST perturbations at large radii.

To construct the surface drag field for the ocean model the radial distance of each ocean grid point from the current storm center is calculated. The axisymmetric part of the surface wind field is then calculated by linear interpolation between the radial nodes of the hurricane model. Next, the vector sum of this axisymmetric wind and the prescribed storm translation velocity is calculated. The resulting total surface wind is finally used in the bulk aerodynamic drag formula to calculate the surface drag field felt by the ocean. An axisymmetric SST field for the hurricane model is calculated by bilinear interpolation from the nearest four ocean grid points to sampling points on the hurricane model's node circles. These sampling points are closely spaced where the strongest SST gradients occur and far apart elsewhere. A distance-weighted average of the SST at the sampling points of a particular node circle is finally passed to the hurricane model as the SST at this particular node of the hurricane model.

In summary, the ocean model is forced by a 3D surface wind field constructed from the axisymmetric flow in the hurricane model and the hurricane translation velocity. In turn, the hurricane model is forced by an axisymmetric SST field constructed through azimuthal averaging of the 3D SST field of the ocean model around the storm center. The respective boundary fields are updated each time step.

As mentioned above, the steady-state hurricane is insensitive to the initial conditions in the hurricane model. In particular, the size of the steady-state hurricane cannot be set by the initial conditions. Since it is nevertheless desirable to force the ocean with storms of different sizes, a size parameter, η, was introduced in the coupling procedure. The atmospheric fields are remapped with a horizontal scale factor of η before they are passed to the ocean model. Analogously, the oceanic fields are remapped with a horizontal scale factor of η^{-1} before they are passed to the hurricane model.

4. Choice of parameters

Many parameters play a role in the SST feedback mechanism. Based on the sensitivity studies with the uncoupled hurricane model (section 3b) and on the results of earlier investigations of the oceanic response to hurricane forcing (e.g., Price 1983), a set of relevant parameters was selected.

- The steady-state hurricane intensity depends strongly on the environmental boundary layer relative humidity ($\mathcal{H}$), on the SST, and on the tropopause temperature (T_{top}).
- The storm size (η) and the storm translation velocity (u_T) determine the interaction timescale between atmosphere and ocean.
- The thermal and dynamical inertia of the mixed layer is set by the unperturbed oceanic mixed layer depth (h_o).
- The stratification below the mixed layer ($\Gamma \equiv \partial T/\partial z$) affects both the availability of cooler water and the speed of the entrainment process.
- Last, the Coriolis parameter (f_o) sets the frequency of the inertial oscillations that dominate the oceanic wake. It also affects the amplitude of the vertical displacement of isopycnals as part of the inertio-gravity wave response. This displacement is larger at lower latitudes.

These eight parameters are considered to govern the SST feedback effect in the coupled model and thus define the parameter space to be explored.

Since it is very expensive to systematically sample an eight-dimensional parameter space it is desirable to

TABLE 1. Dimensional parameters.

Parameter	Dimension	Remarks
$D_1 \equiv h_o$	m	
$D_2 \equiv u_T$	m s^{-1}	
$D_3 \equiv \rho_o^{-1}\,\Delta p\|_{\mathrm{SST}}$	m^2 s^{-2}	$\rho_o = 1.25$ kg m^{-3} is a reference density of air
$D_4 \equiv \eta L_o$	m	$L_o = 5 \times 10^4$ m is a scaling length
$D_5 \equiv f_o$	s^{-1}	
$D_6 \equiv \alpha\Gamma$	m^{-1}	$\alpha = 3.4 \times 10^{-4}$ °C^{-1} is the coefficient of thermal expansion
$D_7 \equiv 1 - \mathcal{H}$	1	

reduce the dimensions of the parameter space. This can be done if some of the parameters enter the problem under consideration only as a fixed combination. For example, $\mathcal{H}$, SST, and T_{top} enter the SST feedback by setting the storm intensity at constant SST ($\Delta p|_{\mathrm{SST}}$), that is, the intensity without SST feedback. Also $\mathcal{H}$ determines the thermodynamic disequilibrium at the sea surface and thus the sensitivity to changes in SST. Therefore, the two-parameter set [$\Delta p|_{\mathrm{SST}}$, $\mathcal{H}$] can be used instead of the three-parameter set [$\mathcal{H}$, SST, T_{top}], reducing the dimension of the parameter space by one.

As it is not always as obvious as in the above example which combination of parameters is relevant to a given problem, the constraint of dimensional consistency can be used to transform a set of m parameters with physical dimensions into another set of m–n nondimensional parameters. According to the Buckingham π theorem (Buckingham 1914) n is the number of independent physical dimensions of the m parameters.

Table 1 lists the suitably scaled dimensional parameters that are considered to govern the SST feedback effect. As only two physical dimensions are contained in this set of seven dimensional parameters [D_i] a set of five nondimensional parameters [N_i] can be defined that still spans the same phase space as the dimensional set [D_i]. There is no unique way of combining the dimensional parameters into nondimensional parameters. The following combination was chosen here:

$$
\begin{aligned}
N_1 &= D_4 D_1^{-1} = \eta L_o h_o^{-1} \\
N_2 &= D_3 D_2^{-2} = \Delta p\,|_{\mathrm{SST}} (\rho_o u_T^2)^{-1} \\
N_3 &= D_1 D_6 = h_o \alpha \Gamma \\
N_4 &= D_2 (D_4 D_5)^{-1} = u_T (\eta L_o f_o)^{-1} \\
N_5 &= D_7 = 1 - \mathcal{H}. \qquad (2)
\end{aligned}
$$

The SST feedback factor F_{SST} is an unknown function of the set of nondimensional parameters [N_i]. This function can be determined experimentally by sampling the five-dimensional parameter space defined by [N_i] with the coupled model. The sampled ranges of the dimensional parameters are listed in Table 2. The corresponding ranges of the nondimensional parameters are given in Table 3.

5. Results

A total of 2083 samples were taken in the region of the parameter space given in Table 3. ‘‘Taking a sample’’ here refers to integrating the coupled hurricane–ocean model for 18 days by which time the model had settled into a statistically steady state. Figure 1 shows the typical evolution of the surface pressure in the eye of the storm as a solid line. The dashed line displays the pressure time series in the control experiment, which differs only in one aspect: the SST is artificially held constant to exclude any SST feedback. Clearly, the noninteractive control storm develops to much greater intensity than the storm that interacts with the ocean. The strength of the SST feedback effect is measured by the feedback factor defined by (1). For the storm displayed in Fig. 1 the SST feedback factor is $F_{\mathrm{SST}} = -46\%$.

An example of a two-dimensional cross section through the parameter space is given in Fig. 6. Here F_{SST} is displayed in a contour plot as a function of D_1 (h_o) and D_2 (u_T). The exact location of this section in dimensional coordinates is $D_3 = 5440$ m^2 s^{-2}, $D_4 = 40$ km, $D_5 = 5 \times 10^{-5}$ s^{-1}, $D_6 = 2.7 \times 10^{-5}$ m^{-1}, and $D_7 = 0.19$. The qualitative dependence of F_{SST} on h_o and u_T is rather intuitive: fast-moving storms are less affected by the SST feedback effect, as are storms over deep oceanic mixed layers with high thermal and dynamical inertia. Surprising is the amplitude of the modelled feedback factors, which range from -10% to less

TABLE 2. Explored dimensional parameter ranges.

Parameter	Range
h_o	20 m ↔ 80 m
u_T	4 m s^{-1} ↔ 10 m s^{-1}
$\Delta p\|_{\mathrm{SST}}$	37 hPa ↔ 92 hPa
η	0.4 ↔ 1.0
f_o	5×10^{-5} s^{-1}
Γ	0.08 °C m^{-1}
$\mathcal{H}$	78% ↔ 87%

TABLE 3. Explored nondimensional parameter ranges.

Parameter	Range
N_1	250 ↔ 2500
N_2	30 ↔ 460
N_3	$5 \times 10^{-4} \leftrightarrow 2 \times 10^{-3}$
N_4	1.6 ↔ 10
N_5	0.13 ↔ 0.22

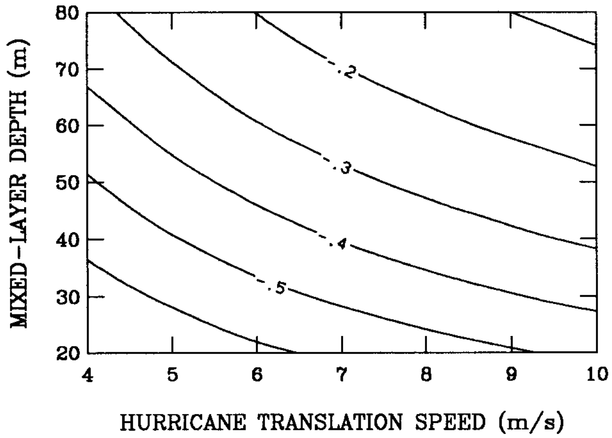

FIG. 6. The feedback factor F_{SST} as function of h_o and u_T. The contour interval is 10%. This cross section of the parameter space is taken at $\Delta p|_{\mathrm{SST}} = 68$ hPa, $\eta = 0.8$, $f_o = 5 \times 10^{-5}$ s^{-1}, $\Gamma = 0.08$°C m^{-1}, and $\mathcal{H} = 81\%$.

than -60%. These numbers suggest that the SST feedback effect plays a key role in setting hurricane intensity. This in turn also means that subsurface oceanic features such as fronts or synoptic eddies have the potential to significantly affect hurricane intensity.

While Fig. 6 illustrates the dependence of the SST feedback factor on h_o and u_T for a particular choice of $(D_i)_{i=3,7}$ the overall dependence of F_{SST} on (D_i) [or on (N_i)] cannot easily be displayed graphically. Therefore an analytic approximation to the dependence of F_{SST} on (N_i) is sought. While only an approximation to the model results, an analytic expression is the most concise summary of the shape of F_{SST} in the phase space.

Inspection of the model results suggested a power law dependence of F_{SST} on (N_i) of the form

$$F_{\mathrm{SST}}([N_i]_{i=1,5}) = \Phi(z), \tag{3}$$

with

$$z \equiv e^{\lambda_0} \prod_{i=1}^{5} N_i^{\lambda_i}, \tag{4}$$

where Φ is an unknown function and the exponents $[\lambda_i]_{i=0,5}$ are unknown coefficients. The set of 2083 samples of F_{SST} can now be used to determine the best-fit values of the unknowns. Let $\hat{\Phi}$ be the inverse of Φ. Then (4) can be written as

$$\ln[\hat{\Phi}(F_{\mathrm{SST}})] = \lambda_0 + \sum_{i=1}^{5} \lambda_i \ln(N_i), \tag{5}$$

which is linear in the unknowns $[\lambda_i]_{i=0,5}$. The function Φ cannot be optimized objectively without specifying a functional form. After detailed inspection of the data an exponential form was chosen:

$$\Phi(z) = \Phi_0 e^{-z}. \tag{6}$$

With these assumptions an iterative method can be used to determine the unknown parameters:

TABLE 4. Best-fit values of the regression coefficients.

Coefficient	Best-fit value
Φ_o	−0.87
λ_0	12.17
λ_1	−1.44
λ_2	−0.78
λ_3	−0.40
λ_4	−0.59
λ_5	0.46

Step 1. Initial guess: $\Phi_0 = -1$.
Step 2. Given Φ_0, perform a multilinear least squares regression to yield $[\lambda_i]_{i=0,5}$.
Step 3. Given values of $[\lambda_i]_{i=0,5}$ as result of step 2, perform a least squares regression to yield Φ_0.
Step 4. Go back to step 2 until Φ_0 does not change anymore between iterations.

This iterative method converges rapidly. The resulting best-fit values for the unknowns are listed in Table 4. Figure 7 displays the resulting analytic expression for F_{SST} as function of z together with all 2083 model runs. A histogram of the deviation of the fitted F_{SST} from the data is shown in Fig. 8; the standard deviation of the fitted F_{SST} from the data is $\sigma = 0.014$.

An analytic expression of the dependence of the SST feedback factor on the dimensional parameters $[D_i]_{i=1,7}$ can be obtained by use of Eqs. (2):

$$F_{\mathrm{SST}} = -.87e^{-z}$$

with

$$z = .55\left(\frac{h_o}{30\ \mathrm{m}}\right)^{1.04}\left(\frac{u_T}{6\ \mathrm{m\ s^{-1}}}\right)^{.97}\left(\frac{\Delta p|_{\mathrm{SST}}}{50\ \mathrm{hPa}}\right)^{-.78} \times \eta^{-.85}\left(\frac{f_o}{5\times10^{-5}\ \mathrm{s^{-1}}}\right)^{.59}\left(\frac{\Gamma}{8\times10^{-2}\mathrm{°C\ m^{-1}}}\right)^{-.40} \times \left(\frac{1-\mathcal{H}}{.2}\right)^{.46}. \tag{7}$$

Reference values for the seven dimensional parameters have been used to formulate the equation in a physically meaningful form. If all the parameters are equal to their reference values the parameter z has a value of $z = 0.55$ and the SST feedback factor is $F_{\mathrm{SST}} = -0.5$. Deviations from the reference values change the SST feedback factor in a physically intuitive way: a stronger negative feedback effect occurs when

- the oceanic mixed layer is thinner,
- the storm moves slower,
- the intensity potential is larger,
- the storm is of greater horizontal size,
- the storm occurs at lower latitudes,
- the thermal stratification below the oceanic mixed layer is stronger, and

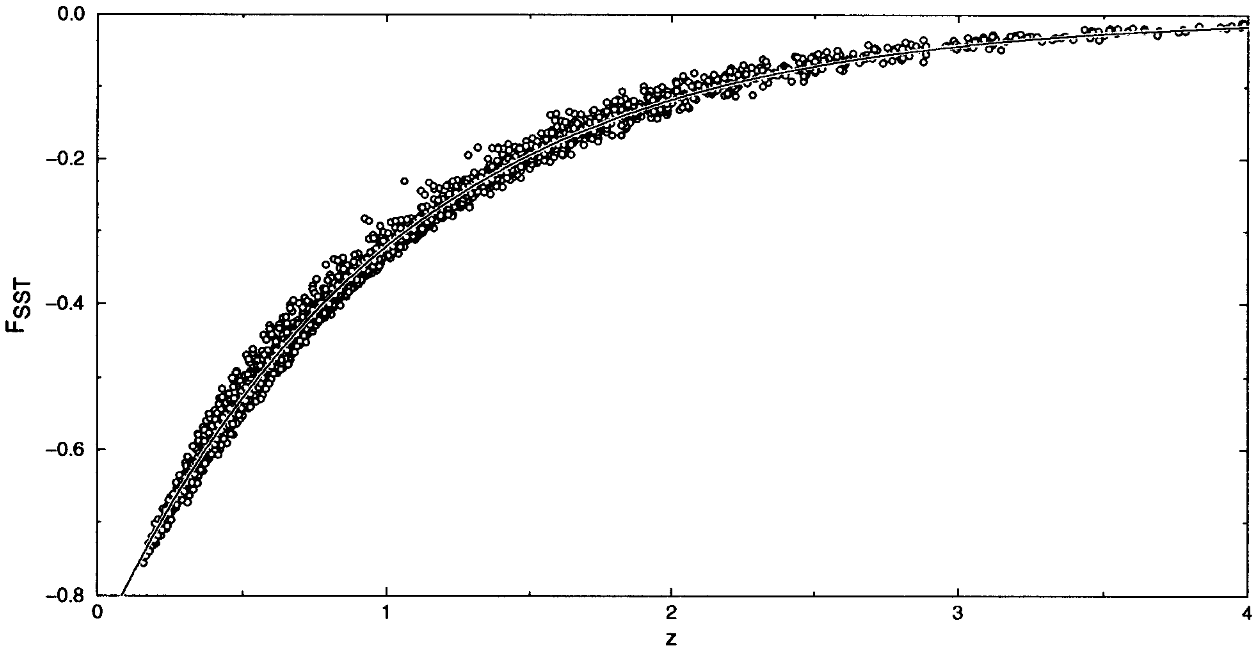

FIG. 7. The feedback factor F_{SST} as function of the parameter z for all model runs. The solid line is the best-fit function. Many of the 2083 data points are too close to the best fit line to be visible (see also Fig. 8).

- the relative humidity in the atmospheric boundary layer is higher.

Equation (7) is a very good approximation to the behavior of the coupled model in the explored region of the phase space as can be seen in Fig. 8. Its purpose is to summarize a rather complex physical process in a very concise fashion. Yet unlike the coupled model, the statistical regression is a purely mathematical tool. It does not know of the physics contained in the model equations. This is both its weakness and strength. It is weak because it cannot take advantage of the known laws of physics governing the problem and thus is valid strictly only in the sampled region of the phase space, and it is strong because it does not require knowledge of all relevant physical processes but rather considers the overall effect of these processes. The approach taken here therefore consists of two very distinct steps. In the first step a simple model of the coupled hurricane–ocean system is constructed. This involves selecting a number of physical processes that are believed to be relevant to the problem and need to be represented adequately in the model. In the second step the output from the coupled model is treated as given and a concise mathematical description of the data is sought. This second step much resembles the analysis of observational data. A final third step in which the data is approximated with a simple physical model rather than with a statistical model is beyond the scope of this paper and is the subject of ongoing research.

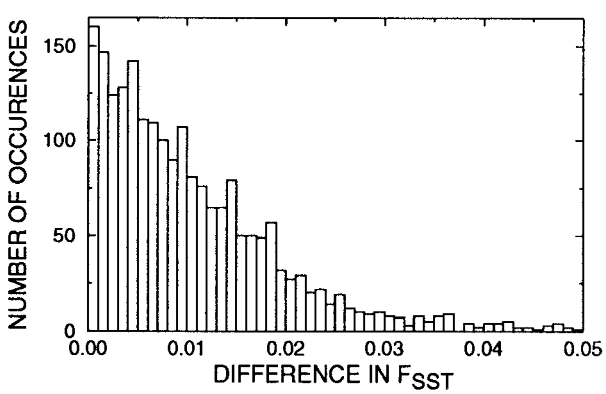

FIG. 8. Histogram of the difference between the modeled F_{SST} and the best-fit function.

6. Conclusions

Using a simple coupled hurricane–ocean model it was demonstrated that the interaction with the ocean significantly reduces the intensity of hurricanes. If the pressure deficit in the eye of the storm is taken as the intensity measure, the SST feedback effect can easily cut the intensity of a hurricane in half compared to a hypothetical storm over an ocean with constant SST. Unfortunately, observational data cannot be used to directly measure SST feedback factors because the necessary control storm over an ocean with constant SST does not exist.

Various environmental effects, such as that of background shear or of upper-tropospheric disturbances, are not included in the simple model. Similarly, the effect of special oceanic situations associated with, for example, warm-core rings, the Gulf Stream, or shallow basins and shelf regions, is not considered in the simple model. The chosen modeling approach *assumes* that for the majority of storms these additional effects are small compared to the SST feedback effect. Conversely, it is expected that individual storms in atypical environments are not well described by the simple model. Regardless of the validity of this basic assumption, it should be kept in mind that the SST feedback is superimposed onto all other processes affecting hurricane intensity, because it directly affects the most fundamental process of a tropical cyclone, the transfer of heat from the ocean to the atmosphere.

Theories for the intensity of tropical cyclones (e.g., Emanuel 1986, 1995; Holland 1997) suggest that over much of the tropical ocean and throughout most of the hurricane season there is the potential for very intense hurricanes. Yet only few of the observed storms develop to the maximum intensity predicted by those theories. The recent revision of Emanuel's theory (Bister and Emanuel 1998), which accounts for the dissipative heating in hurricanes, leads to an even bigger gap between the actually attained intensity and the maximum possible intensity. The authors believe that the SST feedback effect can account for much of this discrepancy.

The model results presented in this paper cast a new light on the effect of the ocean on hurricane intensity. Besides the large-scale SST field, the synoptic-scale subsurface ocean conditions significantly affect a hurricane's intensity. A successful intensity forecast therefore requires knowledge of the upper-oceanic conditions ahead of the storm. Such information could be collected on a routine basis with aircraft expandable bathythermographs as part of hurricane reconnaissance flights.

It is hoped that more attention will be focused on the role of the ocean in limiting hurricane intensity. Much of the theory of turbulent transfer processes both in the ocean and at the interface between ocean and atmosphere is based on laboratory experiments and on the extrapolation to hurricane conditions of measurements taken at low or moderate wind speeds. In light of the fundamental role these transfer processes play in supplying energy to the hurricane, this aspect of the hurricane problem seems to be one of the most promising for major improvements in hurricane intensity forecasting.

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