Cold wake of Hurricane Frances

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[1] An array of instruments air-deployed ahead of Hurricane Frances measured the three-dimensional, time dependent response of the ocean to this strong (60 ms⁻¹) storm. Sea surface temperature cooled by up to 2.2°C with the greatest cooling occurring in a 50-km-wide band centered 60–85 km to the right of the track. The cooling was almost entirely due to vertical mixing, not air-sea heat fluxes. Currents of up to 1.6 ms⁻¹ and thermocline displacements of up to 50 m dispersed as near-inertial internal waves. The heat in excess of 26°C, decreased behind the storm due primarily to horizontal advection of heat away from the storm track, with a small contribution from mixing across the 26°C isotherm. SST cooling under the storm core (0.4°C) produced a 16% decrease in air-sea heat flux implying an approximately 5 ms⁻¹ reduction in peak winds. Citation: D’Asaro, E. A., T. B. Sanford, P. P. Niiler, and E. J. Terrill (2007), Cold wake of Hurricane Frances, Geophys. Res. Lett., 34, L15609, doi:10.1029/2007GL030160.

1. Introduction

[2] Hurricanes draw their energy from the warm ocean and are therefore sensitive to its temperature [Emmanuel, 2003], with no storms developing for temperatures cooler than 26°C. Hurricane wind stress is mixed downward by ocean turbulence [Price et al., 1996], mixing the underlying cold water into the mixed layer and cooling it [Price, 1981]. The negative feedback caused by cold water under the storm core can, in models, reduce the storm intensity by up to 70% [Schade and Emmanuel, 1999]. There have been very few detailed observations of the structure of sea surface temperature (SST) beneath a hurricane. Satellite SST measurements commonly show a wake, 2–5°C cooler than the pre-storm waters behind the right-hand side of hurricanes. However, cooling underneath the central core of the storm is much less, 0–2°C [Cione and Ulthorn, 2003].

[3] SST change beneath hurricanes is sensitive to the pre-storm depth distribution of temperature; a thin layer of warm water cools more easily than a thick layer. The hurricane heat content, \( Q_{26} = \int_{Z_{26}} Tdz \), i.e., the heat contained between the 26°C isotherm depth \( Z_{26} \) and the surface, can be used as a supplement to SST to predict the intensity change of hurricanes [DeMaria et al., 2005]. Here, data from surface drifters and subsurface floats are combined to map the three-dimensional space-time evolution of ocean temperature in the vicinity of Hurricane Frances. The upper ocean response to this storm is shown both in the manuscript figures and in an animation included in the auxiliary material1.

2. Data

[4] Measurements of upper ocean temperature were made from oceanographic sensors air-deployed ahead of Hurricane Frances. Platforms included 27 surface drifters measuring SST, nine modified profiling SOLO floats [Davis et al., 1992] measuring from 200 m to the surface, three modified profiling EM-APEX floats measuring from 0–500 m before the storm and 30–500 m during it [Sanford et al., 2007], and two Lagrangian floats [D’Asaro and McNeil, 2007] measuring from the surface to about 50 m depth. Measurements focussed on the right-hand side of the storm, avoiding the shallow banks starting about 60 km to the left of its track. Black et al. [2007] describes these data in more detail.

[5] Temperature accuracy for the floats is better than 0.01°C. SST values were obtained from floats using the shallowest temperature measurement as long as this was within the mixed layer. Float SST data were smoothed to form a pre-storm SST field and offsets ranging from −0.72°C to 1.37°C (mean 0.15°C) were removed from the drifters to make them consistent with this field. Horizontal velocity was measured on the EM-APEX floats only. Drifter positions were obtained from system ARGOS. SOLO float positions were determined by GPS on the frequent float surfacings. Lagrangian and EM-APEX float positions were determined by interpolating between less frequent GPS positions using horizontal current profile measurements on the EM-APEX floats. All data with a resolution of less than 1 h were interpolated to hourly intervals.

[6] Track and wind data for Hurricane Frances were obtained from daily analyzed H*WIND fields based on all available measurements [see D’Asaro and McNeil, 2007]. Wind data from the day 246.75 analysis were used. Atmospheric boundary layer temperature, relative humidity, and wind speed were obtained from GPS dropsondes deployed from NOAA aircraft on day 246. Few probes reached 10-m altitude. Values at 10 m were estimated using the bottommost data point, as long as this was no higher than 30 m.

3. Ocean Response

[7] Figure 1 shows plan views of SST, the change in \( Z_{24} \), the change in \( Q_{26} \), and selected near-surface velocity vectors all in a storm-centered coordinate system, with the storm moving in the ‘−X’ direction. Only data from days 244–248 and longitudes 68°W–70.9°W are used, thereby excluding drifters and SOLO floats from the western portion of the array. The coordinate system curves by up to 65 km after

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day 246.7 to compensate for curvature in the storm track. The data (dots in Figure 1) are dense enough to accurately resolve the field, so that a simple mapping scheme (separation dependent Gaussian weighting with a scale of 20 km) is sufficient. Figure 1a uses floats and drifters; Figures 1b and 1c use only floats. The southernmost EM-APEX cannot be used to compute $Q_{26}$ from 246.02 to 246.68 because it has no mixed layer data during this time. Heat content is computed using potential temperature, not in-situ temperature, as it is the heat realizable at the surface, not the true thermodynamic heat, that affects hurricanes.

The sea surface temperature (Figure 1a) cools behind the storm at all locations. It is largest (2.2°C) in the cold wake, which is clearly offset from both the center of the storm and from the strongest winds. Less cooling occurs on the left-hand side of the storm (0.8°C) and under the central core (0.4°C). The upper layer velocity is also largest in the cold wake, consistent with the cold wake being formed by shear-driven mixing. The upper layer currents and shear will be most efficiently generated on the right-hand side of the storm where the wind stress rotates in a clockwise direction [Price, 1981].

Temporal variations in currents and isotherm depth occur at nearly the inertial period. The patterns of phase propagation, upward and away from the storm track, and of phase relationships between currents and isotherm depth, indicate the propagation of near-inertial waves downward and away from the storm. This can be seen, for example, by comparison with the simulations of Price [1981].

The heat content $Q_{26}$ (Figure 1c) reflects the patterns of both SST and isotherm depth. The low heat content behind the eye is due to upwelling, which reduces the thickness of the upper layer and thus the heat content. Heat changes due to upwelling are reversed by downwelling, thus $Q_{26}$ has similar values along $y = 0$ km at $x = -100$ and $x = -500$ km. In the cold wake $Q_{26}$ is reduced, but not $Q_{24}$, suggesting that vertical mixing reaches the 26°C isotherm but not the 24°C isotherm.

Figure 2a shows the depth–time, or equivalently $Z$–$Y$, evolution of the cold wake as viewed by the EM-APEX float, which traverses along the center of the cold wake [see also D'Asaro and McNeil, 2007; Sanford et al., 2007]. The 6-hour period of most rapid cooling (day 245.2–246.2) is associated with rapid downward growth of the mixed layer, due primarily to strong shear and reduced Richardson number [Sanford et al., 2007]. Successively colder isotherms enter the 20-m thick, stratified transition layer from below, descend with it, exit into the mixed layer and surface. The mixed layer reaches a maximum depth of about 100 m; the associated mixing, diagnosed from
changes in the distance between isotherms, reaches about 130 m and the 25°C isotherm. The vertical heat flux responsible for deepening the mixed layer is about 25 kW m\(^{-2}\) at the bottom of the mixed layer.

[12] Mixing penetrates below the 26°C isotherm, thereby decreasing \(Q_{26}\) by fluxing cold water upward across the isotherm. This moves the 26°C isotherm downward about 25 m relative to the 24°C, thereby cooling about 25 m of water by about 1–1.5°C. The overall effect is small, reducing \(Q_{26}\) by 25–37 m°C, about 16% of its initial value of about 180 m°C, but sufficient to significantly influence the spatial pattern of \(Q_{26}\).

[13] Figure 2b shows ocean heat content relative to several isotherms at this float. Heat contents \(Q_{23}\) and \(Q_{24}\) are nearly constant through day 245.9 implying small air-sea heat fluxes even though the storm’s eye has already passed and most of the SST cooling has already occurred. Bulk estimates of air-sea heat flux (see section 4) do not exceed 500 W m\(^{-2}\). Covariance estimates from the Lagrangian floats [D’Asaro, 2004] at the peak winds are 1000 ± 800 W m\(^{-2}\). These estimates are only a few percent of the fluxes due to mixing; air-sea fluxes are therefore negligible. The large changes in the heat content seen after day 245.9 for any reference isotherm colder than 25°C must therefore result from horizontal heat transport.

[14] Figures 3a, 3b, 3c, and 3d show selected y–z sections of potential temperature across the storm’s path. Additional frames are shown in an animation included as auxiliary material. Figure 3a shows the pre-storm conditions. The isotherms are nearly flat with a slight descent in the +y direction associated perhaps with the westward-going Antilles Current. The circular symbols show selected positions of the two Lagrangian floats. These cycle vertically across the 30-m-thick mixed layer following the vertical trajectories of mixed layer water parcels forced by the rapidly rising 22 m s\(^{-1}\) winds. The heat content \(Q_{24}\) (black line in Figure 3e) is nearly constant.

[15] Figure 3b shows a section at the time of maximum upwelling, approximately half an inertial period after the previous panel. The ocean has returned to a state very similar to that inertial period earlier. The cold wake has moved back southward and is aligned vertically and the heat content (green line in Figure 3e) is close to that of the initial state.

[16] The heat averaged from \(y = 0\) km to \(y = 160\) km and from the surface to the 24°C isotherm \((Q_{24})\) is plotted against the depth of the 24°C isotherm at \(y = 0\) in Figure 4 for each \(x\) from \(x = -200\) km to \(x = 700\) km. Initially, the isotherm is deep (130–140 m) and the heat content is high. The initial mixing \((x < 100\) km\) results in little change in

![Figure 2.](image-url)
Upwelling reduces the heat to a minimum near $x = 300$ km. However, as the upwelling relaxes, the heat returns along nearly the same line to a minimum near $x = 500$ km. These large reversible variations again show that the heat content changes are due to advection of heat across the northern and southern boundaries of the domain.

There is clearly a net upwelling, averaged over these oscillations, of about 15 m as required by the storm’s net wind stress curl. Figure 4 shows that a net upwelling implies a net decrease in ocean heat content beneath the storm due to the associated net outward advection of surface warm water. This explains the average heat content change seen in Figure 1c. The upwelling geostrophically produces a westward surface flow north of the storm track.

4. Ocean’s Effect on Storm Intensity

[20] Emmanuel [2003] reviews simple models of hurricane intensity and finds the maximum wind speed $V_{\text{max}}$ related to the surface flux of enthalpy $F_k$

$$V_{\text{max}}^2 \approx \frac{T_i - T_o}{\rho C_D F_0} F_k$$

(1)
similar relationship is evident for relative humidity RH (%) between 10-m temperature $T_{10}$ (C) and wind speed $U_{10}$ (ms$^{-1}$)

$$T_{10} = 29 - U_{10}/14, \tag{2}$$

with a typical deviation from this relationship of 1°C. Far from the storm, the air temperature is close to the typical SST of 29.3°C. At maximum winds it is 4.6°C colder. A similar relationship is evident for relative humidity RH (%)

$$RH_{10} = 70 + U_{10}0.75 \quad U_{10} < 40 \tag{3}$$

$$RH_{10} = 100 \quad U_{10} > 40 \tag{4}$$

with a typical deviation of 5% at lower wind speeds. All 13 dropsondes deployed closer than 40 km to the storm center showed 100% humidity, except for one that was clearly in the eye. Heat fluxes were computed using temperature and humidity fields estimated from these relationships, the wind field shown in Figure 1 and standard bulk formulae. The enthalpy flux is approximated as a constant specific heat at constant pressure times the heat flux. An exchange coefficient of $0.8 \times 10^{-3}$, appropriate for hurricane winds, was used for both latent and sensible heat [Black et al., 2007]. Any effects of spray at high winds are therefore ignored.

The effect of SST cooling on fluxes in the storm core is modest. Prestorm SST has a range of 29.3 ± 0.05°C. The heat flux averaged over a radius of 50 km (75 km) from the storm center is 84 ± 2% (82 ± 1%) of that estimated using a constant SST set to prestorm values. Equation (1) therefore predicts that the winds in Hurricane Frances are 92 ± 2% of those expected in the absence of cooling. Estimating an average peak winds of 60 ms$^{-1}$ (Figure 1), the average peak wind without cooling would be 5 ± 1 ms$^{-1}$ higher.

Larger reductions in heat flux are found in the outer parts of the storm where the small but persistent SST cooling reduces the heat flux to 77 ± 2% (61 ± 1%) of the constant SST value when averaged over a 100-km (300-km) radius. Schade and Emmanuel [1999] indicate that these changes will not have a significant effect on the storm intensity.

Larger reductions in heat flux and storm intensity would be possible if the cold wake were closer to the storm core, as might occur for a more slowly moving storm. If, for example, the SST field is moved 100 km in the $-x$ direction and 50 km in the $-y$ direction, so as to place the nose of the cold wake near the storm center, the heat flux is about 62% of the constant SST value averaged over any radius outside of the eye.

5. Summary and Discussion

The three-dimensional response of the ocean to Hurricane Frances was measured using an air-deployed array of floats and surface drifters. Major features include: [26] (1) Sea surface temperature is reduced by up to 2.2°C. The largest reduction occurs in a 50-km wide cold wake centered 60–85 km to the right of the storm track. This reduction is almost entirely due to the upward mixing of water warmer than 24°C rather than due to air-sea fluxes.

(2) Currents of up to 1.6 ms$^{-1}$ are generated in the mixed layer with the strongest currents in the cold wake. These oscillate and disperse downward and horizontally as near-inertial frequency internal waves. The shear associated with these currents is the major cause of mixing and thus SST cooling [Sanford et al., 2007].

(3) The thermocline shoals by up to 50 m behind the storm and oscillates inertially thereafter. The net upwelling is about 15 m.

(4) Heat content above the 26°C isotherm, i.e., the hurricane heat content, decreases behind the storm due primarily to the mean upwelling with a small part, about 16%, due to mixing of cold water upward across the 26°C isotherm.

(5) Heat content behind the storm varies both spatially and temporally as the oscillating vertical and horizontal currents advect heat in three dimensions. The change in heat content from the pre-storm value averaged along cross-track sections in the storm’s wake varies by a factor of 6 depending on position. Accurate estimates of the change in heat content can therefore not be made from a few isolated measurements in the wake.

(6) Sea surface temperature under the storm core cools by 0.4°C, reducing the air-sea heat flux by about 16%. This negative feedback from ocean mixing to the storm intensity is estimated to decrease the peak winds by about 5 ms$^{-1}$ to the observed value of 60 ms$^{-1}$.

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