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Highly resolved observations and simulations of the ocean response to a hurricane

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[1] An autonomous, profiling float called EM-APEX was developed to provide a quantitative and comprehensive description of the ocean side of hurricane-ocean interaction. EM-APEX measures temperature, salinity and pressure to CTD quality and relative horizontal velocity with an electric field sensor. Three prototype floats were air-deployed into the upper ocean ahead of Hurricane Frances (2004). All worked properly and returned a highly resolved description of the upper ocean response to a category 4 hurricane. At a float launched 55 km to the right of the track, the hurricane generated large amplitude, inertially rotating velocity in the upper 120 m of the water column. Coincident with the hurricane passage there was intense vertical mixing that cooled the near surface layer by about 2.2°C. We find consistent model simulations of this event provided the wind stress is computed from the observed winds using a high wind-speed saturated drag coefficient.

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1. EM-APEX Floats and Their Deployment in CBLAST

[2] We have developed an autonomous float, called EM-APEX, that is the combination of an ElectroMagnetic velocity profiler [*Sanford et al.*, 1978] carried onboard an Autonomous Profiling EXplorer (Webb Research Corporation). EM-APEX floats can be air-deployed and can operate under severe wind and sea state conditions. They vary buoyancy to profile the water column, measuring temperature, salinity and pressure to CTD accuracy and relative horizontal velocity by the EM sensor. GPS positional fixes are made while at the surface.

[3] Three prototype EM-APEX floats were air-deployed about one day ahead of Hurricane Frances as it passed to the north of Hispaniola. This deployment was made from a C-130 operated by the U. S. Air Force Reserve 53rd Weather Reconnaissance Squadron in support of the ONR-sponsored Coupled Boundary Layer Air-Sea Transfer experiment (CBLAST) field program [*Black et al.*, 2007]. The floats were deployed along a line perpendicular to the hurricane track; float 1633 emphasized here was deployed about 55 km to the right of the hurricane path and close to the radius of maximum winds, 40 km (see the auxiliary material).[1] A second EM-APEX float was deployed very near the hurricane track, and a third was deployed about 110 km to the right of the track.

[4] For this deployment the floats profiled to 500 m to define the ocean initial condition. After about 10 h they profiled between 30 m and 200 m as intensively as possible during the hurricane passage, giving roughly hourly temporal resolution. About six days after deployment the floats surfaced and transmitted their accumulated data via an Iridium satellite phone link.

2. Modelling the Upper Ocean Response to a Hurricane

[5] The numerical ocean model used to simulate the ocean response is three-dimensional and time-dependent, and solves the momentum, heat, and salt budget equations on a fixed grid [*Price et al.*, 1994]. The grid interval is 10 m in the vertical and uniform down to 250 m where it expands and continues on to 750 m. The horizontal resolution is 5 km and uniform. The only subgrid-scale process is shear-driven vertical mixing, which this model parameterizes by the one-dimensional upper ocean model of *Price et al.* [1986], and hence the three-dimensional ocean model is referred to as 3DPWP. The ocean initial condition is taken to be a state of rest, homogeneous horizontally, and with vertical profiles of temperature and salinity taken from the initial EM-APEX profile data (see auxiliary material). The actual initial condition observed by the floats was nearly uniform in surface temperature but included variation in the near-surface salinity of ±0.2, leading to small horizontal differences in the near-surface static stability. Subsurface density gradients related to a mesoscale eddy clearly influence the floats' drift over their 5-week deployment, but numerical experiments that include similar baroclinic structure do not indicate a significant effect on the high-frequency and short-term response to the hurricane that is emphasized here.

[6] The numerical model requires a wind stress field as a function of time, i.e, $\tau(x, y, t)$ over the entire domain that might affect the ocean response. We used the HWIND analysis provided by the Hurricane Research Division of the NOAA/Atlantic Oceanographic and Meteorological Laboratory [*Powell et al.*, 1998], which is a highly resolved, 10-m wind field analysis for 18 UTC on 1 September. The HWIND field was moved over the ocean model at the translation speed of Frances over the CBLAST region, $U_h = 5.5$ m s^{-1}.

[7] To estimate the wind stress, which is by far the most important atmospheric variable so far as the ocean model is concerned, we employed the usual bulk transfer formula,

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[1] Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2007gl029679. Other auxiliary material files are in the HTML.

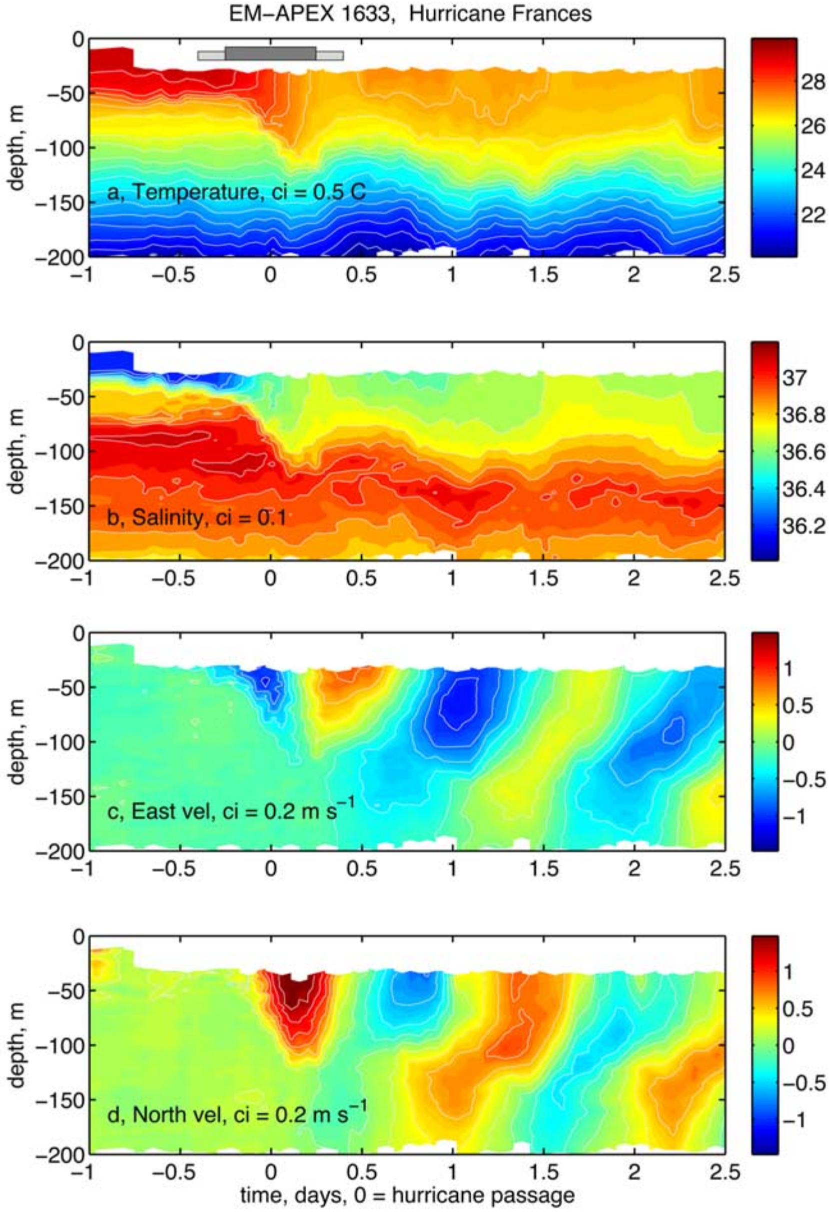

Figure 1. (a) Temperature and (b) salinity measured by EM-APEX float 1633 that was air-deployed about one day in advance of Hurricane Frances and 55 km to the right of the track. The ordinate is depth and the abscissa is time in days, with time = 0 being the closest passage of Hurricane Frances (1700 UTC on 1 September). The grey and dark grey bars show the time interval when estimated wind stress was greater than 0.5 and 2.0 Pa. Notice the change in profiling depth interval at time = −0.8 days. (c) East and (d) north components of horizontal velocity measured by float 1633. Here and in subsequent analysis we have subtracted a small, pre-hurricane mean velocity, 0.15 m s^{-1} to the west north west.

$\tau = \rho_a \, Cd \mathbf{U_{10}} U_{10}$, where ρ_a is air density, Cd is the drag coefficient, and U_{10} is the 10-m wind from HWIND. Two different drag coefficients were tested. The well-established formula of *Large and Pond*'s [1981], $Cd = (0.49 + 0.065U_{10}) \times 10^{-3}$, was compiled from many separate studies of stress and wind speed at moderate to low wind speeds, $U_{10} \leq 25$ m s^{-1}. Using this drag coefficient at the highest wind speeds of Frances amounts to an extrapolation well beyond the wind speed range accessible to *Large and Pond* [1981], and hence we term our use the 'extrapolated' Large and Pond Cd. *Powell et al.* [2003] made use of GPS wind sondes from hurricanes to find that Cd increased with U_{10} in parallel with *Large and Pond* [1981] up to about 30 m s^{-1}, but then leveled off and declined at still larger wind speeds: $Cd = [1.7\ 2.0\ 1.8\ 1.5] \times 10^{-3}$ for $U_{10} = [28\ 34\ 40\ 50]$ m s^{-1} [*Powell et al.*, 2003, Figure 3c]. The reported uncertainty on Cd is substantial, about ±20% (95% confidence limits) at any specific U_{10} but the saturation or decrease at high wind speeds is well-defined, and hence we refer to this as a high wind-speed saturated Cd. *Donelan et al.* [2004] inferred a similar result from laboratory studies. We have had to extrapolate *Powell et al.*'s [2003] result as well, and have assumed that Cd remains constant at 1.5×10^{-3} for wind speeds greater than 50 m s^{-1}.

[8] These drag coefficients have been calibrated against stress estimates made in the lower atmosphere and not

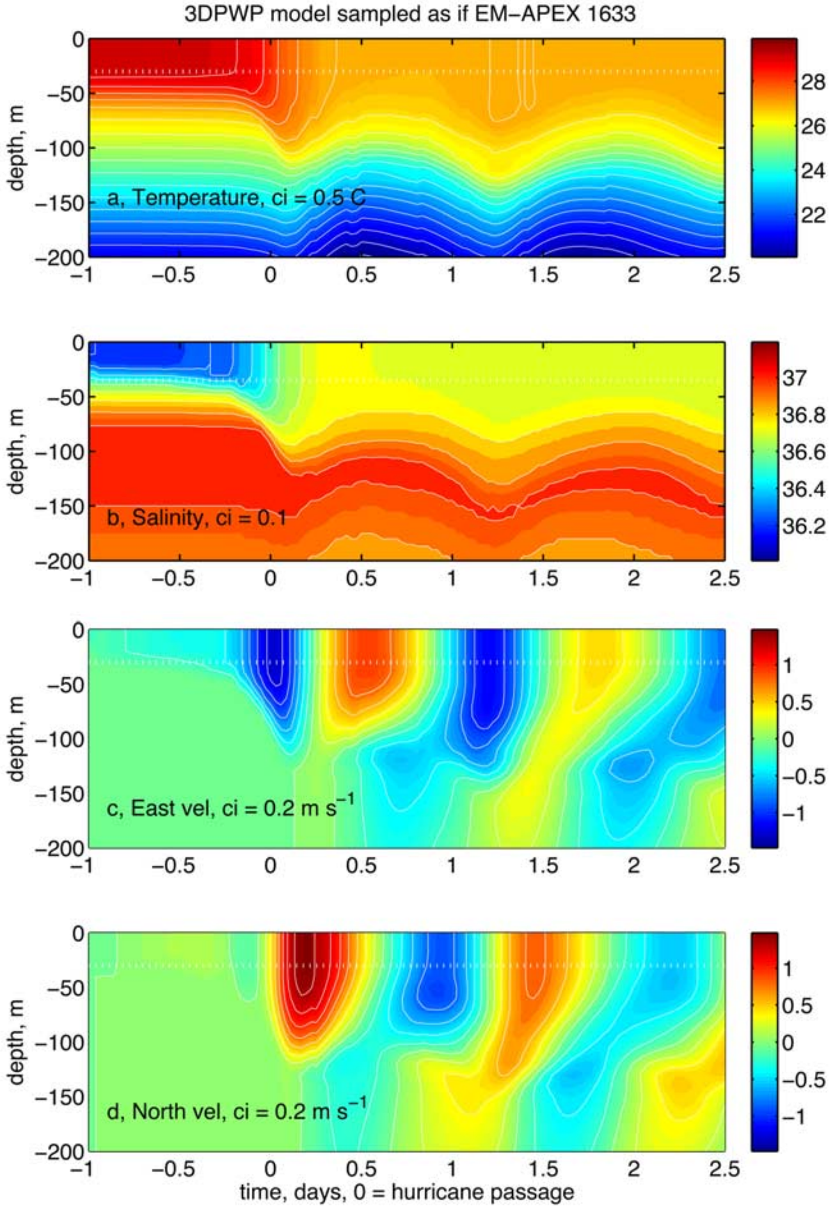

Figure 2. (a) Temperature and (b) salinity computed by the 3DPWP model. The solution was sampled in the horizontal starting at X_o = 55 km, and then advected by the horizontal velocity as if an EM-APEX float. The dashed white line at 30 m depth is the approximate upper limit of EM-APEX sampling during and just after the hurricane passage. (c) East and (d) north components of horizontal velocity computed by the 3DPWP model.

against the stress in the upper ocean that we require for an ocean model. The lower atmospheric and upper oceanic stresses could differ owing to non-stationary surface gravity waves [*Chen et al.*, 2007; *Black et al.*, 2007]. The EM-APEX horizontal velocity data available in this study afford an opportunity to check the consequences of these *Cd* values against oceanic observations (section 3.2, Parameterized Features/Dynamics).

3. Comparison of the Model Solutions and the EM-APEX 1633 Field Data

[9] To compare the ocean model solution with EM-APEX float data (Figures 1 and 2) the model fields are sampled along a simulated float track that begins where the EM-APEX floats were launched, X_o = 0, 55, and 110 km, and then advected with the model-computed horizontal velocity that is depth-averaged from 30 to 200 m depth.

[10] To continue this comparison we sort the phenomenon into those that are well resolved, in the sense that similar structure would be computed reliably by any other three-dimensional ocean model driven by the same hurricane, and those dependent upon parameterizations, and so could be different from one model to the next.

3.1. Resolved Features/Dynamics

3.1.1. Velocity

[11] To a first approximation the surface layer velocity is a clockwise-rotating inertial motion that is driven (locally) by the time-dependent wind stress of the moving hurricane

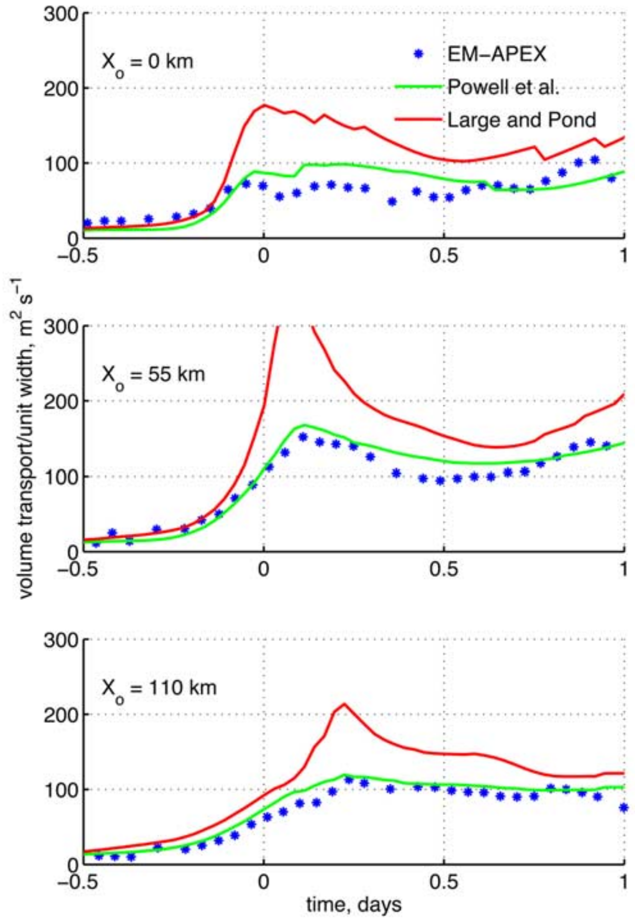

Figure 3. The volume transport/unit width, *M*, estimated from three EM-APEX floats (blue points) and as computed from the 3DPWP model. The model solutions are shown by the red and green lines which correspond to the solution computed using the extrapolated *Large and Pond* [1981] *Cd* (red line) or the high wind-speed saturated form of *Powell et al.* [2003] (green line). Uncertainty estimates on the latter are shown in Figure 4. Notice that the maximum value of *M* occurs at later times with increasing distance to the right of the track. The time-dependence of *M* after the hurricane passage, time ≥0.5 days, is due mainly to vertical advection and the resulting pressure gradient, i.e., to inertial pumping.

[*Zedler et al.*, 2002]. The wind stress vector rotates clockwise with time on the right side of the track and thus is partially resonant with inertial motions. The wind stress turns anti-clockwise with time on the left side of the track, which is anti-resonant. The result is that the amplitude of the surface layer velocity is highly asymmetric across the track, being considerably stronger on the right side than the left. In the model solution, the surface layer velocity is near a maximum at the site of float 1633, launched 55 km to the right of the track.

3.1.2. Inertial Pumping and Energy Dispersion

[12] The divergence of the surface layer horizontal velocity field produces near-inertial period up- and downwelling, also termed inertial pumping, which has an amplitude of about ±20 m in the upper thermocline (Figures 1a and 1b) and clearly evident in the model solution (Figures 2a and 2b). This vertical displacement of the mass field produces a hydrostatic pressure perturbation that couples the surface layer with the thermocline. To a second approximation the velocity is a *near*-inertial motion having a frequency that is blue-shifted by the pressure gradients. Thus the velocity and density seen here locally have the properties of an inertial-internal wave field that disperses energy and momentum from the surface layer, which is directly forced by the hurricane wind stress, into the thermocline. This downward energy dispersal is a fully resolved feature that would be found in any comparable three-dimensional ocean model solution.

3.2. Parameterized Features/Dynamics

[13] Other aspects of the simulated upper ocean response are dependent upon parameterizations that are intended to represent unresolved, small-scale, turbulent processes. Presuming that wind speed is given, the first of these is the parameterization of wind stress, which is of great importance in setting the amplitude of the ocean response. Vertical mixing within the upper ocean must also be parameterized, and is of importance for the amplitude of the surface layer velocity and especially for the cooling of SST.

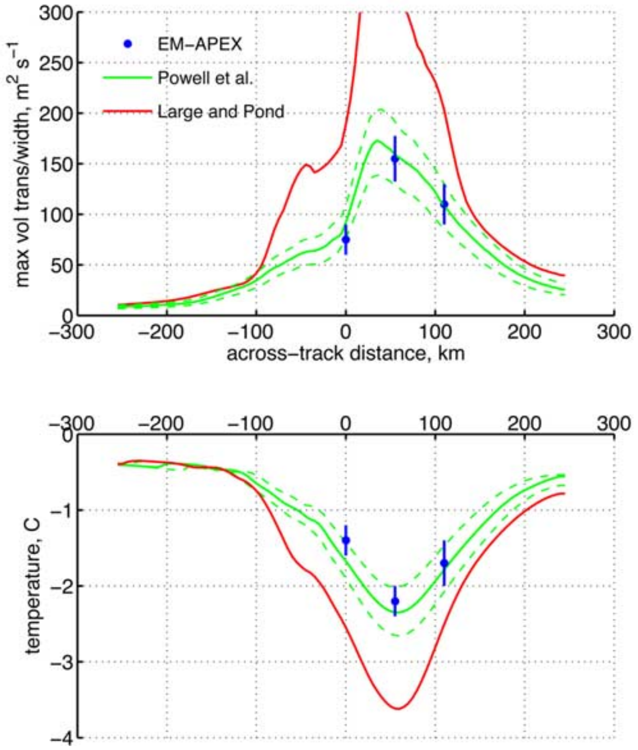

Figure 4. (top) The across-track profile of the maximum *M* during and just after the hurricane passage. The three blue points are estimates from EM-APEX floats. The red and green lines are from the model solution wherein stress was computed using the extrapolated *Large and Pond* [1981] *Cd* and the *Powell et al.* [2003] *Cd*, respectively. The dashed green lines show the effect of a systematic ±20% variation imposed on the latter. (bottom) The across-track profile of the cooling of surface layer temperature is estimated from EM-APEX floats (three blue points and bars) and computed by the numerical ocean model (red and green lines as above). Note that the across-track profiles of maximum *M* and of surface layer cooling are mirror images when reflected about the x-axis.

[14] To examine the wind stress parameterization in near isolation from the vertical mixing parameterization we have analyzed a depth-integrated variable, the volume transport per unit width, M, estimated from EM-APEX data as

$$M = \int_{-200}^{-z_s} |\mathbf{V}| dz + z_s |\mathbf{V}(z = z_s)|, \qquad (1)$$

where z_s is the shallowest depth sampled, usually 30 m, and 200 (m) is the deepest depth sampled. The time-dependence of M is shown in Figure 3 and the maximum value of M during and just after the hurricane passage, $-0.5 \leq \text{time} \leq 1.0$ days, is shown as a function of the across-track distance in Figure 4 (top). The second term of equation (1) represents the near-surface layer that was not sampled by EM-APEX; the M contribution from this near-surface layer was estimated by continuing the shallowest measured velocity to the surface. The blue bars shown with the EM-APEX derived estimates of the maximum M (Figure 4, top) are ± the largest magnitude of the second term. In the model solution we have $z_s = 0$. M omits any information regarding velocity direction (but see Figures 1c, 1d, 2c, and 2d).

[15] When the wind stress is computed using *Powell et al.*'s [2003] drag coefficient (together with the HWIND wind field described in section 2) the magnitude of the resulting, model-computed M compares reasonably well with M estimated from the EM-APEX observations (Figures 3 and 4, top). On the other hand, the extrapolated *Large and Pond* [1981] *Cd* gives at least 50% too much M for locations within 100 km of the track (and less in outlying regions where the wind speed was less). Similarly, wind stress computed from *Powell et al.*'s [2003] or *Donelan et al.*'s [2004] *Cd* values yields reasonable values of SST cooling (Figure 4, bottom) while the extrapolated *Large and Pond* [1981] *Cd* gives excessive cooling, up to 1°C near the track, though this is not independent of vertical mixing. These results, especially the comparison of M, are strongly supportive of the application of a high-wind speed saturated *Cd* for the very high wind speed conditions of a hurricane, $U_{10} \geq 30$ m s^{-1}.

4. Remarks

[16] The EM-APEX float data show the horizontal velocity response in as much detail as they show the response of temperature and salinity. The most fundamental conclusion is that the scalar fields (temperature, salinity, and density) and velocity are very closely coupled. Even if one's interest was mainly the SST cooling response, the velocity field is crucially involved, not only by advecting the thermal field vertically and laterally, but also by causing vertical mixing through shear flow instability (not shown here).

[17] An important corollary of our main result is that model solutions for SST cooling are sensitive to the wind stress and thus to the drag coefficient. These results are supportive of either of the new, high wind-speed saturated forms deduced by *Powell et al.* [2003] or *Donelan et al.* [2004]. We acknowledge that this is not unexpected, given that *Powell et al.*'s [2003] *Cd* was developed from hurricane wind observations. It would be very useful to know if the sensible heat and water vapor exchange coefficients exhibit any comparable wind speed variation.

[18] While the new wind-speed dependent *Cd* values give overall positive results and represent a significant advance, we doubt that they represent the final word on wind stress estimation in hurricanes. Our simulations show that the model-computed M and model-computed SST cooling are consistent with the observed values at the two positions to the right of the track, but are somewhat larger, by roughly 20%, than observed along the track (Figure 4). This kind of model error could come from any of several sources, viz., an asymmetry of Hurricane Frances that was lost in the wind field analysis (section 2), a surface gravity wave-induced, azimuthal dependence of *Cd* not defined by *Powell et al.* [2003], or possibly undefined, pre-hurricane oceanic variability. Additional case studies that include in situ observations from the left of the hurricane track along with detailed observations of hurricane winds and surface gravity waves will likely be required to learn whether these errors are random or systematic.

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