reach their maximum values at distances comparable to the ones found for the previous transect. Even in this section, tangential velocities decrease quite rapidly with depth, mainly within depths between 80 and 110 m, giving further indication of the shallow nature of Cyclone *Opal*. Tangential velocities in Transect 4 never reach near zero values as in Transect 3 since the transect did not pass through the center of the eddy.

Vertical and horizontal shears of velocity were computed by using finite differencing of the following partial differential equations:

$$\frac{\partial \bar{U}}{\partial z} = \left(\left(\frac{\partial C_\theta}{\partial z} \right)^2 + \left(\frac{\partial C_r}{\partial z} \right)^2 \right)^{1/2} \tag{2}$$

$$\frac{\partial \bar{U}}{\partial d} = \left(\left(\frac{\partial C_\theta}{\partial d} \right)^2 + \left(\frac{\partial C_r}{\partial d} \right)^2 \right)^{1/2} \tag{3}$$

where C_θ and C_r are tangential and radial components of velocity, respectively, and d is the distance along the transect. None of the velocity data were discarded for computing the two quantities.

Vertical sections of vertical and horizontal shear from Transects 3 and 4 are shown in Fig. 16A to D. Contour maps of the two quantities were superimposed on density contours in order to determine to what extent the shear distribution is related to the density field. These vertical sections show features that are common to both transects. Fig. 16A and C shows that maximum values of vertical shear are found within 25–35 km of the center where velocities are usually higher, and that they roughly follow the doming of the $\sigma - t_{24}$ isopycnal surface. Again, this surface generally coincides with the depth of the mixed layer. This indicates that the thermocline most likely acts to prevent a deep penetration of the cyclonic circulation, and confines the dynamical structure of *Opal* within the surface mixed layer. Vertical sections of horizontal shear in Fig. 16B and D do not display any major structures. However, there are two narrow areas of high values limited to the upper 100 m that occur close to the center of the eddy. These peaks occur in the areas where tangential velocities increase linearly with radial distance from the center of the eddy. Along Transect 4 two other shallow areas of high values of horizontal shear occur at distances of 60 and 120 km. From Fig. 16D, it is apparent that these two peaks arise from sharp variations of the radial component of velocity rather than from variations of the tangential component.

Vertical sections of angular velocity (C_θ/r) from Transects 3 and 4 are shown in Fig. 17A and B, respectively. Values of angular velocity are highly sensitive to radial distance, and even small tangential velocities result in very large values of angular velocity when divided by small radial distances. For this reason, the tangential velocities from which angular velocities were computed are the same ones used in Fig. 15A and C. Vertical sections of angular velocity show similar structure to those of the vertical sections of tangential velocity for both transects. As expected, Transect 3 displays a more symmetrical distribution of angular velocities than observed for Transect 4. Transect 3 angular velocity distribution is also characterized by a region of minimum values that occur close to the center of the eddy where tangential velocities decay to very small values. An analogous minimum region is not evident in the angular velocity distribution of Transect 4; as expected, less symmetry is seen in the angular velocity of Transect 4. The less accurate estimated position of the eddy center for Transect 4, which results from the offset of the transect from the true center of the eddy, likely explains part of the asymmetry. Both transect sections show areas of high values of angular velocity that are bounded by zones of sharp gradients. While these areas are relatively shallow in both transects, their horizontal extent is much broader in Transect 3 than in Transect 4. Again, this difference between the two transects likely arises from the fact that the two transects crossed *Opal* at different distances from its center. As already mentioned, the areas characterized by similar values of angular velocity can be used to roughly define where the eddy rotates as a solid-body. According to angular velocity data for the two sections, the portion of Cyclone *Opal* that was in near solid-body rotation was roughly 50–60 km in diameter, and hardly reached depths greater than 100–130 m. Thus, from a dynamical perspective, Cyclone *Opal* was a relatively shallow feature and was most likely limited to the mixed-layer region.

3.4. Potential vorticity

Important information concerning the dynamics of a vortex can be inferred from the analyses of the various terms that contribute to the equation for conservation of potential vorticity (e.g., Olson, 1980; Simpson et al., 1984). This equation is derived by taking the curl of the momentum equations and then the scalar product of the resulting vorticity equation and the gradient of potential density (Pedlosky, 1979). In cylindrical coordinates, the conservation of potential vorticity can be expressed as

$$\frac{D}{Dt}\left[\frac{\partial \rho}{\partial r}\left(\frac{1}{r}\frac{\partial w}{\partial \theta} - \frac{\partial C_\theta}{\partial z} \right) + \frac{1}{r}\frac{\partial \rho}{\partial \theta}\left(\frac{\partial C_r}{\partial z} - \frac{\partial w}{\partial r} \right) + \frac{\partial \rho}{\partial z}\left(\frac{C_\theta}{r} + \frac{\partial C_\theta}{\partial r} - \frac{1}{r}\frac{\partial C_r}{\partial \theta} + f \right) \right] = 0 \tag{4}$$

The quantity inside the brackets is the potential vorticity normal to isopycnal surfaces. The terms in parentheses are the components of the relative (ζ) and planetary (f) vorticity assuming a β-plane approximation. These terms are modulated by the spatial derivatives of the potential density which provide an effective length scale of the vortex.

ADCP and CTD observations were used to estimate the order of magnitudes of the terms in Eq. (4). The Coriolis parameter f was chosen to be $4.9 \times 10^{-5}\,\mathrm{s}^{-1}$ (average value for the latitudinal extent of the eddy), and is taken to be constant because of the relatively short north-south scale of *Opal* (i.e., f-plane approximation). Rough estimates of vertical velocities (w) were computed by integrating the continuity equation. According to the scaling results, the potential vorticity, π, of Cyclone *Opal* can be expressed to a first order of approximation by the equation

$$\pi = \frac{\partial \rho}{\partial z}\left(\frac{C_\theta}{r} + \frac{\partial C_\theta}{\partial r} + f \right) \tag{5}$$

where $\partial\rho/\partial z$ is the vertical gradient of density; C_θ/r the angular velocity; and $\partial C_\theta/\partial r$ the radial gradient of tangential velocity. This approximation was used to compute π for each transect.

Velocity and density fields are characterized by different horizontal and vertical resolutions. For this reason, the first step in the analysis was to interpolate one of the two variables over the grid of the other one. CTD data are very well resolved in the vertical but have poor horizontal resolution. On the other hand, ADCP data are characterized by slightly coarser vertical resolution, but much finer horizontal resolution. In order to maintain a good horizontal resolution in the data, we chose to interpolate the density measurements over the grids of the ADCP measurements. The vertical gradients of potential density and the radial gradients of tangential velocity were then computed by finite differencing the partial derivatives in Eq. (5). These gradients, being staggered with respect to the velocity grid, were then interpolated again over the ADCP data grid in order to multiply each term within the parentheses by the vertical density gradient and then to sum them together.