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The two-way coupling between a deep-water wave and a current vortical circulation with an upwelling or downwelling

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A theory is developed to investigate two-way, wave-current coupling involving significant vertical currents. Specifically, it concerns deep-water, surface gravity waves and current circulations having a vortex whose axis is nearly parallel to the wavenumber. Examples of such circulations include Langmuir circulation and some submesoscale frontal circulation. To overcome the difficulties occurring in Eulerian theories at the heights between the wave troughs and crests, this theory is developed with a coordinate system which follows the water surface. The wave solutions are analytically obtained to the order accurate enough to reveal the current effects on waves. The results show four types of higher-order wave solutions influenced by 1) the vertical current, 2) a vertical shear of the horizontal current, 3) a mean wave momentum, and 4) gradients of the wave properties. The Doppler-shift velocity is found to deviate from the conventional value as the current structure becomes narrower. The vortical circulation may also affect the evolution of the wave action density. Using the current-influenced wave solutions, the average influences of the waves on the averaged flows are explicitly evaluated. Because some averaged flows may violate the incompressibility and become numerically unsolvable, the theory derives an averaged flow satisfying the incompressibility. A wave effect on this averaged flow is similar to a force known as the vortex force or Stokes-shear force in previous theories. However, it may have a critical difference from the previous one due to the Doppler shift effect.