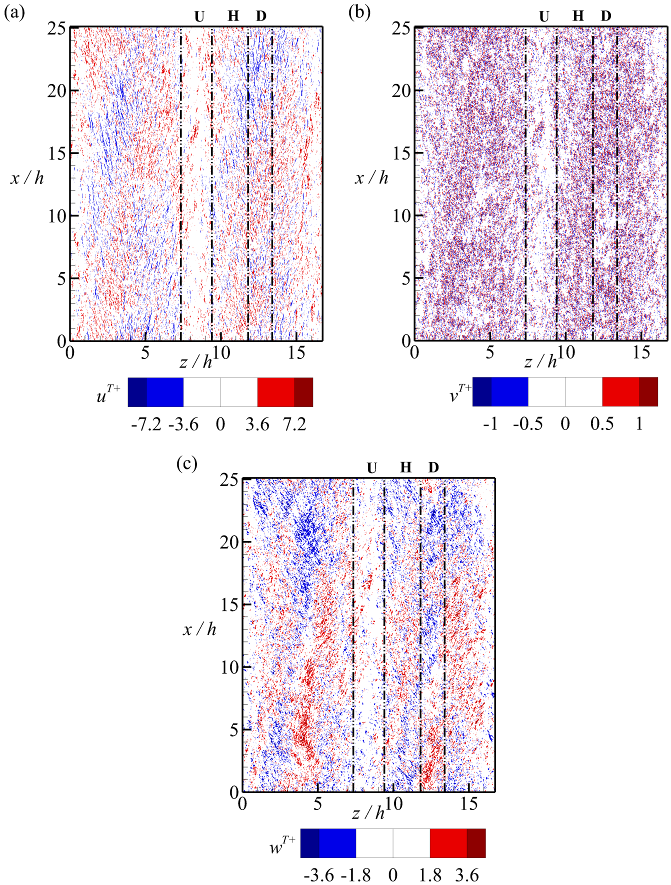

FIGURE 1. Instantaneous fields of (a) u^T, (b) v^T, and (c) w^T on the x–z plane near the bottom (located at $y/h = 0.015$). The results of case 1 are shown.

A. Instantaneous field of small-scale turbulence

Figure 1 shows the contours of the instantaneous background turbulence velocity fluctuations u_i^T near the water bottom at $y/h = 0.015$. As shown in figure 1(a), the magnitude of u^T is larger in the D-region than in the H- and U-regions. Moving from the D-region to the U-region, the magnitude of u^T decreases gradually. Similar to u^T, as shown in figures 1(b) and 1(c), the intensities of v^T and w^T are stronger in the D-region than in the U-region. The results shown in figure 1 indicate that the background turbulence is respectively enhanced and suppressed in the regions with positive and negative large-scale streamwise velocity fluctuations.

Figure 2 shows the contours of u_i^T in the x–z plane at $y/h = 1.985$. Similar to the observation in the near-bottom region (figure 1a,b), the magnitudes of u^T and v^T near the surface are larger in the D-region than in the U-region (figure 2a,b). The localizing effect on the background turbulence spanwise velocity w^T is different from that on u^T and v^T near the water surface. As shown in figure 2(c), the intensities of w^T in the D- and U-regions are comparable.

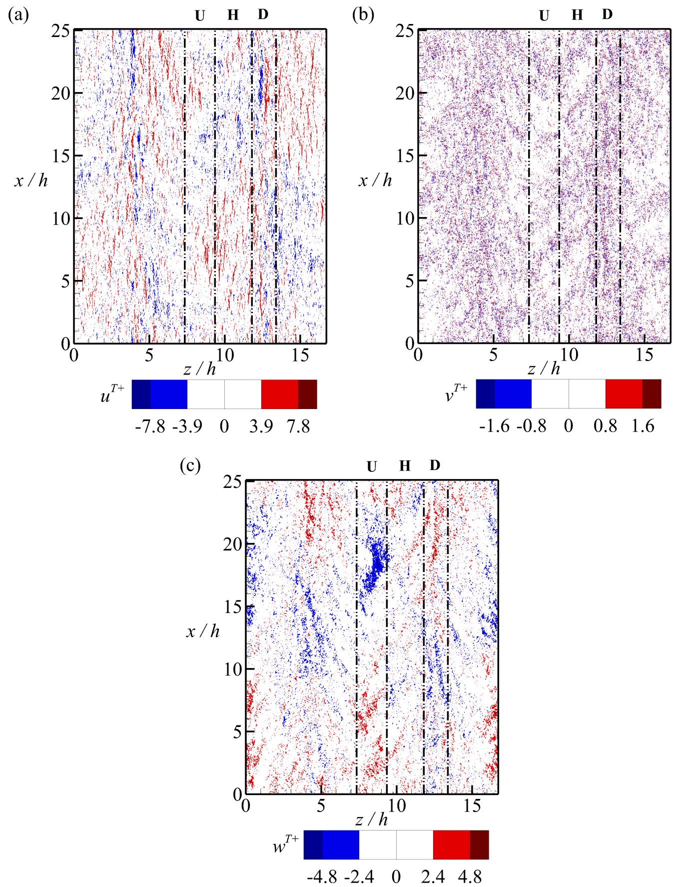

FIGURE 2. Instantaneous fields of (a) u^T, (b) v^T, and (c) w^T on the x–z plane near the water surface (located at $y/h = 1.985$). The results of case 1 are shown.

B. Derivation of transport equations of localized Reynolds stresses

According to the triple decomposition of the velocity, the governing equation of the mean velocity $\langle u_i \rangle$, the Langmuir cell content velocity fluctuation u_i^L, and the background turbulence velocity fluctuation u_i^T can be obtained through the following steps. First, the governing equation of $\langle u_i \rangle$ is obtained by applying the time and plane averaging to the C–L equation, which is expressed as

$$\langle u_j \rangle \frac{\partial \langle u_i \rangle}{\partial x_j} + \frac{\partial \left\langle u_i' u_j' \right\rangle}{\partial x_j} = -\frac{\partial \langle \Pi \rangle}{\partial x_i} + \nu \frac{\partial^2 \langle u_i \rangle}{\partial x_j \partial x_j} + \epsilon_{ijk} u_j^S \langle \omega_k \rangle + \frac{\partial \left\langle \tau_{ij}^{sgs} \right\rangle}{\partial x_j}. \tag{B.1}$$

Then, subtracting (B.1) from the C–L equation gives the following governing equation for the total velocity fluctuation u_i':

$$\begin{aligned} &\frac{\partial u_i'}{\partial t} + u_j' \frac{\partial \langle u_i \rangle}{\partial x_j} + \langle u_j \rangle \frac{\partial u_i'}{\partial x_j} + u_j' \frac{\partial u_i'}{\partial x_j} - \frac{\partial \left\langle u_i' u_j' \right\rangle}{\partial x_j} = \\ &-\frac{\partial \Pi'}{\partial x_i} + \nu \frac{\partial^2 u_i'}{\partial x_j \partial x_j} + \epsilon_{ijk} u_j^S \omega_k' + \frac{\partial \left(\tau_{ij}^{sgs}\right)'}{\partial x_j}. \end{aligned} \tag{B.2}$$

The streamwise averaging of (B.2) results in the governing equation for the Langmuir cell content velocity fluctuation u_i^L, expressed as

$$\begin{aligned}&\frac{\partial u_i^L}{\partial t}+u_j^L\frac{\partial\langle u_i\rangle}{\partial x_j}+\langle u_j\rangle\frac{\partial u_i^L}{\partial x_j}+u_j^L\frac{\partial u_i^L}{\partial x_j}-\frac{\partial\left\langle u_i^L u_j^L\right\rangle}{\partial x_j}-\frac{\partial\left\langle u_i^T u_j^T\right\rangle-\left\langle u_i^T u_j^T\right\rangle_x}{\partial x_j}=\\&-\frac{\partial\Pi^L}{\partial x_i}+\nu\frac{\partial^2 u_i^L}{\partial x_j\partial x_j}+\epsilon_{ijk}u_j^S\omega_k^L+\frac{\partial\left(\tau_{ij}^{sgs}\right)^L}{\partial x_j}.\end{aligned}\tag{B.3}$$

Further subtracting (B.3) from (B.2) gives the following governing equation for the background turbulence velocity fluctuation u_i^T:

$$\begin{aligned}&\frac{\partial u_i^T}{\partial t}+u_j^T\frac{\partial\langle u_i\rangle}{\partial x_j}+\langle u_j\rangle\frac{\partial u_i^T}{\partial x_j}+u_j^L\frac{\partial u_i^T}{\partial x_j}+u_j^T\frac{\partial u_i^L}{\partial x_j}+u_j^T\frac{\partial u_i^T}{\partial x_j}-\frac{\partial\left\langle u_i^T u_j^T\right\rangle_x}{\partial x_j}=\\&-\frac{\partial\Pi^T}{\partial x_i}+\nu\frac{\partial^2 u_i^T}{\partial x_j\partial x_j}+\epsilon_{ijk}u_j^S\omega_k^T+\frac{\partial\left(\tau_{ij}^{sgs}\right)^T}{\partial x_j}.\end{aligned}\tag{B.4}$$

Here, $\Pi^T=u_j^S u_j^T+p^T$ is the effective pressure and $\omega_k^T=\epsilon_{knm}\partial u_m^T/\partial x_n$ is the vorticity. To derive the transport equation of $\langle u_i^T u_j^T\rangle_{xt}$, the governing equation of u_i^T is rewritten as

$$\begin{aligned}&\frac{\partial u_i^T}{\partial t}+(\langle u_k\rangle+u_k^S)\frac{\partial u_i^T}{\partial x_k}=-u_k^T\frac{\partial\langle u_i\rangle}{\partial x_k}-\frac{\partial p^T}{\partial x_i}-\frac{\partial u_i^T u_k^T}{\partial x_k}+\frac{\partial\langle u_i^T u_k^T\rangle_x}{\partial x_k}\\&+\nu\frac{\partial^2 u_i^T}{\partial x_k\partial x_k}+\frac{\partial(\tau_{ik}^{sgs})^T}{\partial x_k}-u_k^T\frac{\partial u_k^S}{\partial x_i}-u_k^L\frac{\partial u_i^T}{\partial x_k}-u_k^T\frac{\partial u_i^L}{\partial x_k}.\end{aligned}\tag{B.5}$$

To derive (B.5) from (B.4), the two parts of the effective pressure are separated, and the identity $\epsilon_{ijk}\epsilon_{knm}=\delta_{in}\delta_{jm}-\delta_{im}\delta_{jn}$ is applied. The transport equation of u_j^T is also obtained by substituting all superscripts i in (B.5) with j. Multiply the governing equations of u_i^T and u_j^T with u_j^T and u_i^T, respectively, and then take the summation of the two resultant equations, we obtain to the following transport equation of $u_i^T u_j^T$:

$$\begin{aligned}&\frac{\partial u_i^T u_j^T}{\partial t}+(\langle u_k\rangle+u_k^S)\frac{\partial u_i^T u_j^T}{\partial x_k}=-u_j^T u_k^T\frac{\partial\langle u_i\rangle}{\partial x_k}-u_i^T u_k^T\frac{\partial\langle u_j\rangle}{\partial x_k}\\&-\left(\frac{\partial u_j^T p^T}{\partial x_i}+\frac{\partial u_i^T p^T}{\partial x_j}\right)+p^T\left(\frac{\partial u_j^T}{\partial x_i}+\frac{\partial u_i^T}{\partial x_j}\right)\\&-\frac{\partial u_i^T u_j^T u_k^T}{\partial x_k}+\left(u_j^T\frac{\partial\langle u_i^T u_k^T\rangle_x}{\partial x_k}+u_i^T\frac{\partial\langle u_j^T u_k^T\rangle_x}{\partial x_k}\right)\\&+\nu\frac{\partial^2 u_i^T u_j^T}{\partial x_k\partial x_k}+\left(\frac{\partial(\tau_{ik}^{sgs})^T u_j^T}{\partial x_k}+\frac{\partial(\tau_{jk}^{sgs})^T u_i^T}{\partial x_k}\right)\\&-2\nu\frac{\partial u_j^T}{\partial x_k}\frac{\partial u_i^T}{\partial x_k}-\left((\tau_{ik}^{sgs})^T\frac{\partial u_j^T}{\partial x_k}+(\tau_{jk}^{sgs})^T\frac{\partial u_i^T}{\partial x_k}\right)\\&-\left(u_j^T u_k^T\frac{\partial u_k^S}{\partial x_i}+u_i^T u_k^T\frac{\partial u_k^S}{\partial x_j}\right)-\frac{\partial u_i^T u_j^T u_k^L}{\partial x_k}-\left(u_j^T u_k^T\frac{\partial u_i^L}{\partial x_k}+u_i^T u_k^T\frac{\partial u_j^L}{\partial x_k}\right).\end{aligned}\tag{B.6}$$

Applying the time and streamwise averaging to (B.6) yields the transport equations of the localized Reynolds stresses $\langle u_i^T u_j^T\rangle_{xt}$.

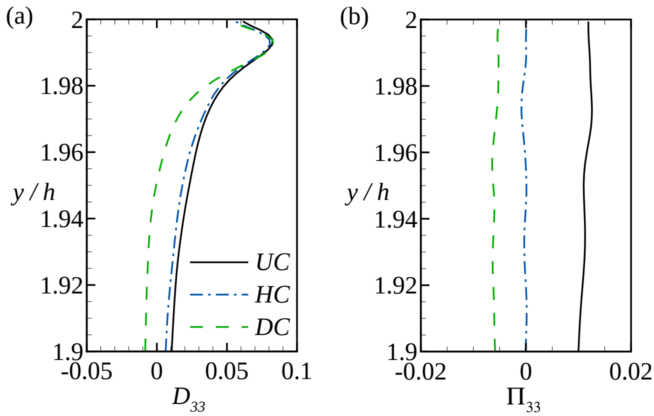

FIGURE 3. Vertical profiles of budget terms (a) D_{33} and (b) Π_{33} at UC, HC, and DC. The results of case 1 are shown. The budget terms are scaled by u_τ^4/ν.

C. Comparison of pressure terms in the budget equation of localized spanwise Reynolds normal stress near the surface

Figure 3 compares D_{33} and Π_{33} among UC, HC, and DC. As shown, D_{33} is comparable at HC and UC. In contrast, Π_{33} acts as a secondary source at UC, while at HC the contribution of Π_{33} in the budget balance is unimportant.