Atmospheric Boundary Layer Turbulence Closure Scheme for Wind-Following Swell Conditions

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ABSTRACT

Over the ocean, atmospheric boundary layer turbulence can be altered by underlying waves. Under swell conditions, the impact of waves on the atmosphere is more complicated compared to that under wind-wave conditions. Based on large-eddy simulation (LES), the wind-following swell impact on the atmospheric boundary layer is investigated through three terms: swell-induced surface momentum flux, the vertical profile of swell-induced momentum flux, and the swell impact on atmospheric mixing. The swell-induced surface momentum flux displays a decreasing trend with increasing atmospheric convection. The swell-induced momentum flux decays approximately exponentially with height. Compared with atmospheric convection, the decay coefficient is more sensitive to wave age. Atmospheric mixing is enhanced under swell conditions relative to a flat stationary surface. The swell impact on the atmospheric boundary layer is incorporated into a turbulence closure parameterization through the three terms. The modified turbulence closure parameterization is introduced into a single-column atmospheric model to simulate LES cases. Adding only the swell impact on the atmospheric mixing has a limited influence on wind profiles. Adding both the impact of swell on the atmospheric mixing and the profile of swell-induced momentum flux significantly improves the agreement between the 1D atmospheric simulation results and the LES results, to some extent simulating the wave-induced low-level wind jet. It is concluded that the swell impact should be included in atmospheric numerical models.

1. Introduction

The air–sea interface is a complex system in which surface waves interact with the turbulence of the lower atmosphere and the upper ocean (Hristov et al. 2003; Kudryavtsev and Makin 2004; Hristov and Ruiz-Plancarte 2014; Wu et al. 2015a, b). Accordingly, surface waves can affect the momentum, heat, and mass fluxes between the atmosphere and ocean (Woolf 2005; Veron et al. 2008; Grare et al. 2013). Extended to large scales, surface gravity waves can affect weather and mesoscale systems (e.g., tropical cyclones and storms surges) (Sullivan et al. 2012; Rabe et al. 2015; Wu et al. 2015b) as well as climate (Carlsson et al. 2008; Wu et al. 2016). In recent years, the impact of surface waves on air–sea interaction processes has attracted increased interest. Even so, many physical mechanisms at the atmosphere–wave–ocean interface are still unclear.

Many efforts have focused on parameterizing wind stress (i.e., surface momentum flux) over the ocean

(Drennan et al. 2005; Högström et al. 2015). Measurements and numerical simulations have indicated that the surface momentum flux over the ocean differs greatly from that over land. The total momentum flux over the ocean can be expressed as the sum of turbulent momentum flux ($\tau_t$), wave-induced momentum flux ($\tau_w$), and viscous momentum flux ($\tau_v$) (Smedman et al. 2003; Grachev et al. 2003), as follows:

$$\tau(z) = \tau_v(z) + \tau'(z) + \tau''(z). \tag{1}$$

Viscous stress is only important in a very thin layer near the surface and is neglected in this study. At the surface ($z = 0$), the turbulent momentum flux is negative [i.e., $\tau'(0) < 0$] and transfers momentum from the atmosphere to the ocean. The sign of the wave-induced momentum flux depends on the wave state. For growing waves, the wave-induced momentum flux is negative [i.e., $\tau''(z) < 0$], and it is positive (from ocean to atmosphere) under low winds and decaying waves. When the amplitude of the wave-induced positive momentum flux is larger than the turbulent momentum flux [i.e., $|\tau''(0)| > |\tau'(0)|$] the total momentum flux is directed from ocean to
atmosphere, and a wave-induced low-level wind jet occurs. These phenomena have been observed in the equatorial western Pacific Ocean (Grachev and Fairall 2001) and the Baltic Sea (Smedman et al. 1999; Semedo et al. 2009) and demonstrated in numerical simulations (Sullivan et al. 2008). The situation with swell is of interest for the global climate. Semedo et al. (2011) demonstrated that swell waves prevail over most of the world’s oceans. However, upward momentum flux cannot be simulated in most atmospheric numerical models. In this study, an improved turbulence closure methodology is proposed in order to include the swell influence on the momentum flux.

Wind stress parameterizations that are dependent on wave state (e.g., wave age and wave steepness) have improved the agreement of momentum flux results between models and measurements (e.g., Drennan et al. 2005). However, there is still a nonnegligible scatter of momentum flux when comparing models and measurements, especially under swell and high-wind conditions. To reduce the scatter of momentum flux when comparing model results and measurements under swell conditions, some studies suggest calculating the wave-induced momentum flux and turbulent momentum flux separately (Rieder and Smith 1998; Högström et al. 2015). The surface turbulent momentum flux is calculated using a function of wind speed at 10 m ($U_{10}$), whereas the surface swell-induced momentum flux (peak wave contribution) is parameterized as a function of swell wave slope by Högström et al. (2015). Following the same idea, a turbulence closure scheme for the atmospheric boundary layer is parameterized using two terms in this study: the turbulent momentum flux and the wave-induced momentum flux.

How to filter out the wave-induced momentum flux from measurements is a key question when parameterizing the wave-induced momentum flux. The linear filter method (Hristov and Ruiz-Plancarte 1998) and linear transform techniques (Veron et al. 2008) have been used to calculate the wave-induced momentum flux as well as heat flux from measurements. Measurements (Grare et al. 2013) and numerical simulations (e.g., Kihara et al. 2007) have indicated that the wave-induced momentum flux varies with wave age. The ratio between the wave-induced momentum flux and total momentum flux varies between studies. For growing waves, the ratio is less than 10% in the study of Grare et al. (2013) at a height of 10 m and less than 5% according to Hristov and Ruiz-Plancarte (2014). For older waves, the wave-induced momentum flux is up to 20% of the total wind stress when $c_p/U_0 > 60$, where $c_p$ is the peak wave speed (Grare et al. 2013).

The wave-induced momentum flux filtered out of the total momentum flux is usually estimated at a certain height when using measurements. However, the wave-induced momentum flux at the surface is required when parameterizing the total surface momentum flux. The methodology for interpolating the wave-induced momentum flux at measurement heights to the surface is an open question. In some studies (e.g., Semedo et al. 2009), the wave-induced momentum flux is assumed to decay exponentially with height, which is expressed as follows:

$$
\tau^w(z) = \tau^w(0) \exp^{-Akz},
$$

where $k$ is the wavenumber and $A$ is a dimensionless parameter (the decay coefficient). The exponential decay of the wave-induced momentum flux has been demonstrated in measurements and numerical simulations (Belcher and Hunt 1993; Sullivan et al. 2008; Högström et al. 2015). However, the decay coefficient varies between studies. Hanley and Belcher (2008) treated the decay coefficient as 10, while (Semedo et al. 2009) treated it as 2 and Makin and Mastenbroek (1996) as 5 for short waves. From measurements, the range of 1–2.1 is reported in Högström et al. (2015). In Makin and Kudryavtsev (1999) and Makin (2008), the wave-induced momentum flux decaying with height is expressed as follows:

$$
\tau^w(z) = \tau^w(0) \exp^{-Akz} \cos \left( \frac{\pi Akz}{2} \right),
$$

where the decay coefficient $A$ is supposed to be 10–100. Few studies have tried to investigate the impact of wave states and atmospheric convection on the decay coefficient. In this study, the impact of atmospheric convection and wave age on the decay coefficient of the wave-induced momentum flux profile is investigated based on large-eddy simulations (LESs).

Parameterizing the turbulent momentum flux is another important issue in the turbulence closure scheme under swell conditions. In many studies, the turbulent momentum flux (i.e., $\tau'$) is assumed to be calculated using the eddy viscosity and wind gradients (Hanley and Belcher 2008; Semedo et al. 2009), as follows:

$$
\tau'(z) = -K_m \frac{dS}{dz},
$$

where $K_m$ is the turbulent eddy viscosity and $S$ the mean horizontal wind speed (i.e., $S = \sqrt{U^2 + V^2}$, where $U$ is the mean wind speed in the wave direction and $V$ the mean wind speed in the cross wave direction). The eddy viscosity in many turbulence closure schemes is treated as a function of turbulent kinetic energy, a length scale, and atmospheric stability. Traditional parameterizations of
the atmospheric mixing length are usually used in parameterizing surface wave effects (Hanley and Belcher 2008; Makin 2008; Semedo et al. 2009; Song et al. 2015). In the study of Semedo et al. (2009), the turbulent eddy viscosity at the surface layer is treated as the traditional parameterization (i.e., \( K_m = \kappa \mu_0 \) or \( K_m = \kappa \sqrt{TKE} \), where \( \kappa \) is the von Kármán constant and TKE the turbulent kinetic energy). However, the surface turbulence altered by underlying waves can extend to a high layer, which may affect the atmospheric mixing versus under flat conditions (e.g., Rutgersson et al. 2012). The possible impact of swell on the turbulent momentum flux is investigated through changing the atmospheric mixing length scale.

The wave impact on atmospheric turbulence closure schemes has previously been investigated, but there are still some open questions. Previous relevant studies include only the wave impact on surface wind stress (Drennan et al. 2005), include only the profile of wave-induced momentum flux (Makin and Mastenbroek 1996), 3) qualitatively include only the wave impact on atmospheric mixing length (Rutgersson et al. 2012), and 4) include both swell impact on the surface wind stress and atmospheric mixing without considering the profile of wave-induced momentum flux (Wu et al. 2016). Although, improved simulation results compared with measurements have been reported (Semedo et al. 2009; Song et al. 2015), further development is needed. To fully consider the surface wave influences and propose a new framework including the swell influence, the swell-induced momentum flux as well as the swell impact on atmospheric mixing are investigated based on LESs of wind-following swell conditions in the present study. The swell influences are incorporated into the Mellor–Yamada–Nakanishi–Niino (MYNN) boundary layer parameterization in the single-column version of the Weather Research and Forecasting Model (WRF-SCM) to test its performance. In section 2, the wave-induced momentum flux and turbulent momentum flux are investigated based on the LES cases, and the swell impact on the master length scale is parameterized in the MYNN closure scheme. The modified MYNN parameterization and the wave-induced momentum flux are incorporated into the WRF-SCM in section 3, and the WRF-SCM simulations are compared with LES results. The discussion and conclusions are presented in sections 4 and 5, respectively.

2. Large-eddy simulations and their application to a new parameterization

In the present paper, the LES cases are the same as those used in Nilsson et al. (2012). The LES code includes a sinusoidal lower boundary condition representing a swell wave and is described in detail in Sullivan et al. (2008). The simulations range from neutral to moderately convective conditions with and without swell waves (see Table 1). The wavelength and wave slope in those simulations are \( \lambda = 100 \text{ m} \) and \( a_k = 0.1 \) \( (a \) is the wave amplitude), respectively. The wave direction is the same as the geostrophic wind direction. The roughness length used in the simulations is \( z_0 = 0.0002 \text{ m} \). The Coriolis parameter, \( f = 10^{-4} \), is used in the simulations, which approximately corresponds to the Coriolis parameter at latitude 43.291°. The horizontal resolution of the LESs is (4.8, 4.8) m, which well resolves the lower boundary layer. The vertical resolution of the surface layer is about 1 m. The subgrid-scale momentum (\( \tau \)) and scalar (\( \psi \)) fluxes used in the LES model are parameterized (Sullivan et al. 2008), as follows:

\[
\tau_{ij} = -K_m \left( \frac{\partial p}{\partial x_j} + \frac{\partial p}{\partial x_i} \right) \quad \text{and} \quad (5)
\]

\[
\psi_{ij} = -K_m \left( 1 + \frac{2I}{\Delta} \right) \frac{\partial \bar{\rho}}{\partial x_j}, \quad (6)
\]

where the notation \( \bar{u}_i = (u, v, w) \) is used in the equations, \( \bar{v} \) represents spatially filtered variables in the LES, the eddy viscosity is expressed as \( K_m = c_d \epsilon^{1/2} \), \( c_k \) is a constant, \( \Delta \) is a length scale equal to the LES filter \( \Delta_L \) except in the region of stable stratification (Sullivan et al. 2008), and \( \epsilon \) is the subgrid-scale energy. For additional details about the LES cases and the parameterizations used in the LES, we refer to Nilsson et al. (2012) and Sullivan et al. (2008), respectively. The flat cases are used for comparison with the swell cases.

Here we pursue the idea that the total momentum flux can be separately calculated from the turbulent momentum flux and the wave-induced momentum flux. In section 2a, the wave-induced momentum flux character

<table>
<thead>
<tr>
<th>Simulation</th>
<th>( Q_a ) (K m s(^{-1}))</th>
<th>( U_e ) (m s(^{-1}))</th>
<th>( c_p / U_{10} )</th>
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<td>5</td>
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<tr>
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<tr>
<td>FN2</td>
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<td>1</td>
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is analyzed based on the LESs. The turbulent momentum flux and master length scale in the MYNN scheme are investigated in section 2b. The LES results are used to investigate the validity of the original master length scale under swell conditions in section 2b. Then the master length scale including swell influence is proposed in section 2c.

a. Wave-induced flux

According to the Reynolds decomposition, a variable $a$ over waves can be decomposed as follows:

$$ a = \bar{a} + \tilde{a} + a', $$

where $\bar{a}$ is the ensemble average, $\tilde{a}$ the wave-induced fluctuation, and $a'$ the turbulent fluctuation. The wave-induced fluctuation can be expressed as $\tilde{a} = \langle a \rangle - \bar{a}$ (e.g., Rutgersson and Sullivan 2005), where $\langle a \rangle$ is the phase average. The mean-flow variables are identified by uppercase symbols ($A = \bar{a}$).

The wave-induced variances in the swell cases are shown in Fig. 1. The magnitude of streamwise wave-induced variances $\tilde{u}^2$ (Fig. 1a) decays with height approximately exponentially [i.e., $\tilde{u}^2(z) = \tilde{u}^2(0)e^{-a_uz}$]. Under different convective conditions at the same wave age (i.e., FC1, FC2, FC3, and FC4; see Table 1), the exponential decay coefficient is approximately the same ($a_u$ is approximately 0.107). However, at higher wave ages (e.g., FN2), the exponential decay coefficient is larger than at the lower wave age ($a_u$ is approximately 0.117 in FN2), which means that the streamwise wave-induced variances decrease faster with height under higher wave age conditions (i.e., faster waves). The magnitudes of the surface streamwise wave-induced variances $\tilde{u}^2$ are larger in the more convective cases. Rutgersson and Sullivan (2005) found differences in the energy transported between the turbulent and wave-coherent kinetic energy under different wave age conditions, using direct numerical simulations. Under different convective conditions, the energy transported from the wave-induced variance to turbulence may differ because of the effect of buoyancy, which may cause differences in the wave-induced streamwise variance.

Wen and Mobbs (2014) investigated the velocity distribution using the two-layer potential flow solution of Milne-Thomson (1997). To illustrate the differences in wave-induced variances between the turbulent and laminar flow conditions over waves (Fig. 1), the wave-induced streamwise variances in laminar flow in the two wave age cases (MT_Ug5 and MT_Ug1; the geostrophic wind speeds are 5 and 1 m s$^{-1}$, respectively) are calculated using Eqs. (11), (12), and (19) in Wen and Mobbs (2014). The wave parameters (i.e., wavelength, slope, and amplitude) are the same as in our LES cases. The $\tilde{u}^2$ from MT_Ug5 and MT_Ug1 decays exponentially with height (the decay coefficient is the same in the two cases, though the surface value is different). Compared with the present LES case results, the decay coefficients from MT_Ug5 and MT_Ug1 are larger ($a_u = 0.122$). The wave-induced vertical variances for different cases are shown in Fig. 1b. The wave-induced vertical variances are approximately the same, mainly because the wave-induced vertical variances are determined by the orbital movement of waves. The $\tilde{w}^2$ decays approximately exponentially with height [i.e., $\tilde{w}^2(z) = \tilde{w}^2(0)e^{-a_wz}$]. The decay coefficient $a_w$ is around 0.141 in the different convective
At a higher wave age (FN2), the wave-induced vertical variances decay more slowly with height than at a lower wave age ($a_w = 0.131$). The $\bar{w}^2$ from the laminar flow cases (MT_Ug5 and MT_Ug1) decays exponentially with height ($a_w = 0.122$). As in the LES cases, the $\bar{w}^2$ in the higher wave age case (MT_Ug1) is larger than in the lower wave age case (MT_Ug5). In Jiang et al. (2016), $(\bar{u} + u')^2$ exhibits approximately exponential decay with height near the surface, mainly due to wave-induced variance. The wave-induced variances ($\bar{v}^2$ and $\bar{\theta}^2$) are very small (not shown).

The exponential decay profiles of $\bar{u}^2$ and $\bar{w}^2$ show that the wave-induced variances are mainly present in the near-surface layer, which is also apparent in the turbulent kinetic energy (TKE) profiles. In the very near-surface layer, the wave-induced variances take a larger part of the total variances [i.e., $(\bar{u} + u')^2$].

The TKE and dissipation profiles for different cases are shown in Fig. 2. In the very near-surface layer, the TKE in the swell cases is larger than that in flat cases, mainly as a result of the wave-induced variance (i.e., the direct wave impact; see Fig. 1). The wave-induced TKE of the layer higher than 20 m is smaller because of the indirect wave impact. In the swell cases, the wind gradients are much smaller than in the flat cases above 20 m, contributing to the smaller production of TKE in the swell cases. With increasing atmospheric convection, the differences in TKE between the swell and flat cases decrease, possibly because of the influence of the buoyancy-produced turbulence. The relative impact of swell is smaller under more convective conditions. Similar to TKE, the dissipation in the swell cases is also larger than in the flat cases in the very near-surface layer. With the increase in the height and atmospheric convection, the differences in dissipation between the swell and flat cases become smaller.

Under wave-following coordinate system, the total wave-induced momentum flux comprises two terms, the pressure stress, $D_p(z)$, and the wave-induced turbulent flux, $\bar{u} \bar{w}(z)$, $\tau_w(z) = \bar{u} \bar{w}(z) + D_p(z)$. The pressure stress is expressed as $D_p(z) = -(1/\rho) \int_0^1 p^* z_\xi dx$, where $p^*$ denotes the perturbation pressure at the surface, normalized by air density, and $z_\xi$ the slope of the $\zeta$-coordinate lines in physical space. The wave-induced turbulent
momentum flux \[\langle \bar{uw} \rangle(z)\] is shown in Fig. 3. The wave-induced momentum flux increases in the lower surface layer. At certain heights (5–10 m), there is a maximum in the wave-induced turbulent momentum flux. At the same wave age, the wave-induced maximum turbulent momentum height is approximately the same. At the higher wave age (FN2), the maximum wave-induced turbulent momentum height is greater than in the lower wave age cases. No significant trend in the influence of the buoyancy appears in the cases. Compared with the pressure stress, the wave-induced turbulent flux is much smaller according to the LES cases (less than 3\% at the surface). The pressure stress \(D_p(z)\) decreases approximately exponentially with height (not shown here), as also indicated by Jiang et al. (2016).

Measurements made in some studies (e.g., Högström et al. 2015) indicate that the wave-induced momentum flux decays exponentially with height. The total wave-induced momentum flux \(\tau^w(z)\) profiles in different cases are shown in Fig. 4 (the black lines). The blue and red lines show the exponential fit lines following Eq. (2).

One can see that the total wave-induced momentum flux agrees well with the exponential fit functions in all cases. Based on the exponent parameter equations, the wave-induced total surface momentum flux \(\tau^w(0)\) and the exponential decay coefficient \(A\) are shown in Fig. 5. Under the wave conditions, not only the wave state and convection but also the boundary layer height can affect the wave-induced turbulence. Thus, instead of \(z/L\), we use \(w_0/c_p\) \[w_0 = \left(\frac{g z_i}{\theta_0} - T_o + z_i \theta_0/\theta_0\right)^{1/3}\], where the convective velocity scale \(\theta_0\) is the virtual potential temperature, \(T_o\) is the absolute temperature, and \(z_i\) is the mixed-layer depth (i.e., the height where the buoyancy flux is minimum (Nakanishi 2001)) to express the relative impact of the atmospheric convection on the phase speed of the waves. Compared with \(z/L\) \((L\) is the Obukhov length), the parameter \(w_0/c_p\) can also take the boundary depth and wave state impacts into account, making it more suitable for describing the atmospheric convection under wave conditions. The surface wave-induced stress decreases with convective conditions, from 0.0361 m²s⁻² under neutral conditions to 0.0338 m²s⁻² in more convective cases \((w_0/c_p = 0.057)\). The wave-induced surface stress \((0.0371\text{ m}^2\text{s}^{-2})\) is larger in the higher wave age case (FN2), which agrees with the results of Jiang et al. (2016) that the pressure stress is higher at higher wave ages (the total wave-induced surface stress is dominated by the pressure drag). The total wave-induced momentum flux changes with the atmospheric convection following the linear (exponential) fit line \(\tau^w_{\text{lw}} = -0.0397w_0/c_p + 0.0359\) \([\tau^w_{\text{lw}} = -0.0362 \exp(-1.352w_0/c_p)]\) at a wave age of 2.5. The decay coefficient is almost constant (-1.93) at the same wave age, which is in the range \((1.43 \pm 0.5)\) measured by Högström et al. (2015). However, the decay coefficient in the old wave case (FN2) is smaller \((A = 1.81)\), supporting the claim that the wave-induced momentum flux decays less with height than in the younger wave case. The wave-induced heat flux \(\bar{w} \bar{\theta}\) is much smaller than the total heat flux and is not discussed in this study.

b. Turbulent momentum flux

In most local turbulence closure boundary layer schemes, such as the energy–length scale \((E_l;\) Lenderink and Holtslag 2004), Mellor–Yamada–Janjic (Janjic 1994), MYNN (Nakanishi 2001; Nakanishi and Niino 2006), and quasi-normal scale elimination (Sukoriansky et al. 2005) schemes, the turbulent momentum flux is treated as a function of TKE, a length scale, and the atmospheric stability parameters. In the wave-induced wind models (Hanley and Belcher 2008; Semedo et al. 2009; Song et al. 2015), the shear-induced turbulence closure schemes are assumed to be valid. However, the results of Rutgersson and Sullivan (2005) indicate that the wave-coherent structures can affect the turbulent energy distribution. Thus, the validity of turbulence closure schemes under swell conditions should therefore be investigated. Here, we test, based on the LES cases, the MYNN parameterization under swell conditions.

The turbulent momentum flux \(\tau^w\) and the wind profiles are shown in Fig. 6. Under neutral conditions, the countergradient flux contribution is negligible, and the zero turbulent flux occurs at approximately the height

![Fig. 3. The vertical profile of the wave-induced turbulent flux \(\bar{uw}\) in different cases.](image-url)
where the wind gradient is zero. One can see that the zero turbulent momentum flux height is approximately the same as the zero wind gradient height (i.e., the low-level wind jet height) under neutral conditions (Figs. 6a,f).

With increased atmospheric convective conditions, the countergradient contribution flux increases, which gives a larger difference between the zero turbulent momentum flux height and the zero wind gradient.

![Graphs showing wave-induced total flux and its exponent regression lines](image-url)

**FIG. 4.** The vertical profile of wave-induced total flux $\tau_{uw}$ and its exponent regression lines: (a) FN1, (b) FC1, (c) FC2, (d) FC3, (e) FC4, and (f) FN2.

![Graphs showing wave-induced surface stress](image-url)

**FIG. 5.** The wave-induced surface stress under different convective conditions, FN1 and FC1–FC4 (black circle) and FN2 (red triangles): (a) the black (blue) line is the linear (exponential) regression line; (b) the decay coefficients in different cases.
height. In the convective swell cases (Figs. 6b–e), the difference between the zero turbulent momentum flux height and the zero wind gradient height becomes larger with stronger convection. In the local closure boundary layer scheme, a common problem is that the countergradient flux contribution cannot be fully considered in local turbulence closure schemes (Cohen et al. 2015). We assume that the shifts in the zero turbulent momentum flux height and the zero wind gradient height are due to the countergradient flux. In this paper, however, the countergradient contribution is not the focus. The local closure boundary layer parameterization is, to some extent, valid for the turbulent momentum flux.

The turbulent momentum flux is expressed as follows:

$$\tau_{uw}(z) = -K_m \frac{dU}{dz} \quad \text{and} \quad \tau_{sw}(z) = -K_m \frac{dV}{dz}, \quad (8)$$

where the eddy viscosity $K_m$ in the MYNN parameterization is expressed as $K_m = l_M S_m q$, $l_M$ is the master length scale, $S_m$ is the nondimensional diffusion coefficient of momentum, and $q = \sqrt{2TKE}$. Based on the assumptions of equilibrium, isotropic and homogeneous turbulence, the dissipation can be expressed as $\varepsilon = C_\varepsilon q^3/l_M$, where $C_\varepsilon$ is the coefficient. This scale is intimately linked to the Richardson–Kolmogorov cascade (Vassilicos 2015). The evidence of this relationship has been reviewed in Vassilicos (2015). Accordingly, the master length scale can be expressed as (Nakanishi 2001)

$$l_M = \frac{q^3}{B_1 \varepsilon}, \quad (10)$$

where $B_1$ is a constant (i.e., $B_1 = 24$) and $\varepsilon$ is the energy dissipation.

The diagnostic equation for the master length scale $l_M$ in the MYNN parameterization is

$$\frac{1}{l_M} = \frac{1}{l_s} + \frac{1}{l_T} + \frac{1}{l_B}, \quad (11)$$

FIG. 6. The vertical profile of wind speed and turbulent momentum flux: (a) FN1, (b) FC1, (c) FC2, (d) FC3, (e) FC4, and (f) FN2. The thin black line is the maximum wind speed height. The thin blue line is the zero turbulent momentum flux height.
in which $l_S$ is the surface length scale, $l_T$ the length scale depending on the turbulence structure of the planetary boundary layer (PBL), and $l_B$ the length scale limited by the buoyancy effect. The surface length scale $l_S$ is expressed as follows (Nakanishi 2001):

$$
l_S = \begin{cases} 
\frac{\kappa z}{3.7} & \zeta \geq 1 \\
\frac{\kappa z (1 + 2.7 \zeta)}{(1 - \alpha_4 \zeta)^{0.2}} & 0 \leq \zeta \leq 1, \\
\frac{\kappa z (1 - \alpha_4 \zeta)}{(1 - \alpha_4 \zeta)^{0.2}} & \zeta < 0 
\end{cases}
$$

(12)

$$
l_T = \frac{\int_0^z q z \, dz}{\int_0^z q \, dz}
$$

(13)

in which $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ are coefficients, $\zeta = z/L$ is the stability parameter, $N$ the Brunt–Väisälä frequency, and $q_c$ a velocity scale. To test the performance of the diagnostic equation for $l_M$, the master length scale calculated using Eq. (10) [TKE and dissipation are computed from the resolved and subgrid TKE and dissipation from the LES results, respectively, as in Nakanishi (2001)] and the diagnostic equation in the MYNN parameterization [Eq. (11)] are shown in Figs. 7 and 8. In the flat cases, the diagnostic master length scale agrees relatively well with the length scale from the LES results. However, the agreement near the top of the boundary layer is not very good. The boundary layer height $z_i$ is here defined as the height where the buoyancy flux falls to 5% of its surface value (Nakanishi 2001). One possible reason for the deviation is the lower resolution at the higher layer in LES and the significant influence of entrainment. At the top of the boundary layer, the values of TKE and dissipation are small. In the present study, we do not focus on the top of the boundary layer, assuming the length scale difference between the diagnostic results and the LES results does not greatly influence the results in the middle/low part of the boundary layer. In the ZC4 case (Fig. 7e), the master length scale deviates from the LES results, though the deviation is smaller than in the swell cases (Fig. 8e).
Because the master length scale for swell cases is the focus of this study, the deviations between the diagnostic master length and the LES results under more convective conditions are not discussed further here. In another consideration, near-neutral stratification is common over large parts of the world’s oceans (Sahlée et al. 2008). Accordingly, the LES setup used here is for the small air–sea temperature gradient (i.e., sensible heat fluxes are small), which is the normal condition over the ocean. In the swell cases (Fig. 8), the diagnostic master length scale from MYNN is smaller than the LES results because of the swell influence. In swell cases, the most energetic spectral range extends to a lower frequency than in flat cases, resulting in larger integral length scales (Nilsson et al. 2012; Rutgersson et al. 2012). This may cause the dissipation to become less efficient relative to the available turbulent kinetic energy. This could lead to larger master length scales in the swell cases in which Eq. (10) is used because $\varepsilon$ is becoming smaller. Recent field measurements (Nadeau et al. 2011; Nilsson et al. 2016) indicate that the dissipation may be influenced by the boundary layer depth of unstable stratification, and it is well known that the scale of the peak vertical wind variance spectrum is especially related to the depth of the boundary layer. As shown in Rutgersson et al. (2012), in these LESs, the spectrum peak for vertical wind increased surprisingly in the presence of swell compared to that in flat terrain cases with the same prescribed heat flux forcing. The study of Rutgersson and Sullivan (2005) indicates that the underlying waves generate higher turbulence than arises over flat surfaces. The present finding that the master length scale is enhanced compared to that in the flat terrain cases agrees with those results. To improve the diagnostic master length scale equation to adapt to the swell cases, in the next section, the master length scale is tuned to the LES results in the swell cases.

c. Master length scale for swell cases

For the master length scale of the MYNN model, the surface length scale $l_S$ is the dominant scale near the surface. With increasing height above the surface, the TKE length scale $l_T$ and the buoyancy limitation scale $l_B$ play increasingly important roles. Under wave conditions, the existence of the underlying waves will redistribute the turbulent energy in the atmospheric

**Fig. 8.** The mixing length in the different swell cases: (a) FN1, (b) FC1, (c) FC2, (d) FC3, (e) FC4, and (f) FN2. The black lines are calculated using Eq. (10) and the blue lines using Eq. (11). The red lines are from the modified MYNN parameterization [Eqs. (11) and (15)].
boundary layer (Rutgersson and Sullivan 2005). The influence of swell on the atmospheric boundary layer originates from the wave surface and then indirectly influences the entire boundary layer. To agree with the character of the swell impact on the atmospheric boundary layer, the swell impact on the master length scale is added to the surface length scale. The swell impact near the surface is therefore significant, and, with increasing height, the wave-induced contribution will be disturbed by shear- or buoyancy-induced turbulence (Sullivan et al. 2010; Nilsson et al. 2012). Thus, considering the swell influence, the surface length scale is expressed as follows:

\[ l_s = l_w(1 + l_w), \]  

(15)

in which \( l_w \), a nondimensional parameter, is the wave contribution to the surface length scale.

The comparisons between the original diagnostic master length scale and the length scale from the LES cases are shown in Fig. 8. One can see that the various ratios between the master length scales from Eq. (11) and from Eq. (10) increase (approximately exponential) to a certain height, after which the ratios decrease with height (approximately exponential decay). To tune the diagnostic master length scale to agree with the LES results, the wave contribution factor is expressed as follows:

\[ \frac{1}{l_w} = \frac{1}{l_{w1}} + \frac{1}{l_{w2}}, \]  

(16)

where \( l_{w1} \) is an exponential increase term and \( l_{w2} \) is an exponential decay term. The expressions for the two terms are

\[ l_{w1} = B_{w1} \exp(A_{w1} z) \]  

and

\[ l_{w2} = B_{w2} \exp(A_{w2} z), \]  

(17, 18)

where \( B_{w1}, A_{w1}, B_{w2}, \) and \( A_{w2} \) are coefficients related to wave states, which should be further explored based on more data.

The four parameters for the six swell LES cases are shown in Fig. 9. The constants \( B_{w1} \) and \( B_{w2} \) increase approximately linearly (exponentially) with more convective conditions \( w_s/c_p \) at the same wave age. The corresponding linear (exponential) regression lines for \( B_{w1} \) and \( B_{w2} \) are \( B_{w1} = 1.257 w_s/c_p + 0.33 \) \( [B_{w1} = 0.365 \exp(19.45 w_s/c_p)] \) and \( B_{w2} = 34.98 w_s/c_p + 2.11 \) \( [B_{w2} = 2.136 \exp(12.04 w_s/c_p)] \), respectively. However, the constants \( B_{w1} \) and \( B_{w2} \) at a higher wave age (FN2) are larger than in the relatively low wave age case. This is because the swell influence on the boundary layer at a higher wave age is greater than at a lower wave age, which agrees with the wave-induced variances (Fig. 1). For the exponential decay (increase) coefficients, \( A_{w1} \) (\( A_{w2} \)) are approximately constant \((0.08 \) and \(-0.012\), respectively\) at the same wave age, except for \( A_{w2} \) in case FN1. Cases FN1 and FN2 are in one sense important but special cases corresponding to pure neutral atmospheric stratification (i.e., no sensible heat flux to/from the sea). This is an idealized state of the atmosphere that is rarely experienced for long time periods in reality. In case FN2 (i.e., higher wave age), the exponential coefficients are smaller than that at the lower wave age. After considering the wave-contributed length scale, the modified diagnostic master length agrees better with the LES results (Fig. 8).

3. One-dimensional simulations

To test the performance of the modified MYNN parameterization, wave impact is introduced into a one-dimensional atmospheric model. The initial potential temperature profile, wind profile, and surface forcing in terms of sensible heat flux and geostrophic wind forcing used for the 1D atmospheric model are the same as in the corresponding LES cases. The 1D atmospheric simulation results are used to investigate the performance of the modified MYNN parameterization.

a. WRF-SCM

WRF-SCM is designed to test the evolution of vertical profiles in the atmospheric boundary layer. WRF-SCM is based on the assumption of horizontal homogeneity (i.e., \( \partial/\partial x = \partial/\partial y = 0 \)). The basic equations in WRF-SCM are as follows:

\[ \frac{\partial U}{\partial t} = f(V - V_g) - \frac{\partial \tau_{uw}(z)}{\partial z}, \]  

(19)

\[ \frac{\partial V}{\partial t} = -f(U - U_g) - \frac{\partial \tau_{vw}(z)}{\partial z}, \]  

(20)

\[ \frac{\partial \theta}{\partial t} = -\frac{\partial w/\theta}{\partial z}. \]  

(21)

In the present study, the MYNN-2.5 boundary layer parameterization is used. As in the LES settings, the radiation, vapor and cloud schemes are turned off. The roughness length \( z_0 \) is set as constant and, as in the LES cases, \( z_0 = 0.0002 \text{m} \). For the MYNN boundary layer turbulence scheme, two algebraic equations are used to calculate the turbulent exchange coefficients [for details, refer to Nakanishi and Niino (2006)]. The prognostic equation for TKE and the two algebraic equations are expressed as in Nakanishi and Niino (2006), as follows:
\[ \frac{1}{2} \frac{\partial q^2}{\partial t} + U_i \frac{\partial q_{\alpha}}{\partial x_i} = \frac{\partial}{\partial z} \left[ T_{\text{eff}} q \frac{\partial}{\partial z} \left( \frac{q^2}{2} \right) \right] + P_s + P_b - \varepsilon, \]  

(22)

\[ S_m (6A_1A_2G_m) + S_h (1 - 3A_2B_2G_h - 12A_1A_2G_h) = A_2, \]  

(23)

and

\[ S_m (1 + 6A_1^2G_m - 9A_1A_2G_h) - S_h (12A_1^2G_h + 9A_1A_2G_h) = A_1 (1 - 3C_1), \]  

(24)

in which \( A_1, A_2, B_1, \) and \( C_1 \) are constants, \( G_m \) and \( G_h \) are nondimensional variables of wind shear and vertical gradient of virtual potential temperature, respectively, \( P_s \) is the wind shear production, \( P_b \) is the production/destruction by the effects of buoyancy, \( \varepsilon \) is the viscous dissipation, \( S_h \) is the nondimensional diffusion coefficient for heat, and \( S_q \) is an empirical parameter. The shear production \( P_s \) is expressed as follows:

\[ P_s = -(\overline{u w'}) \frac{\partial U}{\partial z} - (\overline{v w'}) \frac{\partial V}{\partial z}. \]  

(25)

### b. Experiment settings

The vertical resolution used in WRF-SCM is similar to the LES settings in the bottom boundary (approximately 1 m from the surface). In the higher layer, the vertical resolution of WRF-SCM is a little higher than the LES setting. In the 0–800-m layer, there are 120 vertical layers in WRF-SCM and 96 in LES. WRF-SCM is used to simulate the LES cases listed in Table 1. The sensible heat fluxes are set to constants corresponding to those of the LES cases, respectively. The latent heat flux...
is zero in all cases. The initial conditions of the wind profiles and potential temperature profiles in the LES cases are used to initialize the WRF-SCM cases. The time step and the simulation time period (around 5 h, with little difference between the cases) used in WRF-SCM simulations are approximately the same as in the LES cases. At the end of the WRF-SCM simulations, there are almost quasi-steady conditions. In the flat cases (i.e., ZN1–ZC4), the MYNN surface parameterization is used. In the swell cases, the friction velocities from the LES cases are prescribed in all experiments. In other words, no surface parameterization is used in the swell cases. To test the impacts of swell (i.e., master length scale and wave-induced momentum flux) separately and combined, three experiments were designed (Table 2).

No swell influence is incorporated into the control (CTL) experiment, whose results are compared with those of other experiments investigating the wave influence. In CTL, the turbulent flux $\tau_{uw}$ in Eq. (19) includes only the turbulent momentum flux (i.e., $\tau_{uw} = \tau'_{uw}$) (the wave-induced flux is not considered). In the experiment MIX, only the modified MYNN master length scale [Eq. (15)] is incorporated into the model. In the full wave influence (FUL) experiment, the wave-induced flux is added to the model as follows:

$$\tau_{uw}(z) = \tau'_{uw}(z) + \tau''_{uw}(z), \quad (26)$$

where the wave-induced flux is incorporated into Eq. (19) following the exponential decay [Eq. (2)] obtained from LES results. After adding the wave-induced flux, the wind shear production in the prognostic equation for TKE is expressed as

$$P_s = -(u'w') \frac{\partial U}{\partial z} - (v'w') \frac{\partial V}{\partial z} + \tau''_{uw} \frac{\partial U}{\partial z}, \quad (27)$$

In the FUL experiment, the swell impact on the master length scale is also introduced. The three experiments (i.e., CTL, MIX, and FUL) are compared with each other to investigate the influence of swell.

c. 1D simulation comparison with LES results

The WRF-SCM simulation results for the flat cases agree well with the LES results (not shown here). The maximum differences in the wind speeds of the $U$ and $V$ components are approximately 0.3 and 0.4 m s$^{-1}$, respectively. The maximum temperature difference is less than 0.1°C.

The swell cases simulated by WRF-SCM (i.e., CTL, MIX, and FUL) and the LES results are shown in Figs. 10, 11, and 12 for cases FN1, FC2, and FC4, respectively. In case FN1, the CTL experiment fails to capture the swell-induced wind in the $U$ wind components (i.e., the swell direction coinciding with the geostrophic wind direction; see Fig. 10a). The ageostrophic $V$ wind component is positive in CTL; in contrast, it is negative in the LES results for case FN1. Adding only the swell impact on the master length scale (in the MIX experiment) has a limited influence on the wind speed results. This improves the wind speed (i.e., the $U$-component wind speed) near the surface layer but decreases the wind speed in the high boundary layer. The results agree with those of Rutgersson et al. (2012) that adding the swell impact on mixing length has a limited impact on the wind speed. Adding both the swell impact on master length scale and wave-induced flux (FUL) significantly improves the model performance, capturing the low-level wind jet (i.e., wind speeds higher than the geostrophic wind speed). The FUL simulation captures the negative wind speed in the $V$ component. In the convective cases (see Figs. 11, 12), the wind speed results are similar. The FUL experiment reduces the model error in wind speeds, though it generally overestimates the wind speed slightly compared with the results of the LES cases.

The simulated temperature profiles results of the three experiments are shown in Figs. 10c, 11c, and 12c. In the neutral case FN1 (Fig. 10c), the three experimental results agree well with the LES results in the atmospheric boundary layer. At the top of the boundary layer, the WRF-SCM temperature is a little higher than the LES temperature. Adding both the swell impact on the master length scale and momentum flux results in the best temperature performance of the three experiments. It should be noted that the potential temperature differences between these experiments are only about 0.1°C, so the effect can be considered small. In the convective cases (see Figs. 11c, 12c), the experiment CTL is more convective near the surface layer, where the temperature gradients are larger, while the gradients are smaller in the mixed layer. In contrast, the temperature is almost constant in the LES results. Adding the swell impact on the master length scale in the MIX experiment increases the temperature gradients in the surface layer, though it reduces the temperature gradients slightly in the mixed layer (approaching the LES results). When both the swell

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Wave impact on master length scale</th>
<th>Wave-induced momentum flux</th>
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<tbody>
<tr>
<td>CTL</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>MIX</td>
<td>Yes</td>
<td>No</td>
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<tr>
<td>FUL</td>
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### Table 2. The WRF-SCM settings.
impact on the master length scale and momentum flux are added, the temperature gradients perform the best. The temperature bias may be due to the model adjustment during the first half hour. Another possibility is different entrainment mechanisms under swell conditions caused by shear-induced engulfment events (Sullivan et al. 2014), which may need further study in our simulations to determine how they contribute to variances and mixing in the middle boundary layer and above.

TKE is lower near the surface in all WRF-SCM experiments than in LES (Figs. 10d, 11d, 12d). One possible reason is that the wind gradients in WRF-SCM (i.e., CTL, MIX, and FUL) are smaller than those in LES near the surface, so WRF-SCM does not capture the variances associated with the orbital velocity boundary condition used in LES. In the higher layer, the TKE from experiments CTL and MIX is much higher than those from LES in the neutral cases. This agrees with the LES result that TKE is smaller in swell cases than flat cases. Adding the swell impact on the master length scale (MIX) has a limited influence on TKE. Adding both the influence of swell on the master length scale and the momentum flux (in the FUL experiment) improves the agreement with the LES results in neutral cases.

In the convective cases, adding the influence of swell on the master length scale slightly increases the TKE compared to that in the CTL experiment. The FUL experiment reduces the TKE relative to the LES results, as the wind shear generally decreases in the boundary layer, except very near the surface. Though the TKE profiles may appear not to match the LES results very well in Figs. 11d and 12d and some further investigation

FIG. 10. The simulation profile results from case FN1 for (a) $U$ wind component, (b) $V$ wind component, (c) potential temperature $T$, and (d) TKE.
may be warranted, on the other hand, the differences are mostly below 0.1 m$^2$ s$^{-2}$, which can be considered quite small.

### 4. Discussion

The atmospheric PBL over waves is a complex system differing from that over flat surfaces. In most atmospheric numerical models, turbulence closure schemes are applied over the ocean without considering the wave influence. A few studies (Hanley and Belcher 2008; Semedo et al. 2009; Song et al. 2015) have tried to formulate models of the near-surface and boundary layer winds. However, how to introduce the wave impact into atmospheric numerical models is still an open question. In this paper, the swell impact on the master length scale and the swell-induced momentum flux are introduced into the MYNN closure scheme. There are some limitations, and below we elaborate on certain issues that need further work.

#### a. Profile of swell-induced momentum flux

The wave-induced momentum flux extends to much higher layers under swell conditions than under wind-wave conditions. The wave-induced momentum flux consists of two terms in a wave-following coordinate model (i.e., wave-induced turbulent stress and pressure stress). Compared with the wave-induced turbulent momentum flux, the pressure stress dominates the total wave-induced momentum flux. LESs demonstrate that the total wave-induced momentum flux decays approximately exponentially with height, which agrees with the results of open ocean measurements presented in Högström et al. (2015). The exponential decay coefficient varies for different wave states. In Jiang et al. (2016), the decay coefficient for pressure stress ranges from 1.0 to 1.4 m$^{-1}$.
from 0.69 to 2.05 for different wave ages, wave slopes, and wavelengths. Because the wave-induced momentum flux is much smaller than the pressure stress, the decay coefficient for the pressure stress approximately corresponds to the decay coefficient of the total wave-induced momentum flux. The decay coefficient $A$ decreases with increased wavelength, wave slope, and wave age (Jiang et al. 2016). In our study, the decay coefficient of the total wave-induced momentum flux is smaller at higher wave ages, corroborating the findings of Jiang et al. (2016). Buoyancy does not have a significant influence on the decay coefficient.

The wave conditions used in the LES cases are very simple. In nature, the wave conditions are much more complicated (i.e., mixed with wind-wave and swell). The exponential decay of wave-induced momentum in a more diverse set of conditions needs to be verified. In Hristov et al. (2003), the wind-wave-induced variance abruptly changes near the critical height. However, the critical height under swell conditions extends to the total boundary layer. At this point, there is no critical layer height under swell conditions. Near the surface layer, the air–sea interaction processes are much more complex and the process scales are very small. The resolution of LES may be insufficient to resolve these processes, and the subgrid parameterization may not able to capture them. However, the aim of this study is to parameterize the swell influence in the numerical models. Those processes very near the surface are very small relative to the resolution used for numerical weather prediction, mesoscale modeling, and climate studies.

b. Swell-induced surface momentum flux

The wave-induced total surface momentum flux is smaller at lower wave ages, which agrees with the results...
of Jiang et al. (2016). The total wave-induced surface momentum flux decreases with increasing $w_a/c_p$. One possible reason for this is that the buoyancy suppresses the wave-induced turbulence (Nilsson et al. 2012). The swell-induced momentum flux is positive (i.e., from ocean to atmosphere) in the LES cases used here. However, measurements (Högström et al. 2015) indicate that the swell-induced momentum flux can also be negative (i.e., from atmosphere to ocean) during moderate winds. In the open ocean, the unresolved waves (i.e., capillary waves) differ between wave phases. In this sense, the roughness lengths in different wave phases should differ from each other. This may result in some changes compared with present LES results, changes that will need to be studied in the future. However, under swell-induced positive momentum flux conditions, the model proposed here should be also valid through changing the wave-induced momentum flux and the master length scale.

c. Swell impact on the master length scale

The swell impact on the turbulent momentum flux is introduced into the diagnostic master length scale in the MYNN scheme. The results from the modified diagnostic master length equation agree well with the LES results. However, in the upper parts of the boundary layer, there are some deviations between the diagnostic master length and the LES results. One possible explanation for this is that the entrainment influence contributes to these deviations. Also, the TKE and dissipation are very small at the top of the boundary layer. However, this aspect is considered outside the scope of this study. Two exponential decay/increase terms are introduced into the swell influence master length fraction coefficient. The coefficients used in the parameterizations [Eqs. (17) and (18)] should be determined based on more experiments and data, as they may depend on many parameters such as wave age, wave slope, and wind-wave alignment.

d. Comparison and sensitivity of results

In this study, swell impacts on the atmospheric PBL are introduced into the MYNN turbulence closure scheme through three terms: the master length scale, swell-induced momentum flux on the surface, and wave-induced momentum flux profile. The first two terms have been introduced into some models (Rutgersson et al. 2012; Wu et al. 2016) with a positive impact on model performance. Adding only the swell impact on the master length scale (Rutgersson et al. 2012) slightly increases the surface wind speed and decreases the wind speed in the high layer (see the red line in Fig. 13) when the direct effect of wave-induced momentum flux is not considered. Applying the swell-induced momentum flux parameterization (Högström et al. 2015) to effective roughness length (Wu et al. 2016) reduces/increases the wind speed (see the gray lines in Fig. 13). The gray dashed (solid) line shows that the drag coefficient (effective roughness length) considering wave impact is smaller than that obtained using traditional parameterizations such as COARE (Fairall et al. 2003). However, introducing wave influence into effective roughness length cannot simulate the change in the profiles due to the swell waves. Introducing the swell-induced momentum flux profile (exponential decay with height) considerably improves the model simulation (see the black line in Fig. 13). Makin (2008) calculated the momentum flux from the turbulence and swell-induced momentum flux, separately, for neutral conditions based on a theoretical analysis. The profile of wave-induced momentum flux was calculated using Eq. (3) with $A = 10$. The wave character impact on the decay coefficient was not discussed in his study. The traditional atmospheric mixing length parameterization was used by Makin (2008) without considering possible surface wave influences. Based on LESs, we conclude that the three terms impacted by swell waves should be considered directly in numerical models to improve the model performance.
Simply speaking, in this study, the friction velocity and the wave-induced momentum flux are prescribed. In other words, the surface parameterization was not used here in our idealized simulations; instead, the friction velocity was provided to WRF-SCM from the LES output. Sensitivity analysis using WRF-SCM with different ratios of friction velocity and wave-induced momentum flux (not shown here) revealed that model results are greatly influenced by this ratio. To reach our ultimate goal of a better and more general surface layer parameterization that takes into account wave effects, we conclude from our sensitivity analysis that the turbulent momentum flux (without the swell-induced momentum flux) and wave-induced fluxes should likely be modeled separately to obtain robust model results. The swell-induced surface momentum flux (upward or downward) and its decay coefficient, as well as the swell impact on the master length scale, should be parameterized based on more data.

The results presented here are based on idealized LESs, which may be sensitive to the model configuration and subgrid schemes. In nature, wave conditions are complex (e.g., mixed wind-wave and swell, complex wave spectrum). The LES model used in this study simplifies wave conditions, resulting in certain differences from open sea measurements. The idealized LES allows us to focus on the fundamental dynamic processes due to wave influences (Jiang et al. 2016). What is more, LES results have shown good representations of measurements (Sullivan et al. 2008). Therefore, LES results can represent swell influences in nature to some degree.

Unlike katabatic flows (jetlike structures over land), which result from stable stratification and sloping terrain (Denby 1999; Grachev et al. 2016), wave-induced low-level wind jets are due to coupling with fast-moving surface waves (Sullivan et al. 2008). In the study of Smedman et al. (1993), marine low-level jets were analyzed assuming self-preservation similarity, and the largest nondimensional terms in the TKE budget were found to be of order 1 when the terms were made nondimensional with the proper scale combination. Low-level wind jets could potentially be somewhat similar in different situations, though their origins differ. The coupling impact of waves on the wind profile is the focus of this study.

5. Conclusions

Over waves, atmospheric boundary layer turbulence is altered by underlying surface waves. Accordingly, the wave influences should be considered in turbulence closure schemes developed for flat terrain to be able to capture wave influences. A turbulence closure scheme frame (i.e., the MYNN PBL parameterization) was investigated based on the LESs of wind-following swell cases through three terms: wave impact on the atmospheric mixing, the wave-induced surface momentum flux, and the profile of wave-induced momentum flux. Compared with the LES results, the modified MYNN scheme is incorporated into the WRF-SCM, which performs better than the original MYNN scheme.

The swell-induced surface momentum flux decreases with \( W_0/c_p \) (i.e., under increasingly convective conditions), possibly because the buoyancy suppresses the wave-induced turbulence. The swell-induced momentum flux displays approximately exponential decay with height. The decay coefficient does not differ significantly between cases with unstable stratification of roughly the same wave age. However, wave age has a significant impact on the wave-induced surface momentum flux and the exponential decay coefficient of swell-induced momentum flux.

The impact of swell on the atmospheric mixing is incorporated into the master length scale in the MYNN scheme by adding a wave contribution term to the surface length scale. Adding the swell impact on the mixing length improves the performance of the diagnostic master length equation. The swell contribution term is dependent on the wave state, which needs to be studied more under various wave conditions.

WRF-SCM simulations indicate that the impact of swell on the master length scale is limited compared with the impact of wave-induced momentum flux, based on the limited LES cases considered here. When both the swell impact on the master length scale and wave-induced momentum flux are considered, WRF-SCM performs better than the control simulation (without considering wave influence). The swell influence on the PBL and surface layer parameterizations should therefore be considered in order to improve the model performance.

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