WAVEWATCH III in CESM and Langmuir mixing parameterization

Qing Li, Baylor Fox-Kemper, Adrean Webb

May 15, 2017

1 WAVEWATCH III in CESM

A full-spectral, third-generation, wind-wave model WAVEWATCH III (version 3.14, Tolman, 2009) has been incorporated into CESM as a new component model. The governing equations and numerical approaches are described in Tolman (2009), and the coupling with POP for the purpose of Langmuir mixing parameterization is discussed in Li et al. (2016). A general overview is given here.

WAVEWATCH III supports various choices of wave physics by different combinations of compile switches. However, all model physics and settings are fixed in the version coupled in CESM, and are based on the recommendations of Rascle et al. (2008) and Ardhuin et al. (2010). The relevant compile switches are ‘ST3’, ‘STAB3’, and ‘FLX0’; all other switches are default. The code is modified to allow the calculation of the Langmuir mixing enhancement factor (Li et al., 2016, and Section 2) and two-way coupling with POP through the compiler. There are a variety of other wave effects on the climate system (Cavaleri et al., 2012), but for CESM2 only the Langmuir enhancement of ocean mixing is explicitly treated as part of the standard model. WAVEWATCH III uses a variety of variables from the coupler to provide the Langmuir enhancement factor (see below).

In the current setup, WAVEWATCH III runs on a 3.2°× 4° latitude-longitude grid with 25 frequency and 24 directional bins (denoted as *ww3a*). The frequency spans from 0.0412 s^{-1} to 0.4056 s^{-1} with an increment factor of 1.1. An ice cap is used in this grid, assuming no wave effects north of 78.4°N. This ice line is chosen to maximize the latitudinal regions covered without degrading model performance by using smaller time steps to account for shrinking grid cell width. Due to the different resolutions and grid alignment, the topography and land mask used by the wave model are different from those used for the ocean model.

The surface wind and temperature from the atmosphere model, surface current, sea surface temperature and boundary layer depth from the ocean model, and sea ice fraction from the sea ice model are required to drive WAVEWATCH III. For the purpose of Langmuir mixing parameterization (see Section 2 for more details), currently only the enhancement factor is passed back to the ocean model. However, other wave variables, such as significant wave height, peak wave period and Stokes drift, are calculated in WAVEWATCH III and can be accessible to other component models with moderate modifications. This implementation allows for rapid experimentation and development of new wave-based parameterizations. The frequency at which WAVEWATCH III exchanges variables with the coupler is flexible. By default it is set to the frequency at which the atmospheric model communicates with the coupler.

The necessary remapping of the variables from different component models is performed in the coupler. Bilinear interpolation is used to remap variables from and to the wave grid *ww3a*, except for ocean and sea ice variables near the coastline, where the nearest neighbor method is used to match the ocean-land boundaries of the wave grid and ocean-sea ice grid.

2 Langmuir mixing parameterization

A new Langmuir mixing parameterization has been developed and implemented in POP. The goal is to account for the enhanced vertical mixing within the ocean surface boundary layer when Langmuir turbulence, a physical process induced by the interaction between the surface gravity waves and the mean flow (e.g., Craik and Leibovich, 1976; McWilliams et al., 1997), is present (Belcher et al., 2012; D'Asaro et al., 2014). The implemented Langmuir mixing parameterization and its implementation in POP is detailed in Li et al. (2016) and further discussed and extended elsewhere (McWilliams and Sullivan, 2000; Van Roekel et al., 2012; Li et al., 2017; Li and Fox-Kemper, 2017). A general overview is described here.

The effect of Langmuir turbulence on enhancing the vertical mixing within the ocean surface boundary layer is parameterized by applying an enhancement factor, $\mathcal{E}$, on the turbulent velocity scale used in the K-profile parameterization (KPP, Large et al., 1994), following the idea of McWilliams and Sullivan (2000). The new turbulent velocity scale in KPP is therefore,

$$W = \frac{\kappa u^*}{\phi}\mathcal{E}, \tag{1}$$

with $\kappa = 0.4$ the von Kármán constant, u^* the water-side friction velocity and ϕ the dimensionless flux profile defined in Large et al. (1994). The formula of the enhancement factor is empirically determined from large eddy simulation based study of Van Roekel et al. (2012),

$$\mathcal{E} = |\cos\alpha|\sqrt{1 + (1.5La_{\mathrm{SL,proj}})^{-2} + (5.4La_{\mathrm{SL,proj}})^{-4}}. \tag{2}$$

The surface layer averaged and projected Langmuir number,

$$La_{\mathrm{SL,proj}} \equiv \sqrt{\frac{u^* \cos(\alpha)}{|\langle \boldsymbol{u}^{\mathrm{S}}\rangle_{\mathrm{SL}}| \cos(\theta_{\mathrm{ww}} - \alpha)}}, \tag{3}$$

is used to describe the relative effects of directly wind-driven shear and the Stokes drift, $\boldsymbol{u}^{\mathrm{S}}$. This definition of Langmuir number distinguishes from the more traditional turbulent Langmuir number (McWilliams et al., 1997), $La_{\mathrm{t}} \equiv \left(u^*/u_0^{\mathrm{S}}\right)^{1/2}$ with $u_0^{\mathrm{S}} \equiv |\boldsymbol{u}^{\mathrm{S}}(0)|$ the magnitude of surface Stokes drift, by accounting for both the effects of the Stokes drift decay depth and the wind-wave misalignment (Harcourt and D'Asaro, 2008; Van Roekel et al., 2012). Generally, the Langmuir turbulence is expected to be weaker if the waves are young (with a shallow Stokes drift decay depth) or misaligned with the wind. Here, θ_{ww} is the angle between wind and waves, and $\langle \boldsymbol{u}^{\mathrm{S}}\rangle_{\mathrm{SL}}$ the surface layer averaged Stokes drift,

$$\langle \boldsymbol{u}^{\mathrm{S}}\rangle_{\mathrm{SL}} = \frac{1}{H_{\mathrm{SL}}}\int_{-H_{\mathrm{SL}}}^{0} \boldsymbol{u}^{\mathrm{S}}(z)dz, \tag{4}$$

with H_{SL} the surface layer depth, taken in CESM2 as proportional to the critical Richardson number based boundary layer depth diagnosed in KPP: $H_{\mathrm{SL}} = 0.2 H_{\mathrm{BL}}$. The angle between wind and Langmuir cells, α, is estimated based on the law of the wall (Van Roekel et al., 2012),

$$\alpha \approx \tan^{-1}\left[\frac{\sin\left(\theta_{\mathrm{ww}}\right)}{\frac{u^*}{u_0^{\mathrm{S}}\kappa}\ln\left(\left|H_{\mathrm{BL}}/z_1\right|\right)+\cos\left(\theta_{\mathrm{ww}}\right)}\right], \tag{5}$$

with z_1 the onset depth of the law of the wall, which is taken as four times the significant wave height (Thorpe, 2007).

Note that $\langle \boldsymbol{u}^{\mathrm{S}}\rangle_{\mathrm{SL}} \to 0, La_{\mathrm{SL,proj}} \to \infty, \mathcal{E} \to 1$ if the boundary layer is already deep. This prevents over-deepening of the mixed layer depth when convection dominates the vertical mixing in winter. In addition, the enhancement factor is only applied to ice-free regions, with an ice fraction threshold of 0.05. Better understanding of the wave-ice interaction is required to accurately represent the Langmuir mixing and other wave effects in the marginal ice zone.

The enhancement factor, (2), is calculated in WAVEWATCH III and passed back to POP. Note that the calculation of $\langle \boldsymbol{u}^{\mathrm{S}}\rangle_{\mathrm{SL}}$ in (4) is implemented analytically and does not evaluate the Stokes drift on a discrete vertical grid and thus is independent of the vertical resolution of the ocean model. Instead, $\langle \boldsymbol{u}^{\mathrm{S}}\rangle_{\mathrm{SL}}$ is calculated from the wave action density spectrum $S(k,\theta)$ in WAVEWATCH III by

$$\begin{aligned}\langle \boldsymbol{u}^{\mathrm{S}}\rangle_{\mathrm{SL}} =& \frac{2}{H_{\mathrm{SL}}}\int_{k_{\mathrm{i}}}^{\infty}\int_{-\pi}^{\pi}\int_{-H_{\mathrm{SL}}}^{0} \hat{\boldsymbol{e}}^{\mathrm{w}}\omega k S(k,\theta)\mathrm{e}^{2kz}\,dz d\theta dk \\ =& \frac{1}{H_{\mathrm{SL}}}\int_{k_{\mathrm{i}}}^{k_{\mathrm{c}}}\int_{-\pi}^{\pi} \hat{\boldsymbol{e}}^{\mathrm{w}}\omega S(k,\theta)(1-\mathrm{e}^{-2kH_{\mathrm{SL}}})d\theta dk + \langle \boldsymbol{u}^{\mathrm{S}}_{\mathrm{tail}}\rangle_{\mathrm{SL}},\end{aligned} \tag{6}$$

where $\hat{\boldsymbol{e}}^{\mathrm{w}}$ is the wave direction, $\omega = 2\pi f$ the angular frequency, k the wavenumber with an initial value of k_{i} and a cutoff value of k_{c}, and $\langle \boldsymbol{u}^{\mathrm{S}}_{\mathrm{tail}}\rangle_{\mathrm{SL}}$ the contribution from the high frequency part of the spectrum (the tail). Deep water wave dispersion relation $\omega^2 = gk$ is used here for illustration. However, the corrections for finite depth water waves are applied in the code. $\langle \boldsymbol{u}^{\mathrm{S}}_{\mathrm{tail}}\rangle_{\mathrm{SL}}$ is approximated by assuming a ω^{-5} tail (see more discussion in Webb and Fox-Kemper, 2015).

$$\begin{aligned}\langle \boldsymbol{u}^{\mathrm{S}}_{\mathrm{tail}}\rangle_{\mathrm{SL}} =& \frac{2\omega_{\mathrm{c}}^4}{gc_g H_{\mathrm{SL}}}\int_{-H_{\mathrm{SL}}}^{0}\left[\mathrm{e}^{2k_{\mathrm{c}}z}-\sqrt{-2\pi k_{\mathrm{c}} z}\,\mathrm{erfc}\left(\sqrt{-2k_{\mathrm{c}}z}\right)\right]dz\int_{-\pi}^{\pi}\hat{\boldsymbol{e}}^{\mathrm{w}}S(k_{\mathrm{c}},\theta)d\theta \\ =& \frac{\omega_{\mathrm{c}}^4}{3gc_g k_{\mathrm{c}} H_{\mathrm{SL}}}\Big[1-(1-4k_{\mathrm{c}}H_{\mathrm{SL}})\mathrm{e}^{-2k_{\mathrm{c}}H_{\mathrm{SL}}} \\ & -2\sqrt{\pi}\,(2k_{\mathrm{c}}H_{\mathrm{SL}})^{3/2}\,\mathrm{erfc}(\sqrt{2k_{\mathrm{c}}H_{\mathrm{SL}}})\Big]\int_{-\pi}^{\pi}\hat{\boldsymbol{e}}^{\mathrm{w}}S(k_{\mathrm{c}},\theta)d\theta \\ \approx& \frac{\omega_{\mathrm{c}}^4}{3gc_g k_{\mathrm{c}} H_{\mathrm{SL}}}\left[1-(1-4k_{\mathrm{c}}H_{\mathrm{SL}})\mathrm{e}^{-2k_{\mathrm{c}}H_{\mathrm{SL}}}\right]\int_{-\pi}^{\pi}\hat{\boldsymbol{e}}^{\mathrm{w}}S(k_{\mathrm{c}},\theta)d\theta,\end{aligned} \tag{7}$$

where ω_{c} is the cutoff angular frequency associated with k_{c}, g the gravitational acceleration, $c_g = \partial\omega/\partial k$ the wave group velocity. The z-integral in (7) is similar to that in Appendix A of Li et al. (2017), and the final step is justified for typical value of $k_{\mathrm{c}}H_{\mathrm{SL}}$.

The enhancement factor does change the boundary layer depth determined by KPP indirectly and the entrainment rate as well. However, Li et al. (2016) argue that Stokes drift should be included in the unresolved shear term of KPP. Li and Fox-Kemper (2017) provide a scaling law for the unresolved shear that produces a rate of entrainment consistent with Large Eddy Simulations. This entrainment factor is not part of the Langmuir parameterization included in CESM2, but is available through the Community Ocean Vertical Mixing Project (CVMix, https://github.com/CVMix).

To enable the Langmuir mixing parameterization, information about the ocean surface waves (primarily the Stokes drift) is required to estimate the enhancement factor. WAVEWATCH III was implemented in CESM specifically for this reason. However, other options are available if the computational cost of WAVEWATCH III is a concern. It is shown in Li et al. (2017) that two alternatives, (a) a monthly enhancement factor climatology, and (b) an approximation to the enhancement factor based on the empirical wave spectra, are able to reproduce the mean effects of Langmuir mixing as estimated using WAVEWATCH III.

The former option, denoted as the *Data Wave* model, is activated by using the 'dwav' option as the wave model component. The 12-month enhancement factor data is taken from the mean over years 2000-2009 of an ocean-wave coupled simulation forced by the inter-annually varying CORE-II atmospheric datasets. The mean enhancement factor is relatively robust to the choice of the averaging period, showing much less variability than other wave variables under changing wind and ocean forcing, which even so are modest over recent decades (Hemer et al., 2013). However, the use of the *Data Wave* model under significantly different climate conditions, such as paleoclimate simulations, is not recommended.

The latter option, denoted as the *Theory Wave* model, is not yet supported in the current release of POP. However, it is already available through CVMix. The enhancement factor is approximated by a function of local 10-m wind speed, friction velocity and boundary layer depth, based on empirical wave spectra and global wave hindcast simulations (see more details in Li et al., 2017). No regionally specific empirical parameters are used in the Theory Wave model. Therefore, it is expected to be more robust than the Data Wave model under climate change, although changes to the swell climate will not be picked up without information from a prognostic wave model.

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