QING Li et al (2019): Compares 11 boundary layer schemes, demonstrates the lack of community consensus, and exposes “limited understanding, numerical deficiencies.”

OMWG will need to prioritize requirements for vertical mixing physics and for numerics, and establish a decision protocol (UNICON vs. CLUBB).

Metrics problem: vertical fluxes can’t be measured, only inferred.

Large Eddy Simulation (LES) solves the Navier-Stokes equations, so can be used to study turbulence (Burchart et al. 2008), and hence to provide metrics from a broad range of oceanic conditions.
OBSERVED OCEAN

\[ U = \{U, V\}; \Theta \ (IC) \]

SURFACE FLUXES & WAVES

Large Eddy Simulation

FLUXES

STAT E

RULES

Validation

FLUXES

Vertical Mixing Scheme (PAR)
Buoyancy flux regimes: Cartoon

REGIME I | REGIME II | REGIME III | REGIME IV
---|---|---|---
06 | 12 | 18 | 24
Local time

Wind

u*

Cooling

Stable (heating)

Waves

\( U_s(z) \)

\( B_0 \)

Heat

Cool

Entrain

Detrain

DEPTHS: \( h \) \( d_G \) \( d_F \) \( d_E \) \( d_{Top} \) \( d_{Bot} \)
Across–Shear momentum flux  🔄  Across–flux shear

\[ \partial_z V' < 0 \]

Wind Stress  \[ \tau_Y > 0 \]

LES shear

\[ \Omega \]

\[ \langle w' u' \rangle \]

\[ \langle w' v' \rangle \]

\[ U_{dn} \]

\[ U_{up} \]
Local and non-local boundary layer transport

\[
<w\theta> = K_s (-\partial_z \Theta) + \Gamma_s = K_s (-\partial_z \Theta + \gamma_s)
\]

\[
<wu> = K_m (-\partial_z U) + \Gamma_u = K_m (-\partial_z U + \gamma_u)
\]

\[
<wv> = \Gamma_v = K_m \gamma_v = <wu> \tan \Omega
\]

\[K_{m,s} = w_{m,s} \text{ Length}_{m,s} ; \text{ not } \text{ Length}^2 / \text{ Time}\]

\[Pr = K_m / K_s\]
Buoyancy flux, $\langle w\theta \rangle$

\[ -B_0 \quad B_h \quad \langle w\theta \rangle \]

\[ \partial_{z} \Theta = 0 \]

Detrain

\[ d_T \]

\[ d_B \]
Buoyancy flux, $\langle w\theta \rangle$
Momentum flux components

**along-shear**

a) $-\langle wu \rangle$ (cm/s)$^2$

b) $-\langle wu \rangle^{PAR}$

**across-shear**

a) $-\langle wv \rangle$ (cm/s)$^2$

b) $-\langle wv \rangle^{PAR}$
Entrainment Rule (production of TKE)

\[(d_E B_E) = 0.2 \text{ Eulerian Shear} + 0.3 \text{ Stokes Shear} + 1.8 \text{ Buoyancy}\]

Pure Convection:
\[(-B_E / B_0) = 0.12 \approx 0.17 \approx 0.2\]
Regime II Detrainment Zone: \(d_T < d < d_B\)

\[\delta \Omega = \sin^{-1}(\frac{\partial_z |U|}{\partial_z U}) - \Omega \approx -10^\circ\]

\[\Gamma_\theta^{DET} = B_0(t_T) R_S G_\theta^{DET}(\sigma^{DET}) F_\theta(\delta t)\]
Some Physics Requirements:

From 2019 CESM workshop:
• Monin-Obukhov Similarity theory holds in surface layer
• Turbulent Prandtl number may exceed 1

Today
• Non-local buoyancy (tracer) flux
• Non-local across-shear momentum flux
• Entrainment rule verified over broader range
• Non-entraining & detrainment capability
• MLD is not an adequate metric
Regime II Detrainment Zone: \( 0 < \sigma^{DET} < 1 \)

\[
\Gamma^{DET}_\theta = B_0(t_T) \ R_s \ G^{DET}_\theta(\sigma^{DET}) \ F_\theta(\delta t)
\]

\[
\tau^{DET} = u^*(t_T) \ G^{DET}_\tau(\sigma^{DET}) \ F_\tau(\delta t)
\]

\[
\Omega^{DET} = \sin^{-1}(\partial_z |U|/\partial_z U) + 10^\circ
\]
Turbulent velocity scales

Turbulent Prandtl Number: \( \left( \frac{w_m^{\text{PAR}}}{w_s^{\text{PAR}}} \right) > 1 \)