A new eddy diffusivity parameterization for ocean models using Assumed Distribution Higher Order closure (ADHOC)

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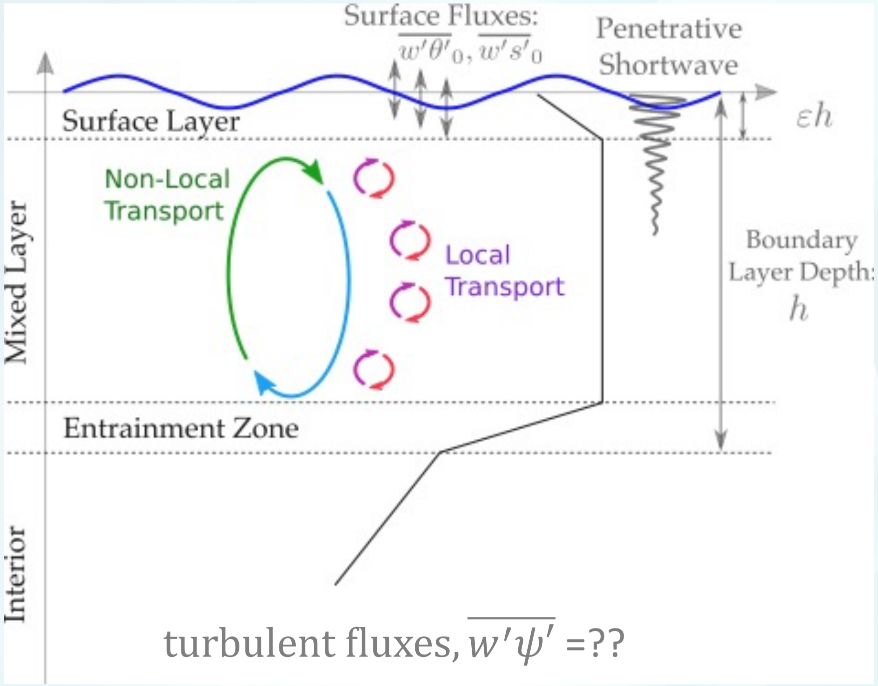
Introduction: Ocean surface boundary layer (OSBL)

- OSBL (O~(0.1-1km deep)) mediates momentum, mass, heat and scalar tracer fluxes between the interior ocean and the atmosphere and plays a significant role in weather and climate variations on timescales from a few days to centuries.

- Capturing OSBL variability on a global scale remains a critical challenge that requires the development of new approaches to observation, estimation and modeling.

- General circulation models (GCMs) used to study climate can not adequately resolve the small-scale turbulent motions associated with the dynamics of OSBL and hence the effects are generally parameterized.



turbulent fluxes, $\overline{w'\psi'}$ =??

Background and Motivation

Current practice and outstanding issues:

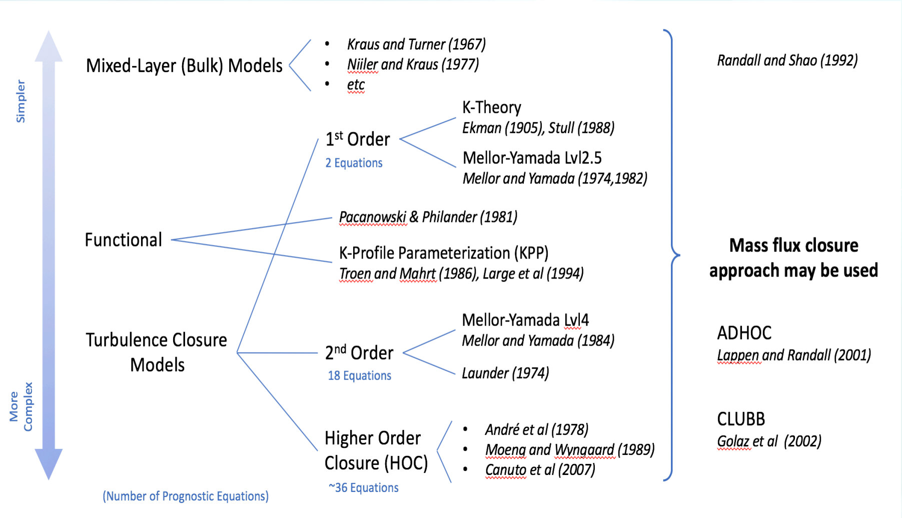
Bulk Mixed Layer models:
- -Energetics included and simple to implement
- -Upper ocean never fully mixed

Functional fits:
- -computationally efficient
- -has dimensional constant, not globally valid,

Two equation models
- -Energetics included
- -Underpredicts mixing, dissipation equation has no physics, sensitive to time and vertical resolutions

HOC -Higher accuracy, computationally expensive

KPP (most commonly used)
- -simple, includes non-local transport
- -only depends on surface forcing, lack of energetics, sensitive to vert. resolution



Simpler

More Complex

(Number of Prognostic Equations)

Mixed-Layer (Bulk) Models
- *Kraus and Turner (1967)*
- *Niiler and Kraus (1977)*
- *etc*

1st Order
2 Equations
- K-Theory *Ekman (1905), Stull (1988)*
- Mellor-Yamada Lvl2.5 *Mellor and Yamada (1974,1982)*

Functional
- *Pacanowski & Philander (1981)*
- K-Profile Parameterization (KPP) *Troen and Mahrt (1986), Large et al (1994)*

Turbulence Closure Models

2nd Order
18 Equations
- Mellor-Yamada Lvl4 *Mellor and Yamada (1984)*
- *Launder (1974)*

Higher Order Closure (HOC)
~36 Equations
- *André et al (1978)*
- *Moeng and Wyngaard (1989)*
- *Canuto et al (2007)*

Randall and Shao (1992)

Mass flux closure approach may be used

ADHOC
Lappen and Randall (2001)

CLUBB
Golaz et al (2002)

A new eddy diffusivity parameterization – Unified parameterization

- Cross fertilization of mass flux closure and higher order closure
- Energetics included
- Represents both local and non-local transports
- Fewer prognostic equation needed than a traditional high level closure and includes closure for higher order moments

Mass Flux Closure (MFC) (Arakawa, 1969)

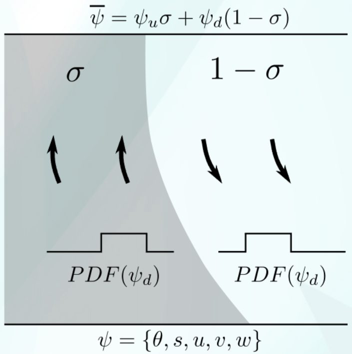
- All dynamic and thermodynamic quantities are represented with a double delta function.
- If at any depth, the area fraction of upward moving fluid is σ and that of downward moving fluid is $1-\sigma$, then mean value of any variable ψ, is defined as the weighted average of the quantities associated with the up (ψ_u) and downdrafts (ψ_u)

$$\bar{\psi} = \sigma\psi_u + (1-\sigma)\psi_d,$$

- Vertical fluxes ($\overline{w'\psi'}$) are represented as a product of convective mass flux M_c and difference in a quantity's values between updraft and downdraft

$$\overline{w'\psi'} = M_c(\psi_u - \psi_d)$$

$$M_c = \sigma(1-\sigma)(w_u - w_d)$$



Mass Flux Closure + High Order closure- ADHOC (Randall, 1992)

- Higher order moments are obtained from mass flux variables and lower order moments
- Uses Assumed joint probability density distribution of the variable of interest (double delta)
- Physically based diagnose of σ and M_c

$$\overline{\psi'^2} = \sigma(1-\sigma)(\psi_u - \psi_d)^2$$

$$\overline{w'\psi'^2} = \sigma(1-\sigma)\,(1-2\sigma)\,(w_u - w_d)(\psi_u - \psi_d)^2$$

$$\overline{w'\psi'^3} = \sigma(1-\sigma)\,(1-3\sigma+3\sigma^2)\,(w_u - w_d)(\psi_u - \psi_d)^3$$

$$\overline{w'\psi'\phi'} = \sigma(1-\sigma)\,(1-2\sigma)\,(w_u - w_d)(\psi_u - \psi_d)\,(\phi_u - \phi_d) = (1-2\sigma)(w_u - w_d)\,\overline{\psi'\phi'}$$

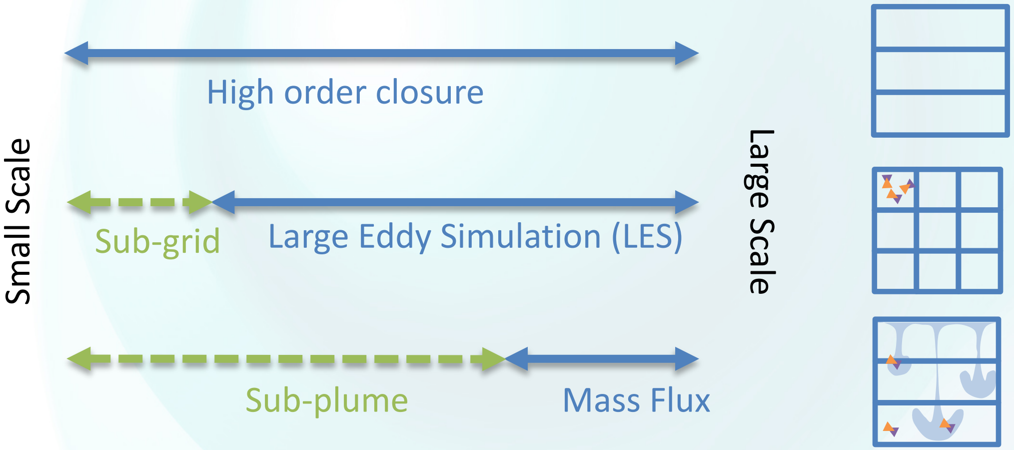
$$\sigma = 0.5 - \frac{S_w}{2(4+S_w^2)^{\frac{1}{2}}}$$

$$M_c = \frac{\left(\overline{w'^2}\right)^{1/2}}{(4+S_w^2)^{1/2}}$$

$$(w_u - w_d) = M_c/\sigma(1-\sigma)$$

Skewness, $S_w = \dfrac{\overline{w'^3}}{(\overline{w'^2})^{3/2}}$

Interpretation of relevant scales



High order closure

Small Scale

Sub-grid

Large Eddy Simulation (LES)

Large Scale

Sub-plume

Mass Flux

- Sub-plume scale effects in ADHOC are included in turbulent flux and mean state equations through generic source/sink term
- Lateral mixing (E+D) are parametrized with convective mass flux and dissipation mixing length

Prognostic equations

There is an *exact* correspondence in the transport and buoyancy terms of the HOC and MFC equations considering plume scales only. For example, for velocity variance equation,

<u>MFC</u>

$$\frac{\partial \overline{w'^2}}{\partial t} = -\frac{\partial \overline{w'^3}}{\partial z} + 2\overline{w'b'} - \frac{2}{\rho_0}\overline{\left(w'\frac{\partial p'}{\partial z}\right)} - \varepsilon_{ww}$$

Turbulent transport

Buoyancy generation

Pressure correlation

Dissipation

<u>HOC</u>

$$\frac{\partial \overline{w'^2}}{\partial t} = -\frac{\partial}{\partial z}\left[M_c(1-2\sigma)(w_u-w_d)^2\right] + 2M_c\left[(b_u-b_d) - \frac{1}{\rho}\frac{\partial}{\partial z}(p_u-p_d) - S_{sps}\right] - (w_u-w_d)^2(E+D)$$

Turbulent transport

Buoyancy generation

Pressure correlation

Sub-plume effects

Dissipation

Need sub-plume scale parameterizations:

$$\frac{\partial e_{sps}}{\partial t} = -\overline{u'w'}_{ses}\frac{\partial U}{\partial z} - \overline{v'w'}_{sps}\frac{\partial V}{\partial z} + g(\alpha_T\overline{w'\theta'}_{sps} - \beta_S\overline{w's'}_{sps}) - \frac{\partial}{\partial z}\overline{w'(e_{sps}+p'/\rho_0)} - \varepsilon_{sps} = S_{PS}$$

Test cases and LES

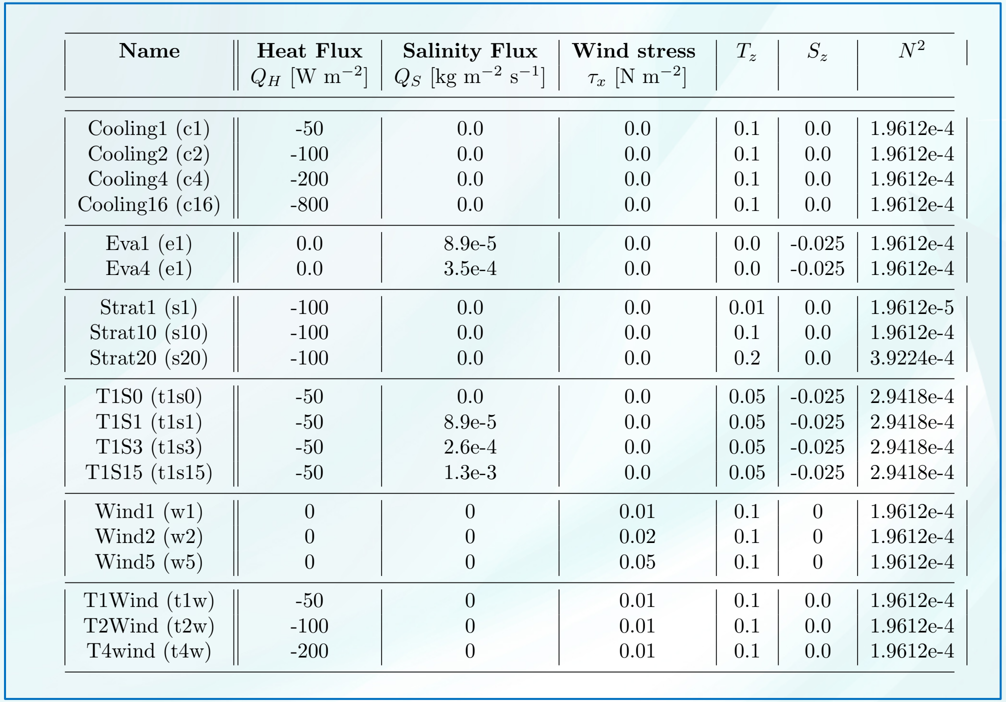
1-D test cases

- c1, c2, c4, c16 are free convection due to surface cooling
- e1, e4 are free convection due to surface evaporation
- w1, w2, w5 are wind stress with Coriolis
- s1, s10, s20 free convection with different initial stratification
- t1s1, t1s3, t1s15 are free convection due to both surface cooling and evaporation
- t1w, t2w, t4w are combination of free convection due to surface cooling and wind stress
- 1m, 2m, 5m, 10m vertical resolution

Large Eddy Simulation

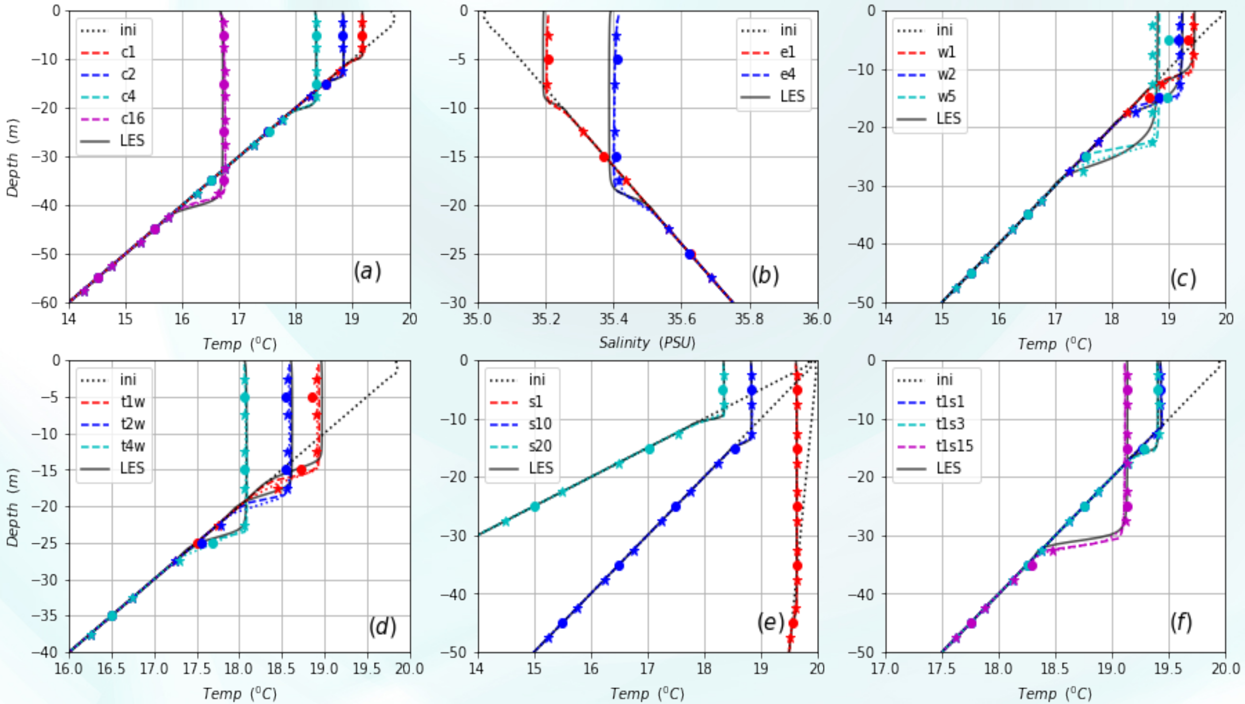
- 128m x 128m x 150m
- 0.5 m horizontal resolution, stretched grid in vertical with 0.1m surface layer thickness
- Pseudo-spectral, 3rd order RK time step
- Deardorff (1980) sub-grid parameterization

Table 1 Forcing and initialization for test cases



Name	**Heat Flux** Q_H [W m^{-2}]	**Salinity Flux** Q_S [kg m^{-2} s^{-1}]	**Wind stress** τ_x [N m^{-2}]	T_z	S_z	N^2
Cooling1 (c1)	-50	0.0	0.0	0.1	0.0	1.9612e-4
Cooling2 (c2)	-100	0.0	0.0	0.1	0.0	1.9612e-4
Cooling4 (c4)	-200	0.0	0.0	0.1	0.0	1.9612e-4
Cooling16 (c16)	-800	0.0	0.0	0.1	0.0	1.9612e-4
Eva1 (e1)	0.0	8.9e-5	0.0	0.0	-0.025	1.9612e-4
Eva4 (e1)	0.0	3.5e-4	0.0	0.0	-0.025	1.9612e-4
Strat1 (s1)	-100	0.0	0.0	0.01	0.0	1.9612e-5
Strat10 (s10)	-100	0.0	0.0	0.1	0.0	1.9612e-4
Strat20 (s20)	-100	0.0	0.0	0.2	0.0	3.9224e-4
T1S0 (t1s0)	-50	0.0	0.0	0.05	-0.025	2.9418e-4
T1S1 (t1s1)	-50	8.9e-5	0.0	0.05	-0.025	2.9418e-4
T1S3 (t1s3)	-50	2.6e-4	0.0	0.05	-0.025	2.9418e-4
T1S15 (t1s15)	-50	1.3e-3	0.0	0.05	-0.025	2.9418e-4
Wind1 (w1)	0	0	0.01	0.1	0	1.9612e-4
Wind2 (w2)	0	0	0.02	0.1	0	1.9612e-4
Wind5 (w5)	0	0	0.05	0.1	0	1.9612e-4
T1Wind (t1w)	-50	0	0.01	0.1	0.0	1.9612e-4
T2Wind (t2w)	-100	0	0.01	0.1	0.0	1.9612e-4
T4wind (t4w)	-200	0	0.01	0.1	0.0	1.9612e-4

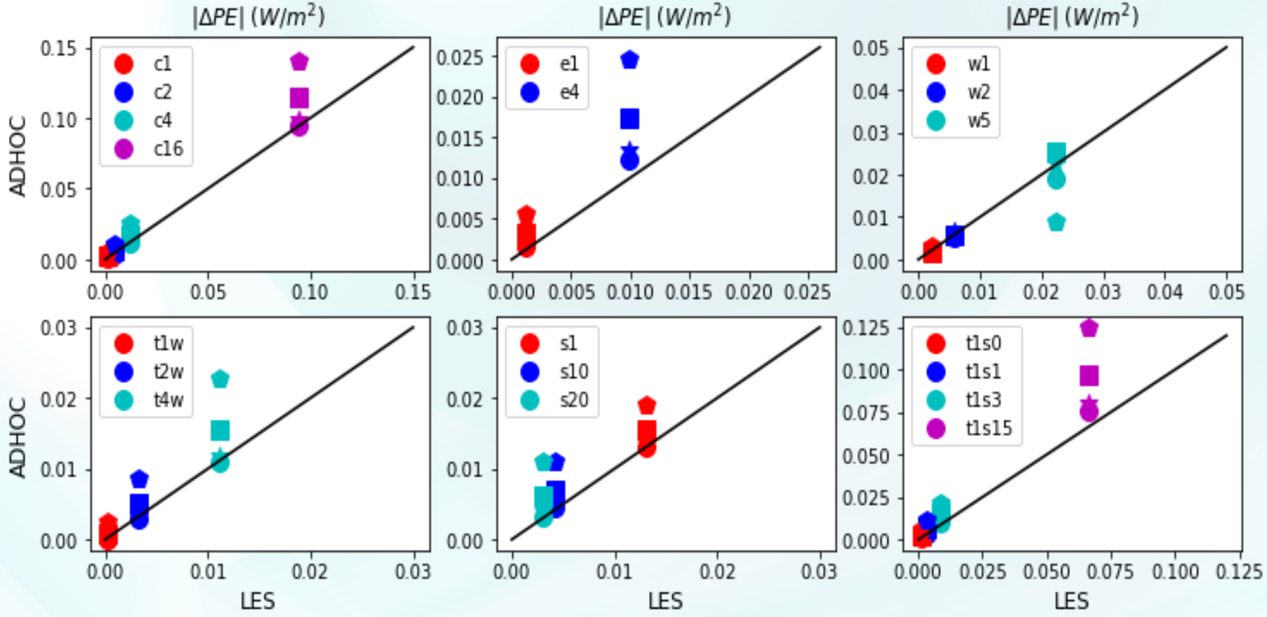
Results: Mean profiles



Comparisons of mean profiles against LES (solid black) for each cases as shown in table 1. different colors indicate the test cases with different surface forcing (table 1) as shown in the legend of each subplot along with different vertical resolutions. For each color, 1m: dashed line, 2m : dotted line, 5m: star, 10m: circle. Dotted black line is the initial stratification for each profile. All results are 6 hour average data representing 3rd day simulation.

- Proposed parameterization captures the growth of boundary layer and mean profiles adequately
- Entrainment zone is comparable to that of LES profiles
- Insensitive to vertical resolution

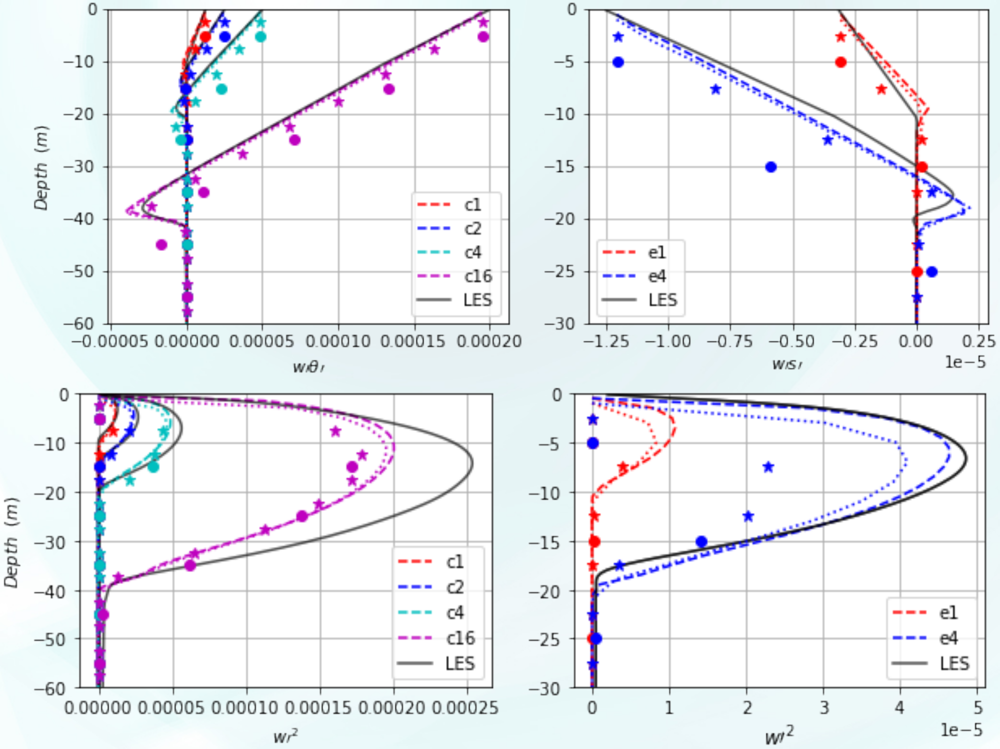
Results: Depth integrated potential energy



Comparisons of change of depth integrated potential energy over 4 days simulations with that of LES . Colors indicate different test cases as shown in each plot. Markers indicate different resolutions. Circle: 1m, star: 2m, square: 5m, pentagon: 10m.

- Rate of change of vertically integrated potential energy suggests good comparison between proposed parameterization and LES for fine resolution, and with acceptable error for coarse resolution

Results: Turbulent fluxes



Comparisons of heat flux (upper panel) vertical velocity variance (lower panel) against LES (solid black) for test cases as shown in table 1. Different color indicate different surface forcing. For each color, 1m: dashed line, 2m : dotted line, 5m: star, 10m: circle. All results are 6 hour average data representing 3rd day simulation.

- Proposed mass flux parameterization shows promising results in capturing second moment

- # Conclusion
  - Mass flux closure approach is more realistic than K-Profile Parameterization closure for representation of higher order transport terms.
  - ADC captures both local and nonlocal transport adequately.
  - Fewer prognostic equations are required compared with conventional HOC.
  - Insensitive to vertical resolution, can be incorporated to large-scale model.
  - Captures mean and turbulent fluxes well.
- # Progress
  - New closure shows promising results.
  - Horizontal entrainment/detrainment and sub-plume contributions are implemented.
  - The closure has been usefully integrated with MPAS-O.
  - Successfully implemented in GPU, 75x faster that CPU.
- # Future work
  - Implement semi-implicit time stepping.
  - Test with global ocean sea ice model.