Eddy-Diffusivity Mass-Flux Parameterization: An Approach to unify Diffusion and Convection in Ocean Models

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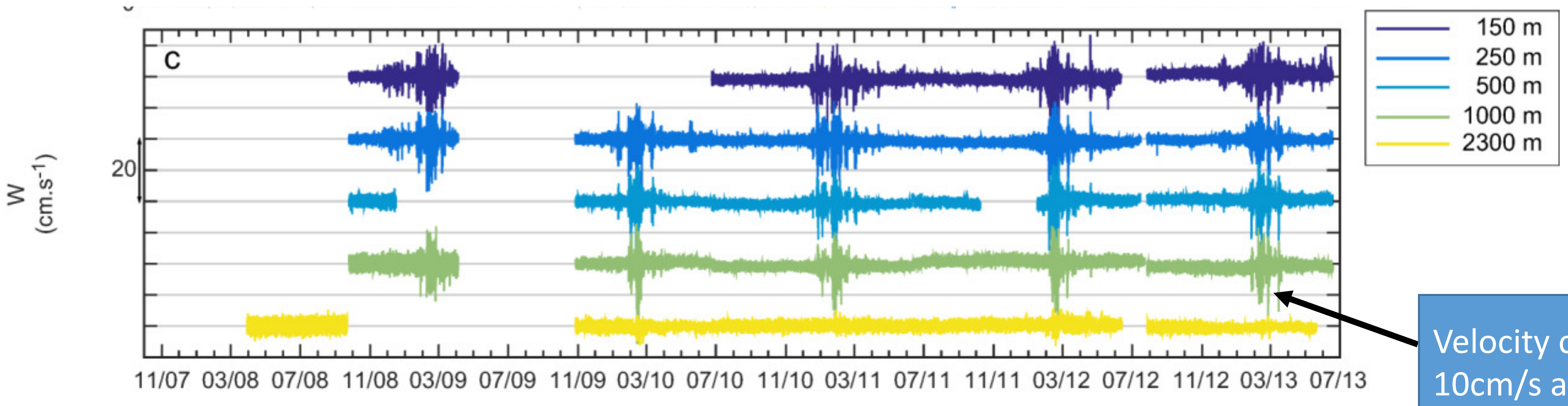
Outline

- **Convection and vertical mixing in ocean**
- **Eddy-Diffusivity-Mass-Flux**
  - Concept
  - Theory
  - Implementation in NEMO
- **1D analytic cases**
  - Surface Buoyancy loss (Marshall et al. 1999)
  - Static instability
- **1D realistic case: Lion Station**
- **Conclusions**

Example of convective velocity in ocean: LION Station

Observation at LION station

(Houpper et al., 2016)



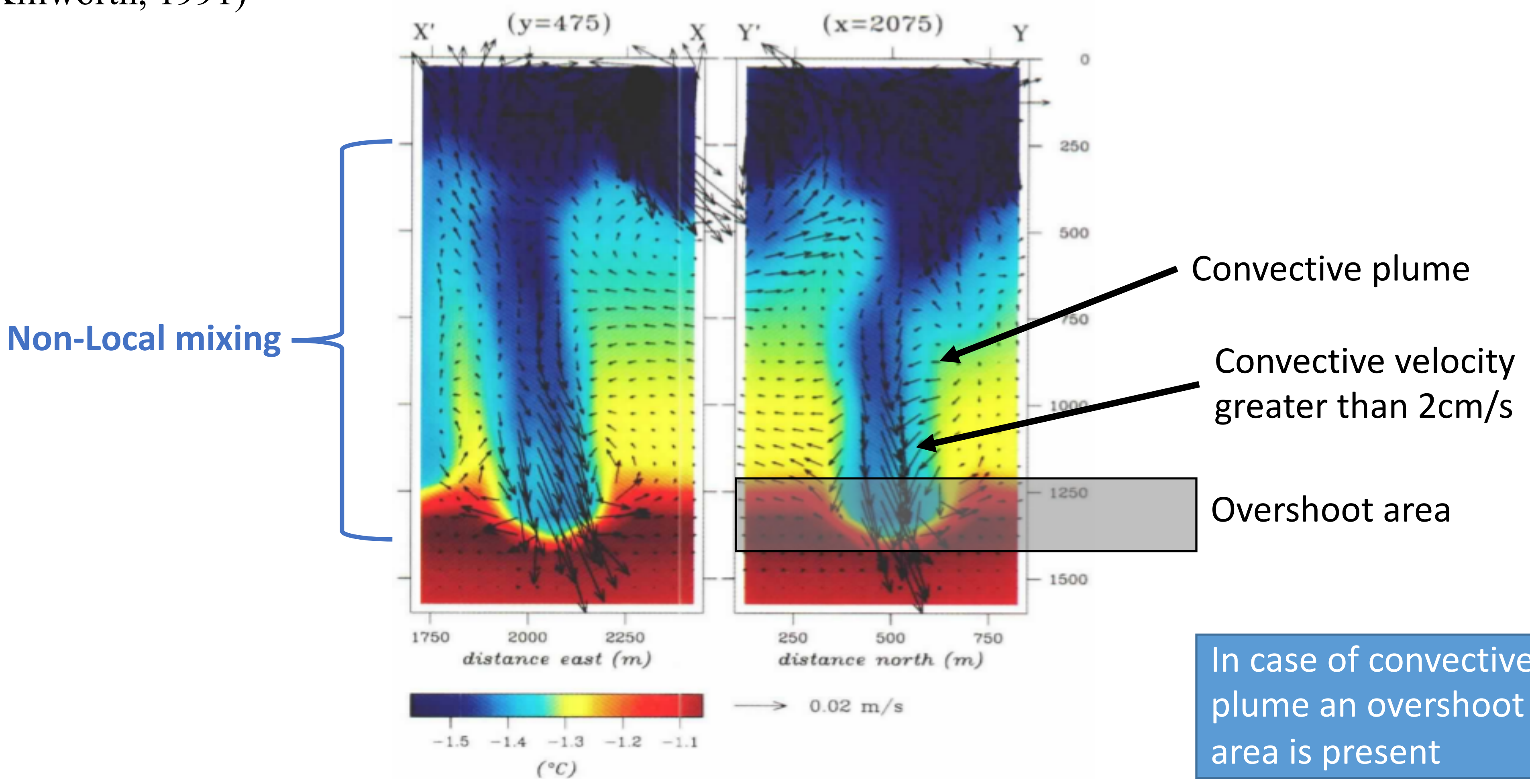
Velocity can reach 10cm/s at 1000m

Observed vertical velocity at LION station for different depths

(each interval corresponds at $10 cm.s^{-1}$)

Example of non-Local vertical mixing

LES: downdrafts perforating the thermocline - Overshoot
(Scott and Killworth, 1991)



In case of convective plume an overshoot area is present

Vertical Mixing

Local : fluxes at a given depth depend on water properties at that depth

Diffusion Fluxes: Small eddies

$$\overline{w'T'} = K\frac{\partial \bar{T}}{\partial z}$$

Non-local : fluxes are influenced by remote forcing

Convection Fluxes: Large eddies

Parcels move regardless of the local gradient

In oceanography, most of the time, the non-local mixing is treated by modification of local formulations by:

Counter Gradient term: $\overline{w'T'} = K\left(\frac{\partial \bar{T}}{\partial z} - \gamma\right)$

Non Penetrative convective Adjustment (NPC)

Enhanced the vertical mixing coefficient: constant (EVD) or profile

} **Density structures and water masses production not realistic**

Eddy-Diffusivity vs Mass-Flux, Concept

Decomposition of mixing in 2 scales : small (Eddy-Diffusivity) and large (Mass-Flux)

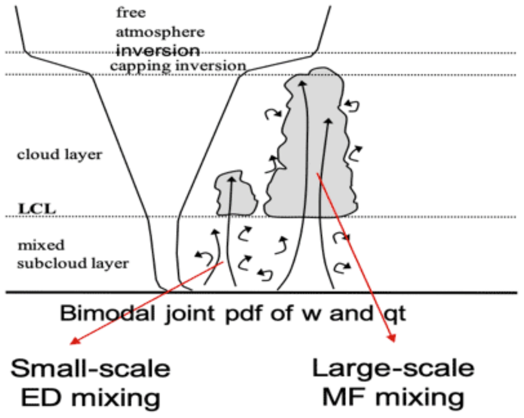
The **Eddy-diffusivity**: standard scheme (TKE in this study)

The **Mass Flux**:

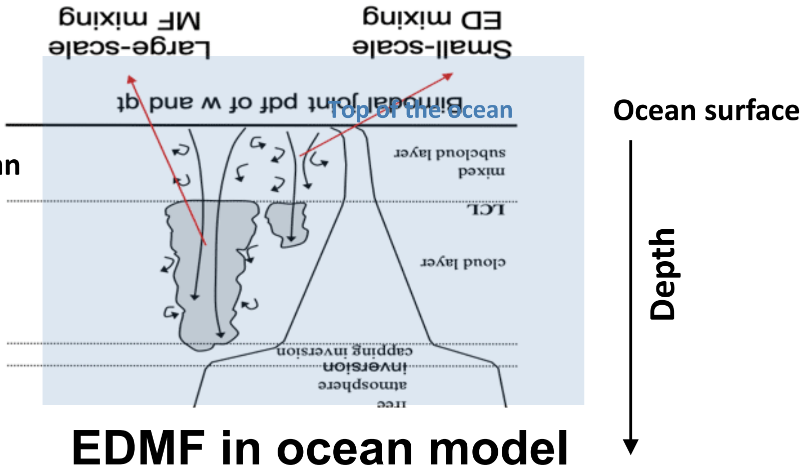
- non local sub-grid process driven by the energy of the buoyancy anomaly
- represents the convective plumes.

This work already done in atmospheric models (Soares et al., 2004; Siebesma et al. 2007; Rio et al. 2012; Hourdin et al 2019).

EDMF in atmospheric model



Idea: applying same approach for ocean

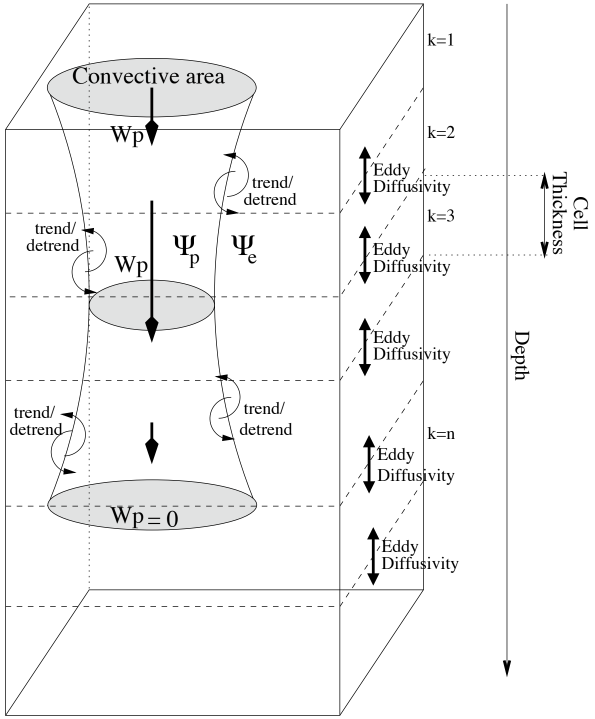


EDMF in ocean model

Mass Flux Convection, theory

Local and non-local (organized large eddies) mixing are computed explicitly at each time step

Scheme of Local and non-local processes in a model:



Schematic representation of a convective plume in a single grid-mesh (Mass Flux). Eddy-diffusivity occurs locally at each level

The equations system solved for Mass-Flux:

$$\begin{cases} \dfrac{\partial \psi_p}{\partial z} = \varepsilon_t(\overline{\psi}_p - \psi_e) & \text{Tracer vertical evolution inside the plume} \\[2ex] \left(\dfrac{1}{2}+\alpha\right)\dfrac{\partial w_p^2}{\partial z} = a_1 F_b(z) - \alpha g \dfrac{\rho_p}{P_h} & \text{Vertical velocity of the plume} \\[2ex] \dfrac{1}{a_p}\dfrac{\partial a_p}{\partial z} = -\dfrac{1}{wp}\dfrac{\partial w_p}{\partial z} - pent + cdet & \text{Convective area of the plume} \\[2ex] F_M = -apw_p & \text{Mass Flux (MF)} \\[2ex] \dfrac{\partial \psi}{\partial t} = \dfrac{\partial F_M(\psi - \psi_p)}{\partial z} & \text{Temporal advance of MF part} \end{cases}$$

Eddy-Diffusivity-Mass-Flux, implementation in NEMO

Unification of local (diffusion, ED) and non-local (convection, MF) vertical mixing

The temporal advance of the variables Ψ expresses as the **diffusive** and **convective** fluxes divergence

$$\frac{\partial \psi}{\partial t} = -\frac{\partial \overline{w'\psi'}}{\partial z}$$

where

$$\overline{w'\Psi'} = \underbrace{-K\frac{\partial \psi}{\partial z}}_{\text{Diffusion}} + \underbrace{F_M\left(\psi_p - \psi\right)}_{\text{Convection}}$$

EDMF scheme written in **unified** matrix form with implicit formulation:

$$\begin{pmatrix} (1+B_{diff}+B_{conv})(k) & C_{conv}(k) & 0 \\ A_{diff}(k) & (1+B_{diff}+B_{conv})(k) & (C_{diff}+C_{conv})(k) \\ 0 & A_{diff}(k) & (1+B_{diff}+B_{conv})(k) \end{pmatrix} \begin{pmatrix} \psi(k-1)^{t+1} \\ \psi(k)^{t+1} \\ \psi(k+1)^{t+1} \end{pmatrix} = \begin{pmatrix} 0 \\ \psi(k)^t - \frac{\overline{F}_M(k)\Delta t}{e3w(k+1)}\psi_p(k) + \frac{\overline{F}_M(k+1)\Delta t}{e3w(k+1)}\psi_p(k+1) \\ 0 \end{pmatrix}$$

where

$$\begin{cases} A_{diff}(k) = -\frac{K_z(k)\Delta t}{e3t(k)e3w(k)} \\ A_{conv}(k) = 0 \\ B_{diff}(k) = \frac{K_z(k)\Delta t}{e3t(k)e3w(k)} + \frac{K_z(k+1)\Delta t}{e3t(k)e3w(k+1)} \\ B_{conv}(k) = -\frac{\overline{F}_M(k)\Delta t}{e3w(k+1)} \\ C_{diff}(k) = -\frac{K_z(k+1)\Delta t}{e3t(k)e3w(k+1)} \\ C_{conv}(k) = \frac{\overline{F}_M(k+1)\Delta t}{e3w(k+1)} \end{cases}$$

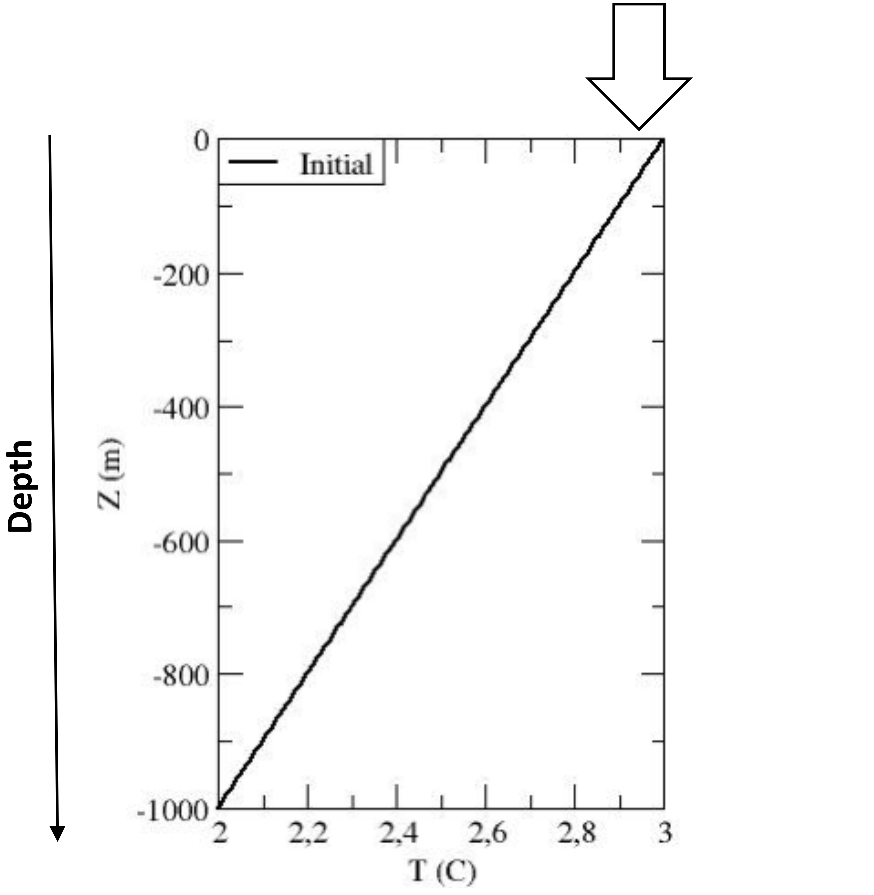
K_z is the vertical diffusion coefficient.

In this approach the unification of Local and non Local mixing is called Eddy-Diffusivity-Mass-Flux: EDMF

EDMF, 1D analytic case: Marshall & Schott 1999 (1)

Strong Surface Buoyancy loss over a Stratified Ocean

$B_0 = -500Wm^{-2}$

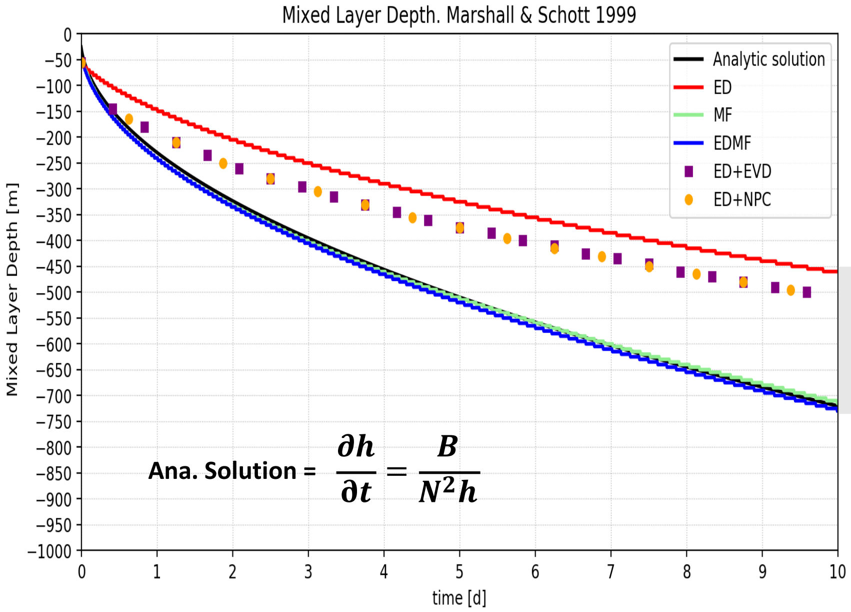


Initial Temperature profile of Marshall and Schott 1999 experiment

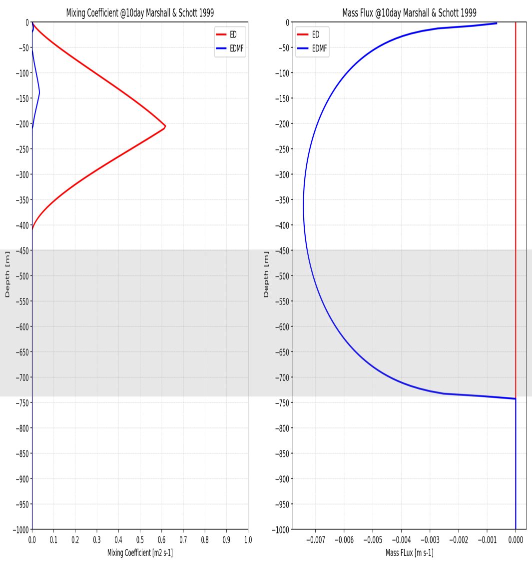
Experiment:

- Stable temperature profile (constant salinity)
- -500 $W.m^{-2}$ during 10 days are apply at the surface

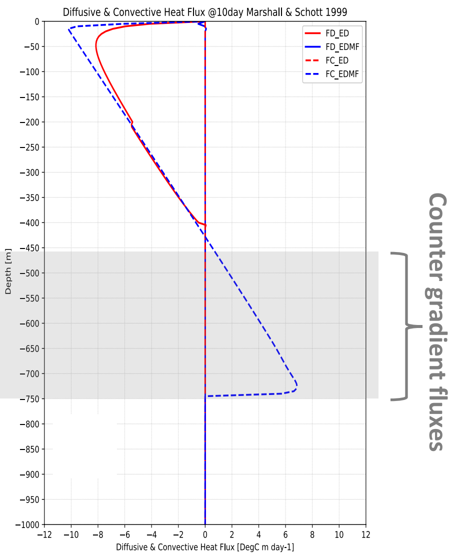
EDMF, 1D analytic case: Marshall & Schott 1999 (2)



Evolution of MLD in Marshall& Schott 1999 experiment. Analytic solution in black; ED-only (tke) in red; EDFM (tke+mf) in blue



Diffusive coefficient (left) and Mass Flux (right) after 10 days of marshall & Schott experiments.
ED-only (tke) in red; EDFM (tke+mf) in blue



Diffusive (line) and convective (dashed) heat fluxes after 10 days of marshall & Schott experiments.
ED-only (tke) in red; EDFM (tke+mf) in blue

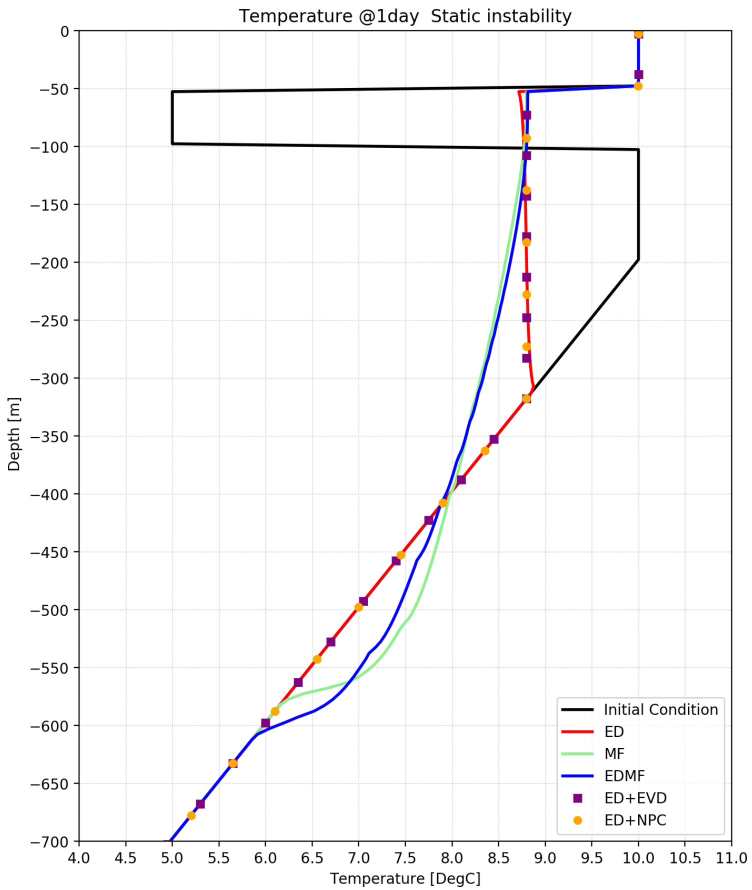
-> MLD simulated with EDMF approach is closer to the analytic one compared to ED (TKE) one
-> EDMF approach, based on the work of the buoyancy force which allows counter-gradient fluxes
-> No diffusion at counter gradient in both simulations but a decrease of Mass Flux in EDMF case

EDMF, 1D analytic case: strong static instability

Experiment: Start from a strong static instability in the water column: Anomaly of 5°C between 50-100m (Black line)
No atmospheric forcing.

Presented plot: Solution of 5 simulations after 240 time steps:

- ED-only: TKE (red)
- ED+EVD: TKE + Enhanced vertical Diffusion (purple square)
- ED+NPC: TKE+ Non Penetrative Convection (purple dots)
- MF-only: Mass Flux (green)
- EDMF: TKE + Mass Flux (Blue)



Temperature for a static instability in the water column. Initial condition in black; after one day for ED (tke) in red; EDFM (tke+mf) in blue

-> EDMF is able to break the stratification in static instability case → Overshoot the thermocline
-> EDMF stable in numerical point of view (very strong static instability)

1D real test case: ASICS-Med Experiment

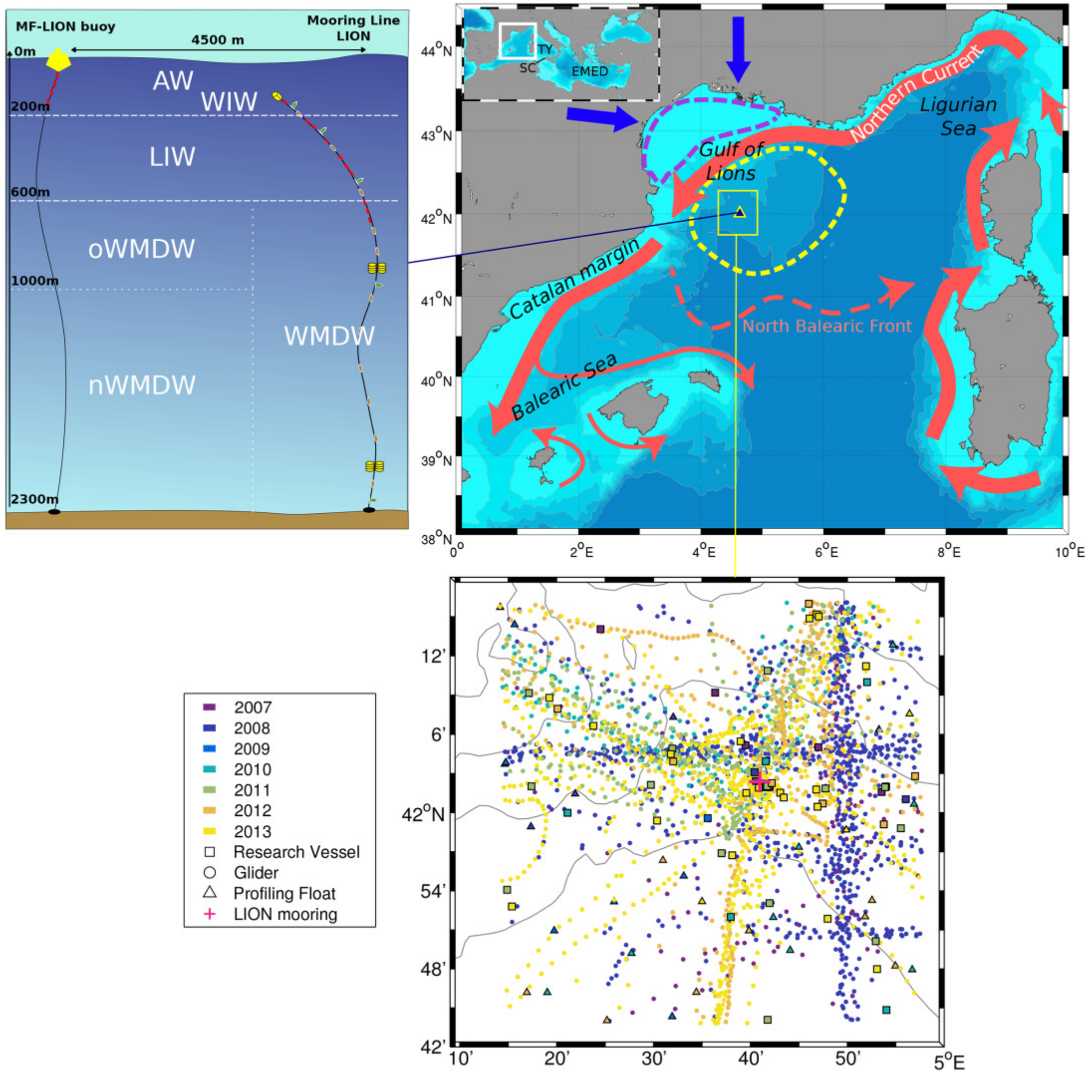
ASICS-Med Experiment :

- Western Mediterranean
- January to March 2013

Model set-up

- 1D NEMO configuration located at Lion Buoy
- Initial Condition deduced from observed profile
- Flux reprocesses (Caniaux et al)
- 2 turbulent closures tested:
    - Eddy-Diffusivity only (TKE)
    - Eddy-Diffusivity-Mass-Flux (TKE+MF)

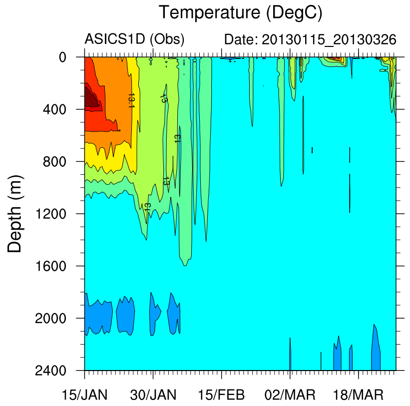
NEMO1D simulation results compare to mooring data



The LION station (Houpper et al. 2106)

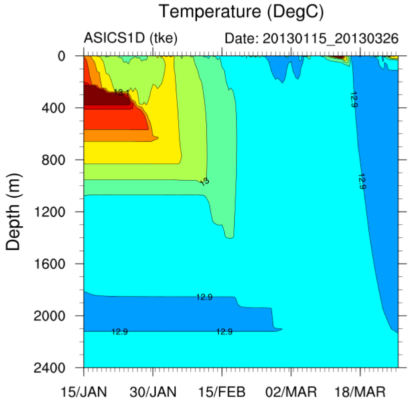
ASICS-Med Experiment: Temperature

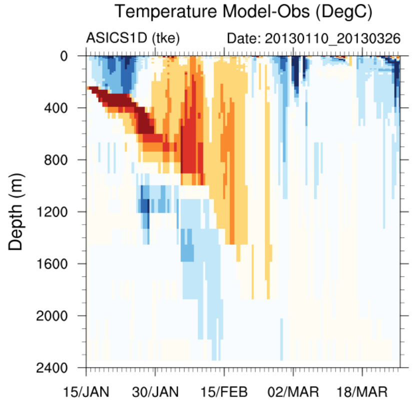
Observed Temperature at LION MOORING



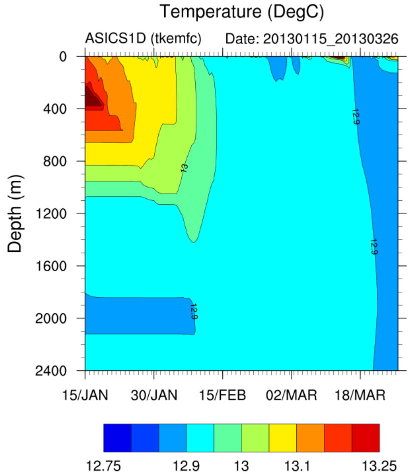
Temperature Model bias

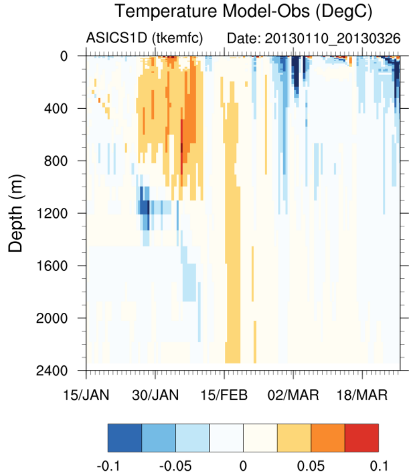
Eddy-Diffusivity only simulation





Eddy-Diffusivity-Mass-flux simulation

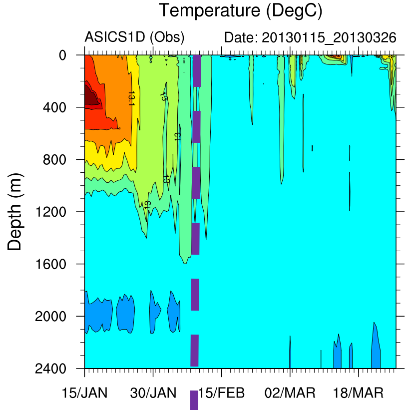




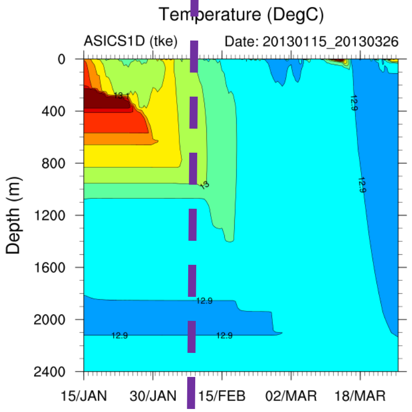
- Better timing in Temperature homogenization
- Reduction of temperature bias thanks to EDMF

ASICS-Med Experiment: Temperature

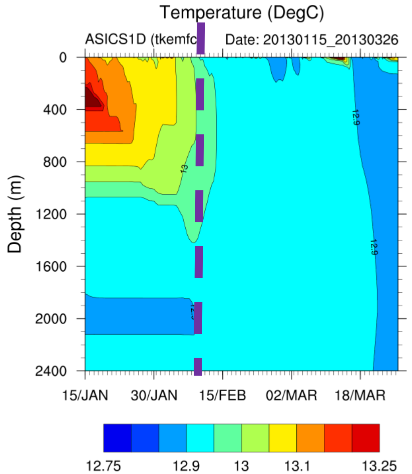
Observed Temperature at LION MOORING



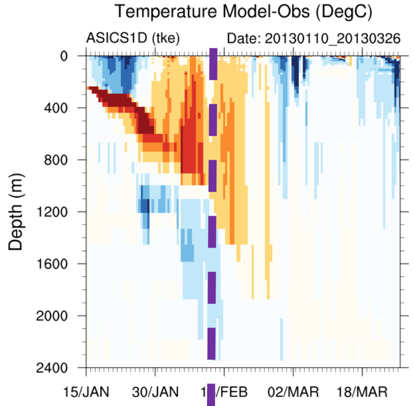
Eddy-Diffusivity only simulation

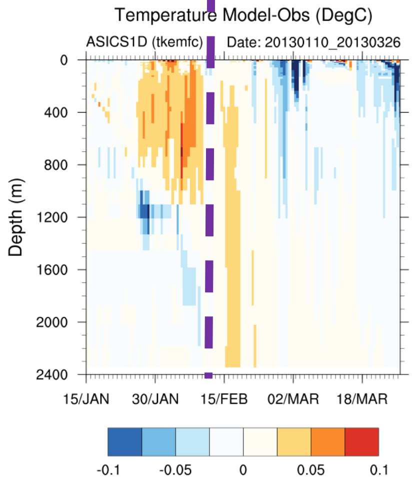


Eddy-Diffusivity-Mass-flux simulation

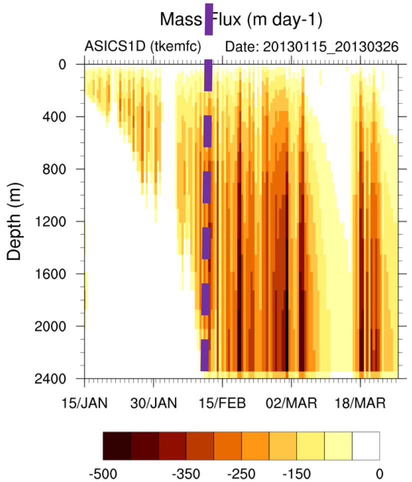


Temperature Model bias





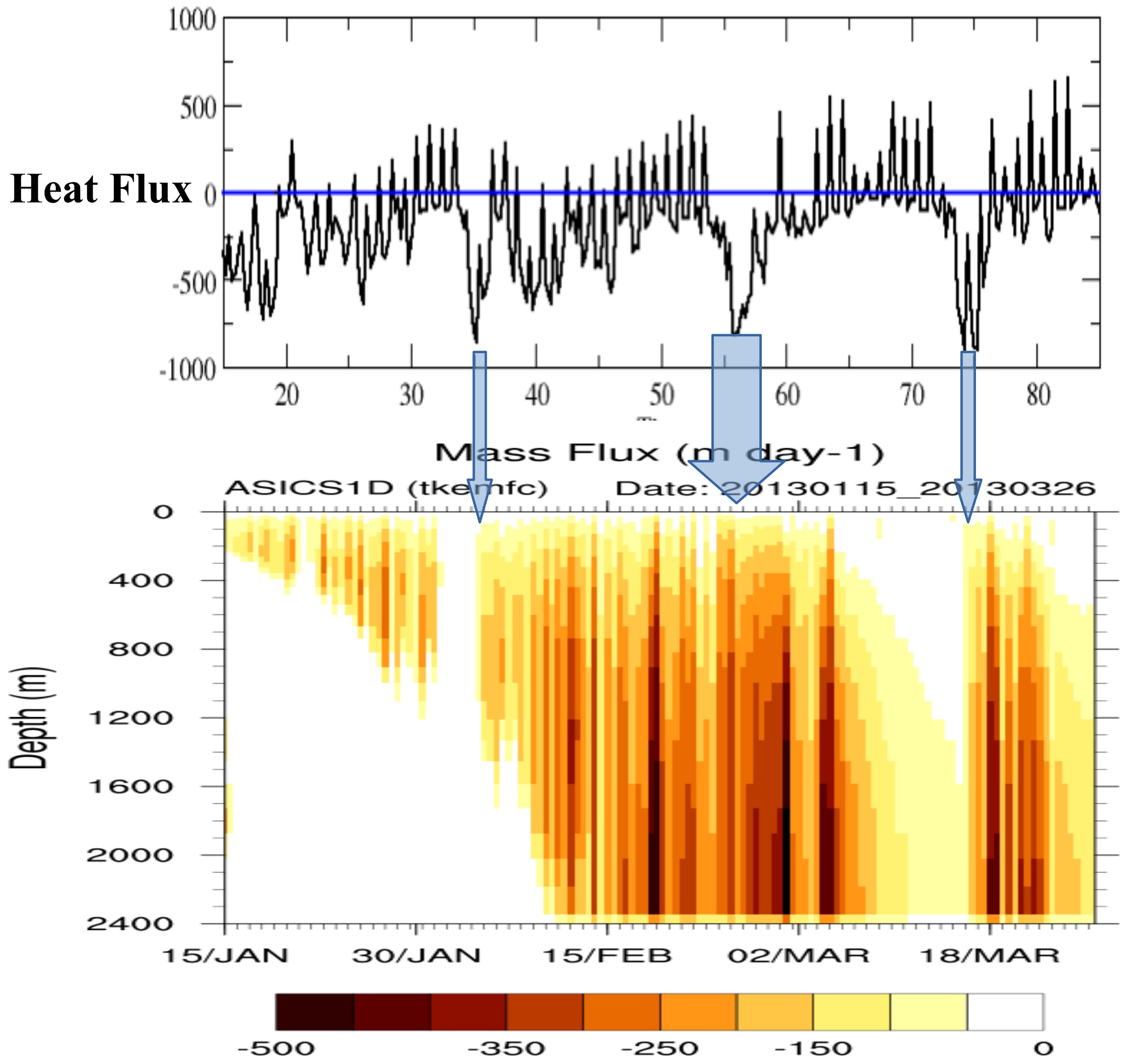
- February 9 first date of convection at sea floor. Argo floats (Coppola et al., 2017)
  -> Very well captured by EDMF
- Convective velocity can be greater than 10 cm/s



ASICS-Med Experiment: Link Mass Flux/Forcing fluxes

Surface Net Heat Flux

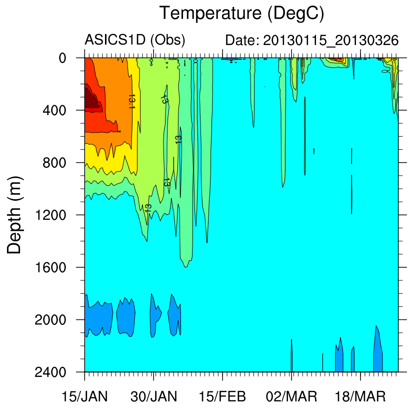
Mass Flux



- Strong negative Heat Flux induces Mass Flux.
- Clear Mass Flux responses to strong negative variation of Heat Flux

ASICS-Med Experiment: Diffusive & Convective terms

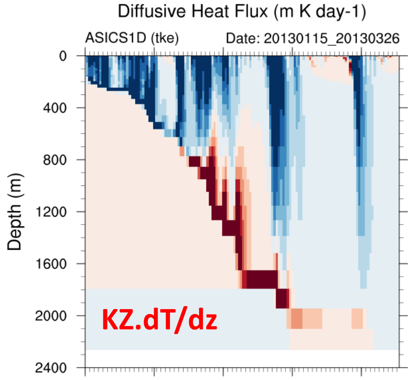
Observed Temperature at LION MOORING

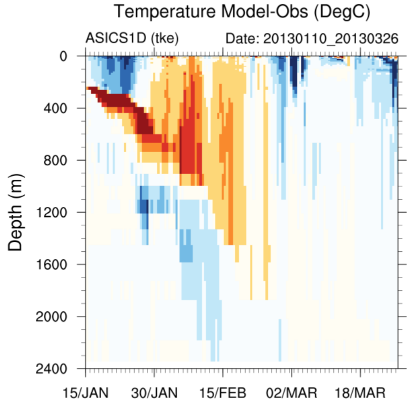


- Diffusive fluxes are lower in EDMF because convective fluxes do the job

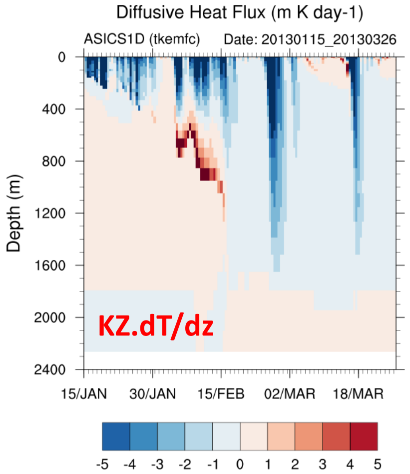
Temperature Model bias

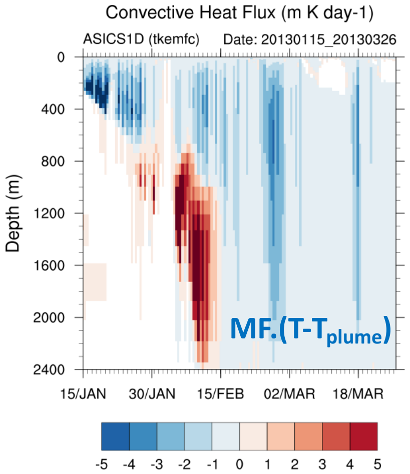
Eddy-Diffusivity only simulation

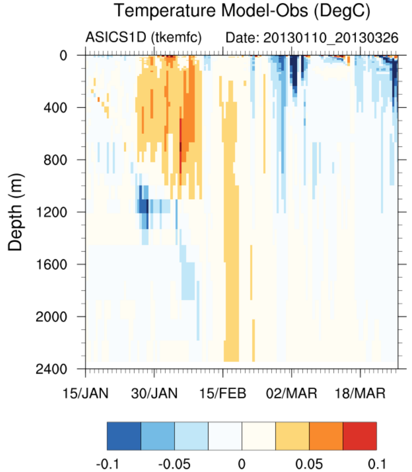




Eddy-Diffusivity-Mass-flux simulation





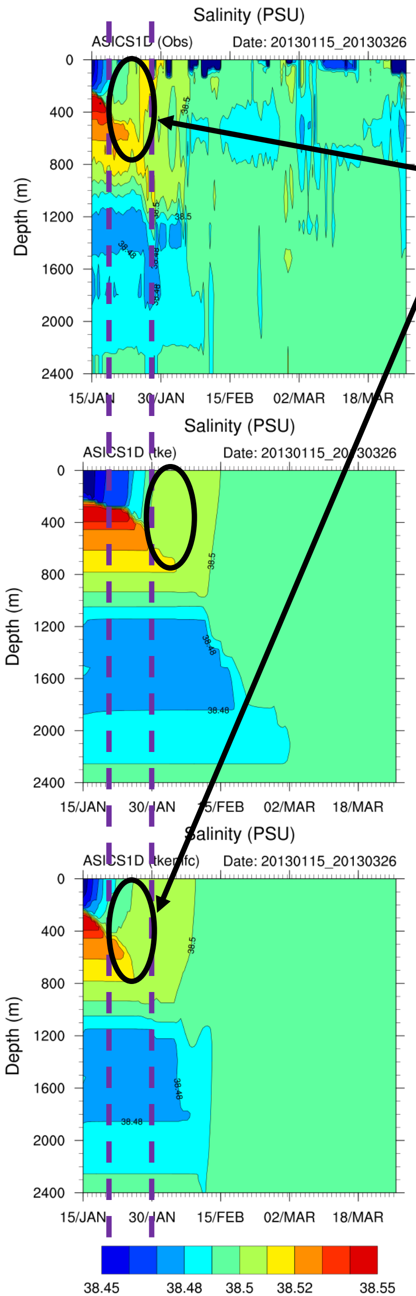


ASICS-Med Experiment: Salinity

Observed Temperature at LION MOORING

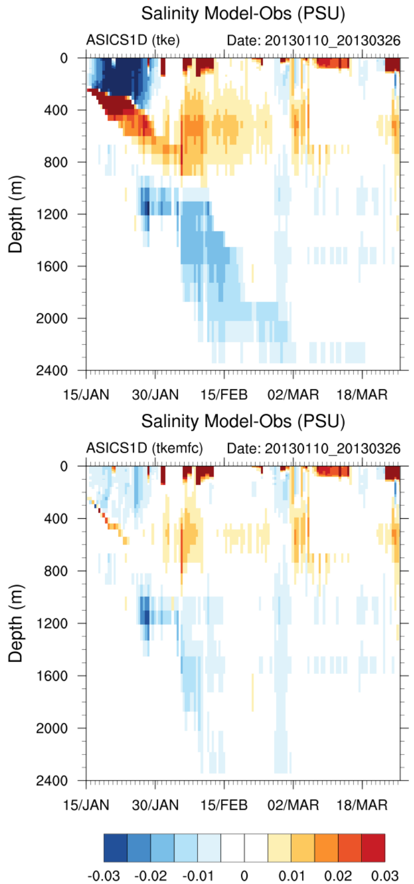
Eddy-Diffusivity only simulation

Eddy-Diffusivity-Mass-flux simulation



Entrainment of LIW January 22-February 6

Salinity Model bias



- Reduction of salinity bias thanks to EDMF
- Right timing in entrainment of LIW with EDMF

Conclusions

Eddy-Diffusivity-Mass-Flux (EDMF):

- Unified approach of Diffusion and Convection in Ocean Models successfully tested
- Separate treatment of diffusion and all regimes of convection
- Good results in 1D cases (analytic and realistic)
- Realistic entrainment flux in stratified thermocline
- Paper submitted at JAMES

Perspectives

- Global Simulations NEMO 1/4° with EDMF:
    - Impact on the SST diurnal cycle
    - ML dynamics
    - Deep convection in the Labrador/Irminger Sea
    - AMOC ...

- Validation of convective fluxes to LES références
- Tune lateral entrainment/detrainment rates to LES references
- Coupling MF to various second-order turbulence closure parameterizations
- EDMF on momentum and TKE
- Sensitivity of BGC models to EDMF