Investigating the influence of Langmuir turbulence parameterization on the Norwegian Earth System Model (NorESM)

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Introduction

- Surface water waves play an important role in modulating air-sea fluxes, hence influencing upper ocean dynamics and mixing. Wave-induced effects can reduce model biases (Belcher et al., 2012).
- We wish to explore the impact of parameterization of Langmuir turbulence (LT) mixing on the upper ocean stratification by coupling WAVEWATCHIII in NorESM.
- The ocean component BLOM of NorESM has been upgraded with a hybrid-coordinate along with the implementation of the K-Profile Parameterization (KPP) scheme (Large et al., 1994).
- Four experiments in coupled ocean and sea-ice configuration, forced with JRA55 based atmospheric reanalysis, have been performed covering one forcing cycle of 61 years, where only the results from years 42-61 average are analyse.

Wave-to-ocean coupling

- The turbulent Langmuir number is defined as $\mathrm{La_t} = \sqrt{u^*/v_0^s}$, measuring the relative effects of the wind-driven shear given by the friction velocity u^* and the magnitude of Stokes drift at the surface v_0^s.
- To account for the Stokes drift penetration depth, Harcourt and D'Asaro (2008) proposed a surface-layer averaged Langmuir number as

$$\mathrm{La_{SL}} = [u^*/(\langle v^{\mathrm{s}}\rangle_{\mathrm{SL}} - v^{\mathrm{s}}_{\mathrm{ref}})]^{1/2}$$

- The surface layer averaged Stokes drift: $\langle v^{\mathrm{s}}\rangle_{\mathrm{SL}} = \frac{1}{\mathrm{H_{SL}}}\int_{-\mathrm{H_{SL}}}^{0} v^{\mathrm{s}}(z)dz$, where $\mathrm{H_{SL}}$ represents the upper 20% of the ocean mixed layer.
- To assess the computational cost, we have considered two approaches:

1. The Stokes drift profile is computed online from the full wave spectrum by WAVEWATCHIII.
2. The surface Stokes drift is **parameterized** from the 10-m wind and then the full profile is reconstructed based on the Phillips spectrum following Breivik et al. (2016). This referred to as Theory wave model in Li et al. (2017), and here used in Exp. VR12PAR.

Langmuir mixing parameterization in KPP

- In the KPP scheme, the turbulent eddy diffusivity of a property X within the ocean surface boundary layer $0 < z < h$ is parameterized as

$$K_x(z,t) = h(t)w_x(z/h,t)G(z/h).$$

- The ocean boundary layer depth h is determined as the shallowest depth at which the bulk Richardson number $\mathrm{Ri_b}(z)$ rises above a critical value Ri_c:

$$\mathrm{Ri_b}(z) = \frac{(B_{\mathrm{r}} - B(z))|z|}{|\mathbf{u}_{\mathrm{r}} - \mathbf{u}(z)|^2 + V_{\mathrm{t}}^2(z)}.$$

- LT effects are parameterized following McWilliams and Sullivan (2000) through an enhancement factor $\mathcal{E}(La_t)$ applied to the turbulent velocity scale as

$$w_x = (\kappa u*/\phi)\mathcal{E}(La_t) \qquad \text{where} \qquad \mathcal{E}(La_t) = \left[1 + C_w/La_t^{2\alpha}\right]^{1/\alpha}$$

- The LT-enhanced unresolved turbulence shear: $V_{\mathrm{t}}^2(z) = \frac{C_{\mathrm{v}}N(z)(\kappa u*/\phi)\mathcal{E}(La_t)|z|}{\mathrm{Ri_c}\kappa^2}\left(\frac{-\beta_{\mathrm{T}}}{c_{\mathrm{s}}\epsilon}\right)^{\frac{1}{2}}$

Table: Description of the four experiments where CNTL is the control run without wave effects. VR12PAR refers to the experiment where Stokes drift profile is **parameterized** from wind, while VR12 and LF17 experiments are coupled with WAVEWATCHIII.

Parameterization	Exp.	Enhancement factor $\mathcal{E}(\mathrm{La_{SL}})$	Unresolved shear	Wave coupling
Large et al. (1994)	CNTL	1	V_t^2	No coupling
Van Roekel et al. (2012)	VR12	$\sqrt{1+(1.5\mathrm{La_{SL}})^{-2}+(5.4\mathrm{La_{SL}})^{-4}}$	V_t^2	WAVEWATCHIII
Li et al. (2017)	VR12PAR	same as VR12	same as VR12	Parameterized Stokes profile
Li and Fox-Kemper (2017)	LF17	same as VR12	V_{tL}^2	WAVEWATCHIII

- LT enhancement of the buoyancy entrainment at the base of the boundary layer (Li and Fox-Kemper, 2017):

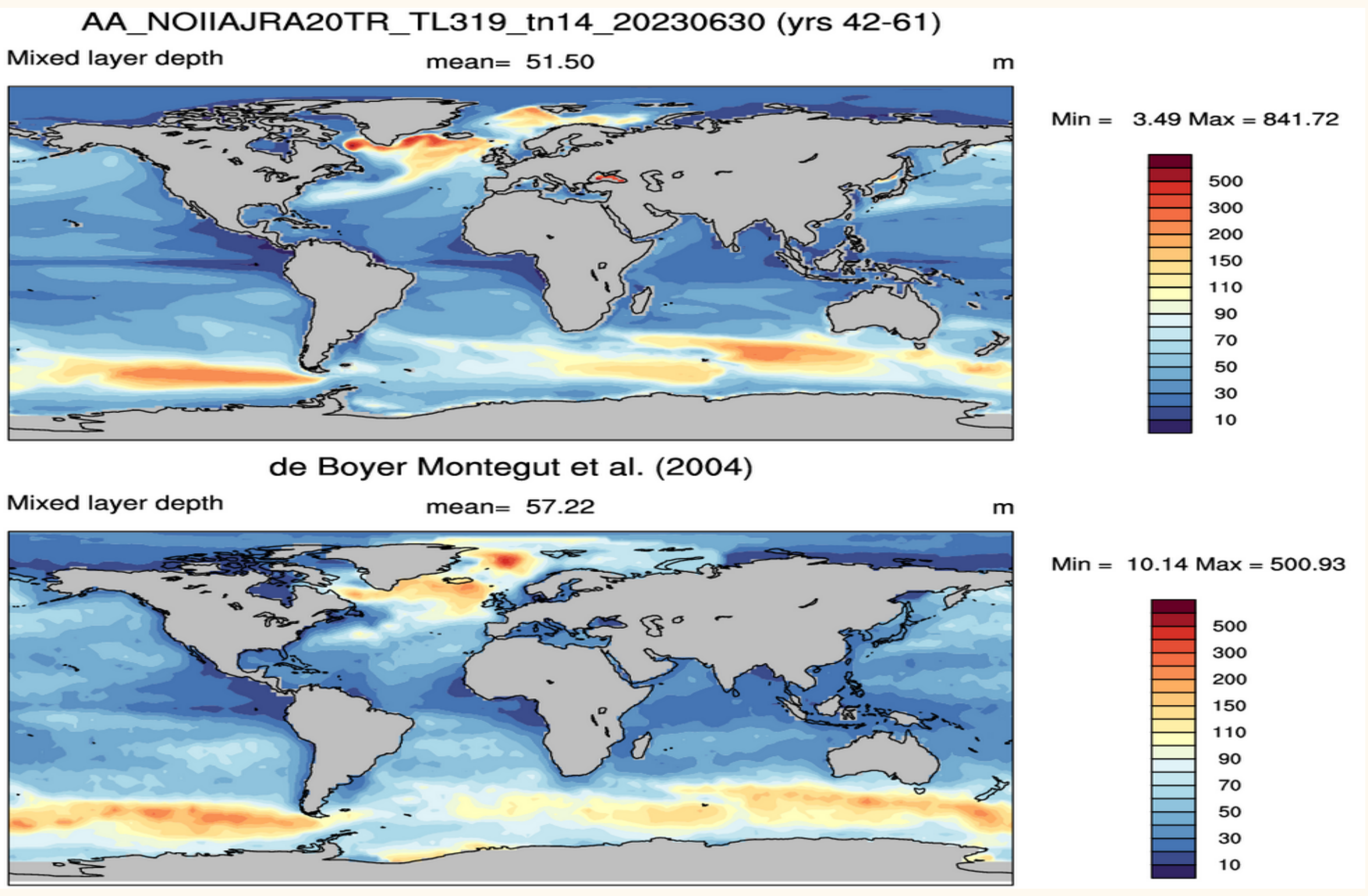
The unresolved turbulence shear is modified:

$$V_{\mathrm{tL}}^2(z) = \frac{C_{\mathrm{v}}N(z)w_{\mathrm{s}}(z)|z|}{\mathrm{Ri_c}}\left[\frac{-\overline{w'b'_{\mathrm{e}}}h}{w_{\mathrm{s}}(z)^3}\right]^{\frac{1}{2}}$$

Enhanced entrainment buoyancy flux:

$$-\overline{w'b'_{\mathrm{e}}} = \frac{u^{*3}}{h}\left(0.17 + 0.083\mathrm{La_{SL}^{-2}} - 0.15\frac{h}{\kappa L}\right)$$

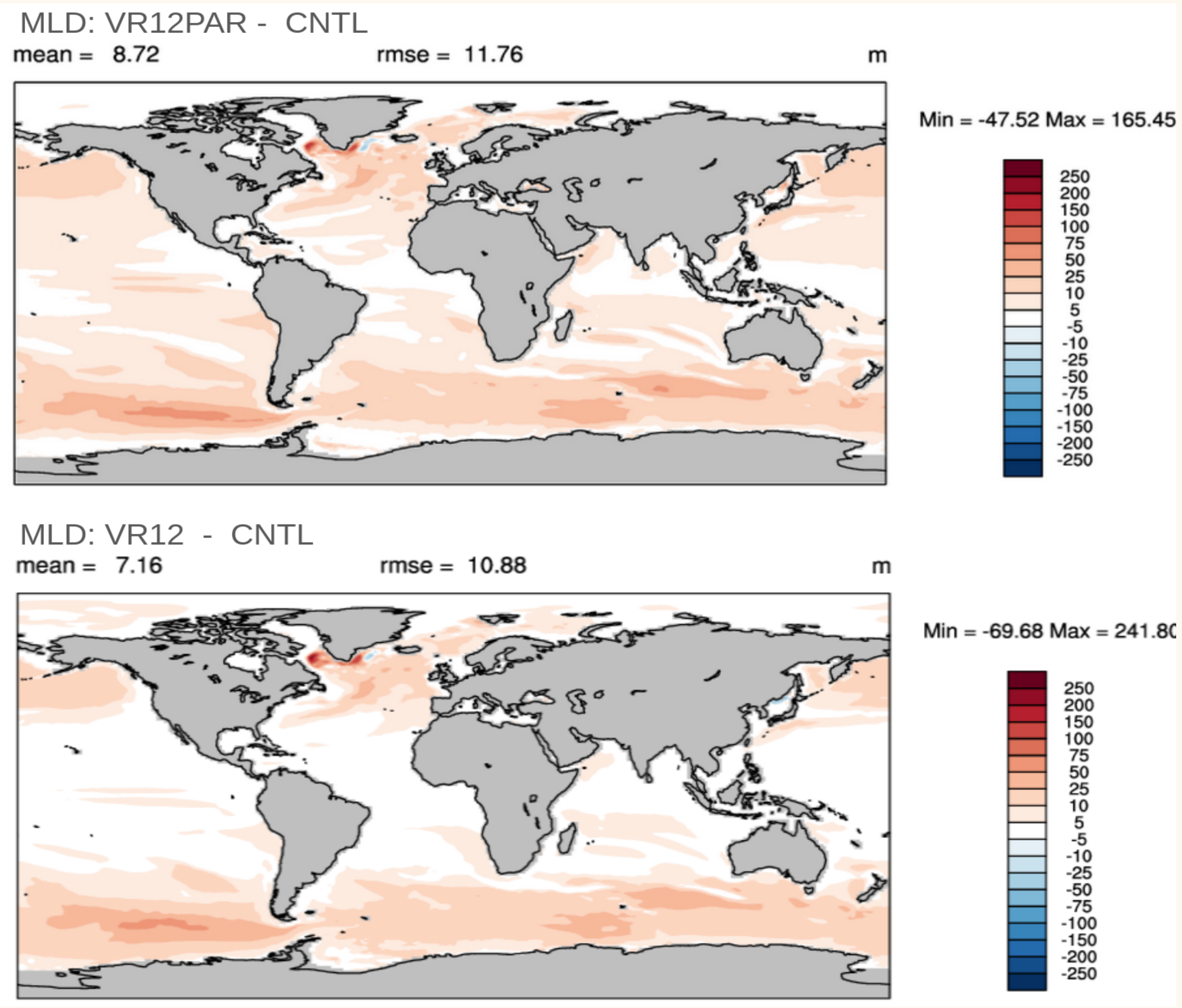
Mixed layer depth: CNTL vs de Boyer Monteguet et al obs.



MLD from the CNTL experiment (top) averaged over the last 20 years of the 61-year run and observation (bottom) from de Boyer Monteguet et al 2004

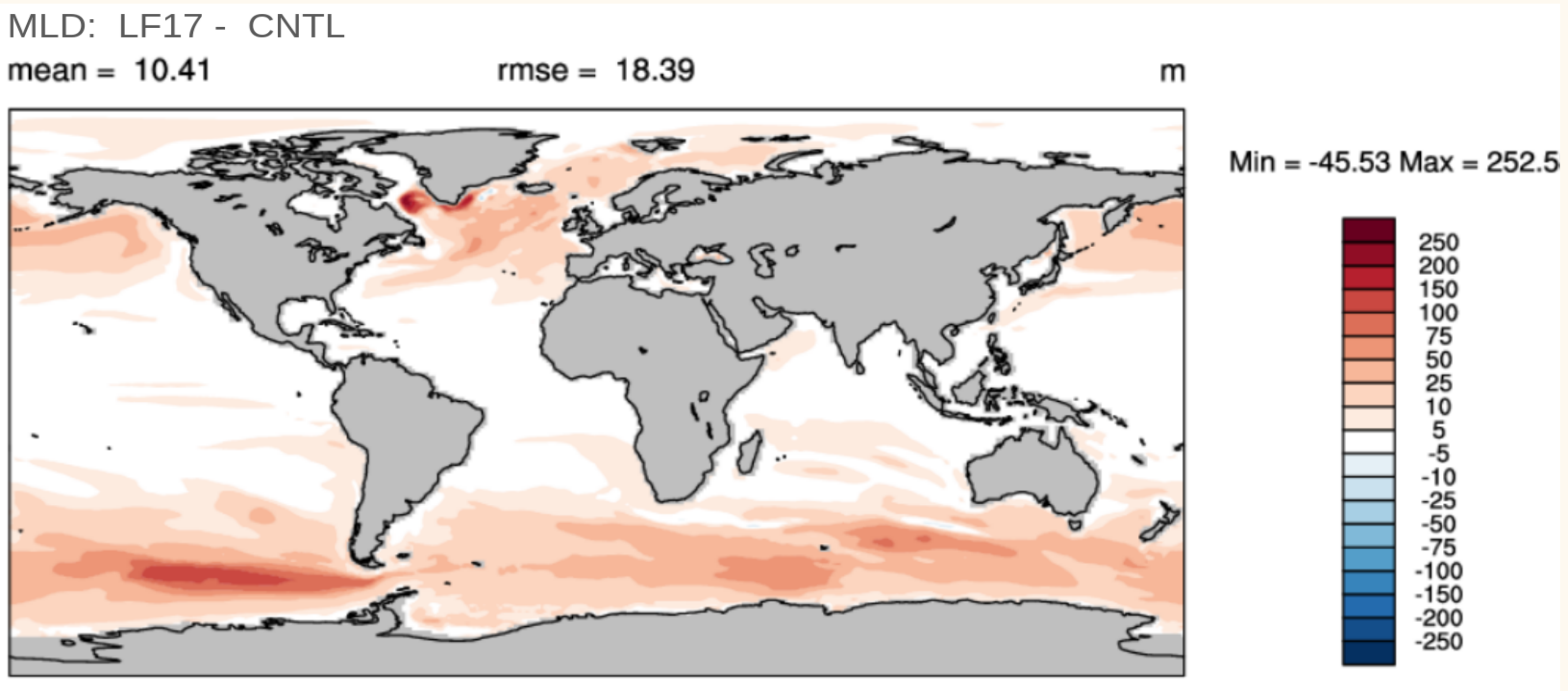
- *The MLD climatology data are from IFREMER (de Boyer Montégut et al., 2004) updated with Argo float data to 2012. The Model MLD is diagnosed using the same density criteria as observations.*

MLD deepening: VR12PAR case vs VR12 case



MLD deepening due to Langmuir mixing from (top) VR12PAR case where the Stokes profile is parameterized from 10m-wind and (bottom) VR12 case where Stokes profile is computed by WAVEWATCHIII. The difference is computed from 20 year average.

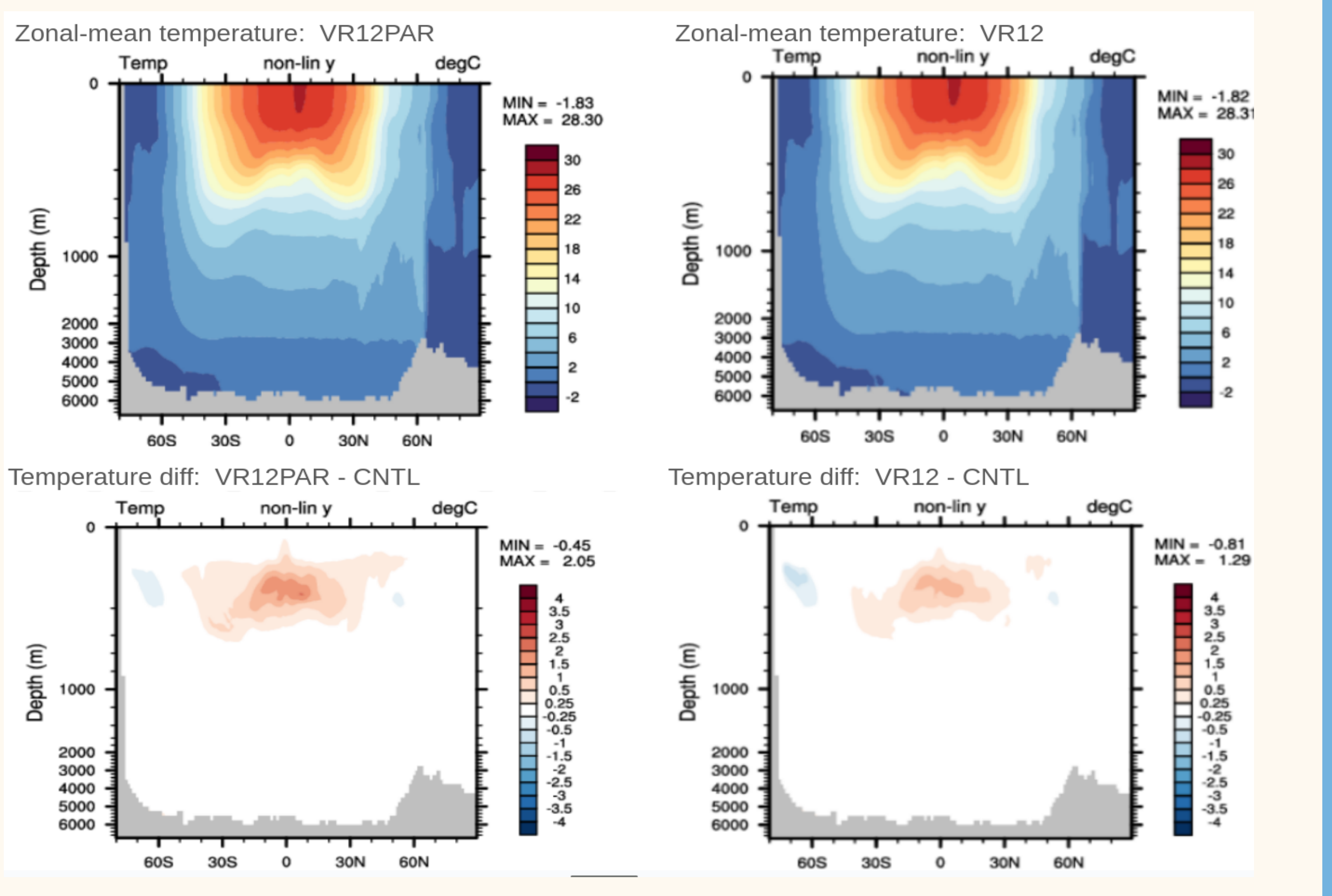
MLD deepening: LF17 experiment



MLD deepening due to Langmuir mixing from the LF17 case averaged over 20 years, where Stokes profile is computed by WAVEWATCHIII.

Impact on Temperature

- The zonal-mean temperature showing the role of the LT parameterization in warming the upper ocean at mid-latitude compared to the CNTL experiment.
- LT mixing enhancement with VR12PAR produces similar but slightly stronger temperature changes to those induced by LT parameterization with VR12.



Impact of the Langmuir mixing on the zonal-mean temperature averaged over 20 years. (top) shows the zonal mean temperature and (bottom) the difference against the CNTL experiment. (left) VR12(theory) and (right) VR12. experiments.

Summary

- There is an overall increase in the mixed layer depth in the southern ocean and sub-polar regions when including LT parameterizations. Thus, shallow MLD biases will be reduced.
- The ocean heat content can increase due to LT mixing that triggers injection of heat from the atmosphere to subsurface water.
- Compared to the VR12 exp., the LF17 case shows stronger MLD deepening, which can be due to LT enhancement of the buoyancy entrainment at the base of the boundary layer.
- LT enhancement from VR12PAR case produces comparable results to the case when using WAVEWATCHIII. However it lacks representation of swells.
- The computational cost of estimating Stokes profile from the 10m wind is negligible compared to the cost of running WAVEWATCHIII as a wave component in NorESM.

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