An assessment of the role of the k-ε vertical mixing scheme in the simulation of Southern Ocean upper dynamics

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Following the work done by Reffrey, Calone and Bourdalle-Badie (2015) we implemented a one dimensional(1D) ocean physical model in the sub-Antarctic Southern Ocean using the Nucleus for the European Modelling of the Ocean(NEMO) model. The 1D model is a first attempt at studying sub-grid scale parameterizations in the region. It was used to test the effects of the k-ε turbulence closure scheme on the simulation of vertical mixing in the water column structure in the North Pacific and Southern Ocean, using the available scattered data as comparison. This analysis also gives indications for the choice of the grid's vertical levels.

Keywords: NEMO, Sub-mesoscale Parameterizations, Turbulence Closure Model, Vertical Mixing, Southern Ocean

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Introduction

Currently the first African based Earth System model, the Variable Resolution Earth Systems Model (VRESM), is being developed at the CSIR and will greatly enhance understanding regional effects of climate change. Many components of the model that were optimized for other locations need to be adapted and optimized before the model can be implemented with focus on the African continent. One of the model components is the use of sub-grid scale parameterization techniques (Gent and McWilliams, 1990; Fox-Kemper et al., 2008) to resolve eddies.

The initial step to achieve this relies on vertical mixing processes. In a general model of the ocean, the choice of the vertical mixing model is essential to achieve more accurate modelling results. The vertical mixing will cause density differences that will result in the stratification of the water column which shifts the thermocline and halocline according to season. This physical process is important for marine species survival.

The objective of this paper is the use of vertical turbulence closure schemes to model vertical mixing processes similar to Reffray et al. (2015). Furthermore, Southern Ocean (SO) conditions were applied to find the temperature and salinity results for 75 and 51 vertical levels.

Instrumentation and Method

Reffray et al. (2015) concentrated on comparing the results of using different vertical turbulence models that come with NEMO (http://www.nemo-ocean.eu; Madec et al., 2016) to observed data in the ocean. The k-ε turbulence model (Versteeg and Malalasekra, 2007) was used in this paper because Reffray et al. (2015) concluded that this model produced the most accurate results in comparison to the other turbulence models.

Reffray et al. (2015) used a 1-dimensional code referred to as the C1D_PAPA case to test the different turbulence schemes. The initial and boundary conditions files are included with C1D_PAPA. This case was later tailored to use SO conditions. C1D_PAPA uses an Arakawa A grid type consisting of a column composed of a 3×3 horizontal grid (x- and y-directions) with an ideal resolution of $0.1° \times 0.1°$ with 75 vertical levels (z-direction). All the 9 water columns are identical and allow removing horizontal processes by zeroing the gradients while keeping the same computer code structure i.e. the 9 columns are needed only for the sound operation of NEMO but every level has the same temperature, salinity, velocity etc. values. The time step used was set to 360 s.

The observed data (needed for comparison with the calculated results) from PAPA Station was obtained from the National Ocean Atmospheric Administration (NOAA, 2016) website. The PAPA Station is located in the North Pacific Ocean. The SO station was ideally located in the sub-Antarctic zone at 46S, 4W. The initial conditions were obtained from the World Ocean Atlas (Locarnini et al., 2013) and the forcing data from European Centre for Medium-Range Weather Forcasts (ECMWF) ERA-interim reanalysis (Dee et al., 2011).

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Reffray et al. (2015) calculated the bias for the temperature by subtracting the calculated data from the observed data. All plots, for the North Pacific and SO, were plotted for the period 15 June 2010 to 14 June 2011 unless otherwise stated.

The following density model was chosen to calculate the density (Millero and Poisson, 1981) using the output from NEMO:

$$\rho(T,S) = AS + BS^{1.5} + CS^2 \tag{1}$$

,where

$$A(T) = 8.24493 \times 10^{-1} - 4.0899 \times 10^{-3}T + 7.6438 \times 10^{-5}T^2 - 8.2467 \times 10^{-7}T^3 + 5.3875 \times 10^{-9}T^4 \tag{2}$$

$$B(T) = -5.72466 \times 10^{-3} + 1.0227 \times 10^{-4}T - 1.6546 \times 10^{-6}T^2 \tag{3}$$

$$C(T) = 4.8314 \times 10^{-4} \tag{4}$$

,where ρ is the density, T the temperature and S the salinity. Note that the density is a function of salinity and temperature only.

The Root Mean Square Error (RMSE) for the temperature was calculated using the standard formula:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(T_i^{Comp} - T_i^{Obs}\right)^2}{n}} \tag{5}$$

Results and Discussion

Results following Reffray et al. (2015) work are shown in Figs. 1-3. Results following Figs. 4-7 were independent of Reffray et al. (2015).

Both the temperature data in Fig. 1 and the temperature bias in Fig. 2 show that within the first five months there was a large stratification with a shallow Mixed Layer Depth (MLD) within a depth of 0 – 60 m. The high bias within the first five months indicated that the model could not represent the observed data accurately. The reason being that the MLD was shallower during the summer because of the surface heating. Seasonal surface cooling then destroyed the stratification for the rest of the year which deepened the MLD and caused the homogeneity. The bias (Fig. 2), found from the distribution of the calculated and observed temperature, followed the same trend as what Reffray et al. (2015) had found. The main difference was that the calculated temperature RMSE values (Fig. 3) were higher than what Reffray et al. (2015) had found.

The temperature RMSE values stabilized from midyear to the end of the year to 0.15±0.05 °C. Reffray et al. (2015) RMSE values stabilized to 0.05±0.3 °C. The discrepancy could have arisen from the averaging of data to obtain the biases as Reffray et al. (2015) had calculated the RMSE values up to 120 m whereas in this paper the RMSE's were calculated up to 300 m. The reason for calculating the RMSE up to 300 m was to take into account the MLD (homogeneous region) which extends lower than 120 m.

The results for the density (calculated using Eqs. 7–10) are shown in Figs. 4 and 5. The calculated densities lie within an error of $\pm 0.5\ \mathrm{kg/m^3}$ from the observed values. The overall form of the graphs for both September (during the mixing period) and October (the beginning of the mixing period) are similar to the observed data. The depth of the pycnocline suddenly increased in October, because of the seasonal change which started the mixing in autumn.

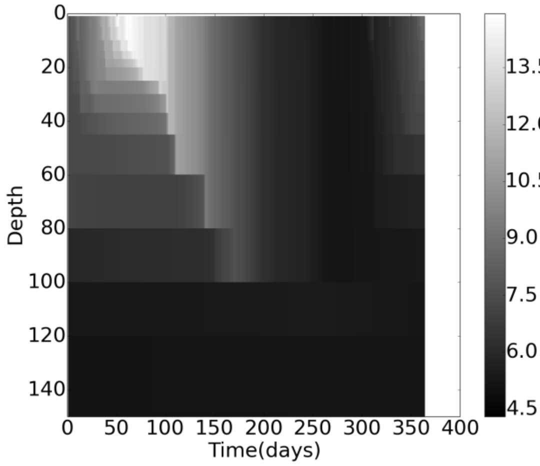

Figure 1: The calculated temperature for the period 15 June 2010 to 14 June 2011 using the NEMO C1D_PAPA case. The k-ε model was used with a time step of 360 s.

The results for temperature and salinity using SO conditions are shown in Figs. 6 and 7. In both the temperature and salinity calculated data the surface fluxes influenced the upper 300 m of the stratified water column. In the upper layer of Fig. 6, the temperature slowly increased and then decreased as time progressed. In the upper layer of Fig. 7, the salinity continually decreased as time progressed, indicating a drift likely due to the one-dimensional approximation.

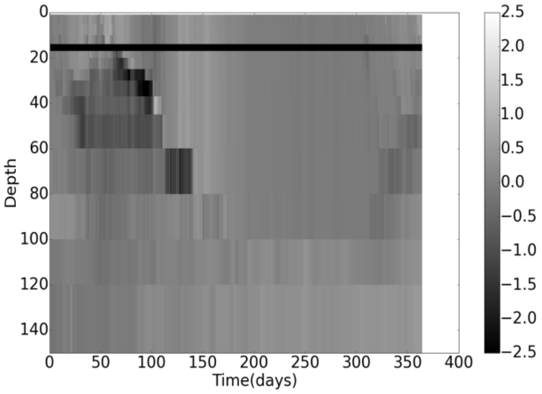

Figure 2: The temperature bias for the period 15 June 2010 to 14 June 2011 using the calculated data from NEMO C1D_PAPA case and the observed data from PAPA Station. The k-ε model was used with a time step of 360 s. There was no observed data for the horizontal band around 15 m.

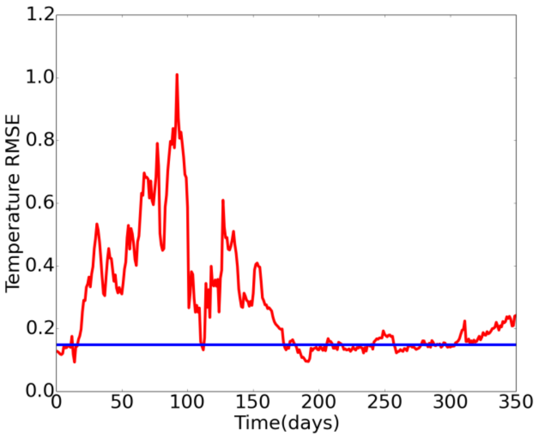

Figure 3: The temperature RMSE calculation for the period 15 June 2010 to 14 June 2011 using the calculated data from NEMO C1D_PAPA case and the observed data from PAPA Station. The horizontal line indicates that the RMSE stabilized to 0.15 °C. The k-ε model was used with a time step of 360 s.

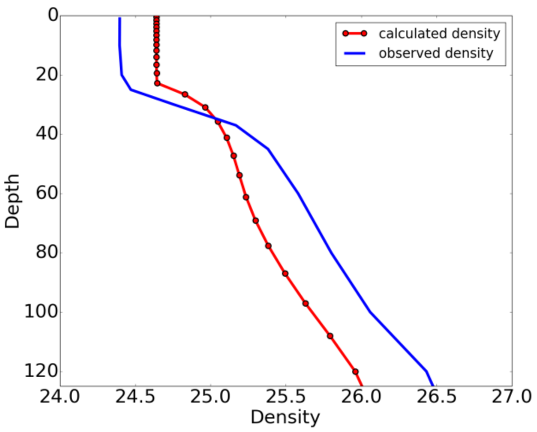

Figure 4: The density calculation for 12 September 2010 (during mixing period) using the calculated data from NEMO C1D_PAPA case compared to the observed data from PAPA Station.

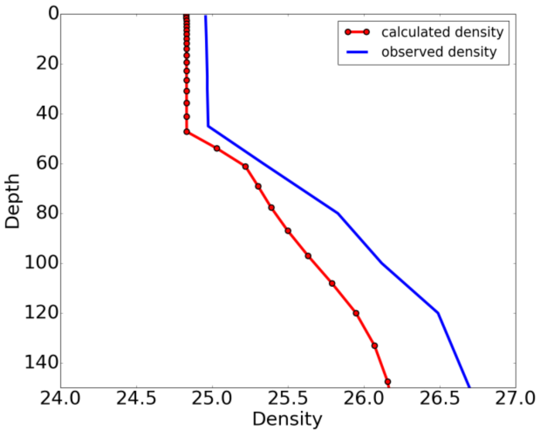

Figure 5: The density calculation for 12 October 2010 (beginning of mixing period) using the calculated data from NEMO C1D_PAPA case compared to the observed data from PAPA Station.

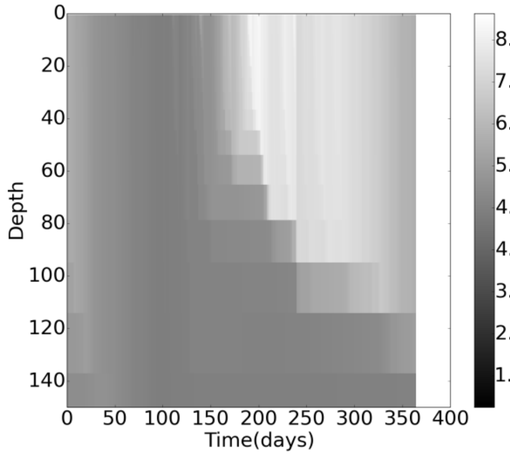

Figure 6: The calculated temperature for the period 15 June 2010 to 14 June 2011 using SO conditions produce the same result for 51 and 75 vertical levels. The k-ε model was used with a time step of 360 s.

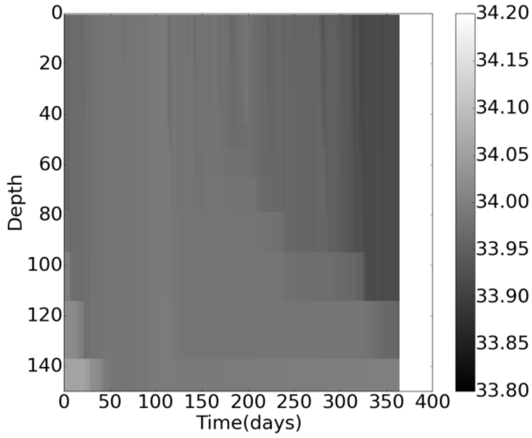

Figure 7: The calculated salinity for the period 15 June 2010 to 14 June 2011 using SO conditions produce the same result for 51 and 75 vertical levels. The k-ε model was used with a time step of 360 s.

A grid sensitivity test for the SO model was done by changing the number of vertical levels from 75 to 51. The temperature and salinity results were the same as Figs. 6 and 7 with no apparent changes in the structures.

Future work will include the modification of C1D_PAPA to verify the results of the other turbulence closure schemes (Turbulent Kinetic Energy (TKE), k-kl, k-ω and Generic). There is scope to test the vertical grid sensitivity further i.e. increase the number of vertical levels to assess whether vertical mixing is affected. Mixed layer depths in the region are usually deeper than 150 m and it is worth assessing whether a 1D model can reproduce them purely through local turbulence. The SO has a stronger horizontal advection which may influence the results and therefore it may also be necessary to consider restoration to avoid drifts as seen for salinity.

Conclusions

This paper highlights the first attempt to study the vertical mixing in the SO using NEMO. The results obtained from Figs. 1-3 were found from following Reffray et al. (2015) and the results from Figs 4-7 were found from applying SO conditions to the tailored C1D_PAPA case. The RMSE values converged within the time period however the value was approximately 0.1 °C bigger than what Reffray et al. (2015) had found. The density model (Eqs. 7-10) produced results within an error margin of 0.5 kg/m^3 and also had a similar form to the observed data. Using SO conditions and changing the vertical levels to 51, it was found that the temperature and salinity results (Figs. 6 and 7) were identical compared to having 75 vertical levels. Scope lies within investigating the results of increasing the number of vertical levels and implementing other turbulence models using SO conditions.

Acknowledgements

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