33rd Annual conference of South African Society for Atmospheric Sciences (SASAS)
POLOKWANE 2017

Investigating the turbulence response of a 1-D idealized water column located in the sub-Antarctic zone with focus on the upper ocean dynamics

Kirodh Boodhraj*, CSIR Modelling and Digital Science, Pretoria and UCT, Cape Town
Marcello Vichi, UCT and Marine Research Institute, Cape Town
Jacoba E. Smit, CSIR Modelling and Digital Science, Pretoria

Abstract

A one-dimensional ocean physical model was implemented in the sub-Antarctic Southern Ocean using the Nucleus for the European Modelling of the Ocean (NEMO) model. It was used to examine the effects of the turbulence response of the simulation of vertical mixing in the water column structure in the Southern Ocean (SO), using the available scattered data as comparison. The Brunt Väisälä frequency, turbulent diffusivity and turbocline provided valuable information regarding the turbulence response of the water column and the effect of an entrapped warm water parcel below cool waters was observed.

Keywords: NEMO, Sub-Mesoscale Parameterizations, Turbulence Scheme, Vertical Mixing, Southern Ocean

Introduction

Currently, the development of the first African based Variable Resolution Earth Systems Model (VRESM) is being carried out by the Council for Scientific and Industrial Research (CSIR) and will enhance the regional understanding and implications of climate change. Resolving eddies is an integral component of VRESM involving the use of sub-grid scale parameterizations (Gent and McWilliams 1990). Initial steps for understanding these parameterizations relies on oceanic vertical mixing processes which are essential for understanding surface stratification during the austral summer and deep mixing during winter. Ocean turbulence is a dominating physical process involving the distribution of momentum and energy and is modelled numerically using a turbulence scheme (Thorpe 2007). In this study, NEMO was used to simulate a 1D fluid column. The governing equations consist of a 1D version of the Navier-Stokes (Primitive) Equations. The objective of this paper is the use of turbulence schemes to model vertical mixing processes and to analyse various turbulence indicators. Furthermore, a warm water parcel was found trapped beneath cooler upper waters and is discussed.

Data and Method

This study focussed on the sub-Antarctic zone of the Southern Ocean region off the coast of South Africa (47ºS 4.5ºE), chosen due to the availability of in situ glider data. A configuration (named SAZ1D) was created in NEMO (based upon the work of Reffray et al. (2015) who modelled a 1D column in the Northern Pacific ocean), to model the turbulence response of a vertical 1D idealized fluid column at the chosen location. SAZ1D uses an Arakawa A grid with z-coordinates for numerical efficiency. The vertical grid had a variable number of levels (31, 51, 75, 101 and 151) for different simulations. Bathymetry ($4500\ m$) was obtained from the General Bathymetric Charts of the Oceans (GEBCO 2016). Vertical levels were distributed into the bathymetry via a scaled hyperbolic tangent function due to it being smooth and creating tight spacing in the upper fluid column (which is integral to resolving atmosphere-ocean interactions).

This paper focusses on 101 vertical levels as this is an achievable future goal for global ocean models due to continuous improvements in computational power. Current global models generally employ 50-75 vertical levels (MERCATOR 2008). All simulations were performed for 15 June 2010 to 14 June 2011 with time step of $360\ s$. Various reanalysis products namely, the European Centre for Medium-Range Weather Forecasts Interim (Dee et al., 2011), Japanese Reanalysis (JRA55) (JMA 2016), National

Corresponding author: Tel: +27 21 8882501; Email: kboodhraj@csir.co.za

Aeronautics and Space Administration (NASA) (NASA 2016) and National Centres for Environmental Prediction (NCEP) (NCEP 2016) provided surface forcing data (wind speed, specific humidity, solar and thermal fluxes, total precipitation and air temperature) for the simulations. Chlorophyll data from the European Space Agency (ESA) (ESA 2017) was used in conjunction with reanalysis data for all simulations. Initial conditions were obtained from the World Ocean Atlas (Locarnini et al. 2013) consisting of temperature and salinity profiles. Vertical mixing in the water column was simulated using the k-ε, k-ω, k-kl, GLS (Umlauf 2003), TKE0, TKE10, TKE30 (Blanke 1993) and Pacanowski-Philander (PP) (Pacanowski 1981) turbulence schemes. Simulations were run for all possible combinations of turbulence schemes and reanalysis data ($8 \times 4 = 32$ simulations in total).

Turbulence indicators include the Brunt Väisälä frequency, turbulent diffusivity, turbocline and Mixed Layer Depth (MLD). The Brunt Väisälä frequency was calculated using $N^2 = (g/\rho_0)\, d\rho/dz$, where $g = 9.8\, ms^{-2}$, $\rho_0 = 1034\, kgm^{-3}$ (reference density), z the vertical depth from mean sea level and ρ the density. Density was calculated using TEOS10 (McDougall 2012) and MLD calculated using a density criterion of $0.1\, kgm^{-3}$. The turbocline is the depth where the upper turbulent layer is separated from the (less turbulent) fluid below, calculated by finding the minimum depth for where turbulent diffusivity (which indicates the turbulent strength) falls below $5 \times 10^{-4}\, m^2 s^{-1}$.

Results and Discussion

Figures 1 and 2 display the water column temperature and salinity time evolution. There is a distinct inter-annual variability and temperatures reached a maximum (minimum) of 12 (3) °C in the upper $300\, m$ while salinities vary within a small band of $33.9 - 34.2\, PSU$. These temperature and salinity values lie within the bounds of glider data (Swart et al. 2015) obtained from the region. The winter deep mixing penetrates down to $150\, m$ (above the permanent pycnocline) while during the summer stratification, high temperatures penetrate down to $100\, m$.

The temperature, salinity and density profiles (Fig. 3) indicate an entrapped warm water parcel around $150\, m$. This warm parcel is also present for combinations of other turbulence schemes and reanalyses. The warm parcel presence during deep mixing (September 2010), beginning of stratification (November 2010) and start of deep mixing (April 2011) is shown in Table 1. Regarding turbulence schemes, only NASA resulted in an entrapped warm parcel using k-ε. For all reanalyses, the PP scheme always produces a warm parcel. Regarding reanalysis, NASA always produced a warm parcel for all turbulence schemes. NCEP only produces a warm parcel using the PP scheme. Interim and JRA55 tend to have persistent warm parcels that are still visible at the beginning of the deep mixing period (April 2011). The exact cause of the entrapped warm water parcel is still unclear. It is believed the cold convection of water during the winter does not penetrate deep enough to fully mix the upper layer i.e. the warm parcel is an impression from the previous season. The monotonically increasing density, made stable due to salinity, is a possible reason for the warm water parcel (Fig. 3). The absence of density instabilities implies no need for mixing, suggesting erosion (or entrainment) of the layer above or below does not happen.

The Brunt Väisälä frequency (Fig. 4) indicates the strength of stratification. The permanent pycnocline is observed at $150\, m$. Multiple stratification events occur (seen from spike in the average Brunt Väisälä frequency) before the permanent onset of the seasonal pycnocline ($50\, m$). The stratification events filter from the upper water column and terminate on the seasonal pycnocline because for stratification to occur, surface effects must be convected into the water column. The descent of the seasonal pycnocline indicated cooling of surface waters. Fig. 5 displays the turbulent diffusivity, turbocline depth and MLD. During austral winter/spring there are high

Table 1: The presence of the warm particle is shown for a combination of turbulence schemes and reanalysis products. † indicates the entrapped warm parcel's presence during deep mixing (September 2010), ‡ at start of stratification (November 2010) and * at beginning of deep mixing (April 2011). Empty cells indicate the absence of the entrapped warm parcel.

Turbulence scheme	**Interim**	**JRA55**	**NASA**	**NCEP**
k- ε			†	
k-ω	†‡	†	†	
k-kl	†‡	†	†	
Generic	†	†	†	
TKE0	†‡	†‡	†	
TKE10	†‡*	†‡	†	
TKE30	†‡*	†	†	
Pacanowski-Philander	†‡*	†‡*	†‡	†

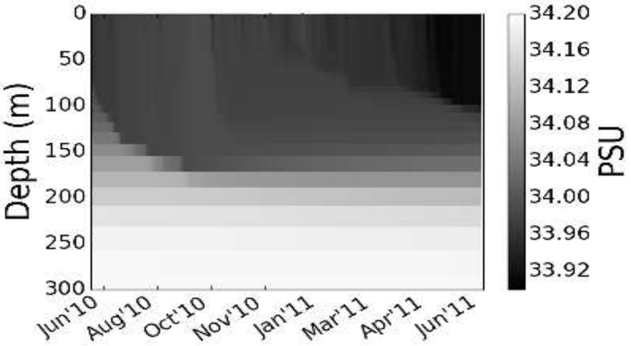

Figure 1: Water column temperature plotted for annual period June 2010 to June 2011 using Interim data and the k-kl turbulence scheme.

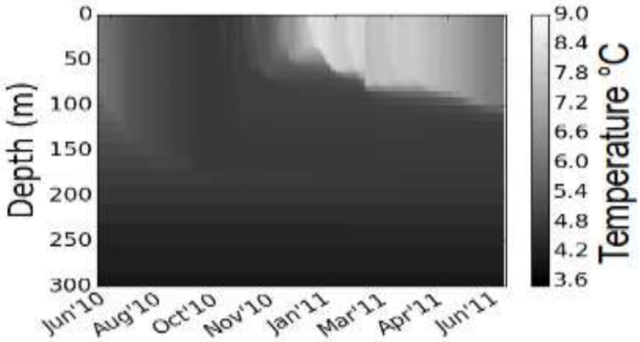

Figure 2: Water column salinity plotted for annual period June 2010 to June 2011 using Interim data and the k-kl turbulence scheme.

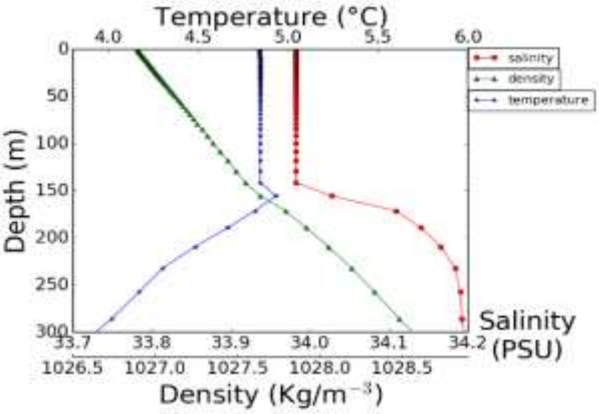

Figure 3: Water column temperature, salinity and density profiles using Interim data and the k-kl turbulence scheme during the deep mixing period (September 2010). Note the entrapped warm parcel at 150 m.

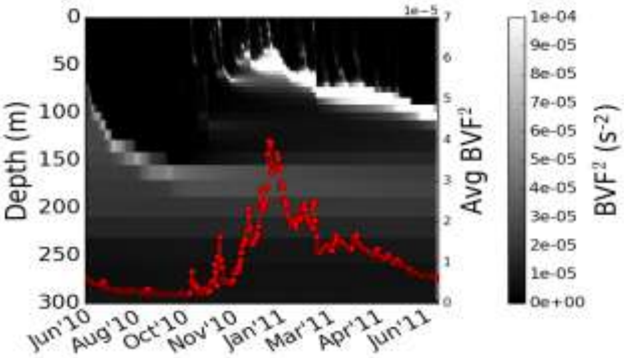

Figure 4: Brunt Väisälä frequency plotted for annual period June 2010 to June 2011 using Interim data and the k-kl turbulence scheme. The column average is shown for comparison.

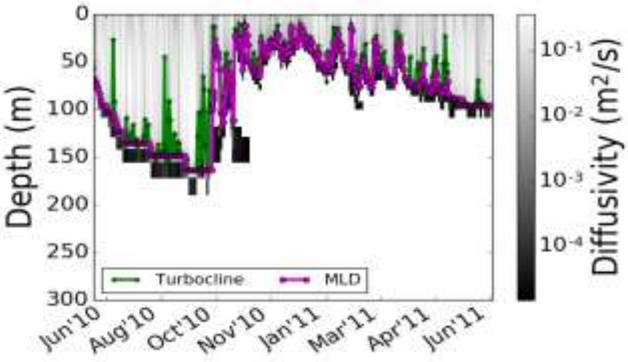

Figure 5: Turbulent diffusivity (with MLD and turbocline) plotted for annual period June 2010 to June 2011 using Interim data and the k-kl turbulence scheme.

diffusivities down to 180 m but shallows to 50 m in summer and slowly descends to 100 m in June 2011. This implies turbulence acts deeply during winter and diminishes during the summer stratification. The turbocline borders the diffusivity and is more sensitive to stratification events than the MLD. This is observed during winter, where the turbocline spikes while the MLD does not.

Future work includes investigating the effects of the warm parcel by simulating the water column beyond June 2011 and assessing whether a 1D model is accurate enough to provide guidance on turbulence scheme choice for global models.

Conclusions

In conclusion a warm water parcel was present for different combinations of reanalysis and turbulence schemes. Reasons for why this parcel formed were possibly due to lack of deep penetration of cold water convection due to a stable density profile. The turbocline was found to show higher sensitivity to the turbulent response of the water column compared to the MLD. The turbulent diffusivity correctly indicated the seasonal turbulent behaviour for an ideal vertical ocean model i.e., higher (diminished) turbulence during the austral winter (summer).

Acknowledgements

Acknowledgement is given to the CSIR as the present work is funded by the CSIR Parliamentary Grant and the VRESM SRP project coordinated by Prof. Francois Engelbrecht.

References

(i) Journals:

Blanke, B. and Delecluse, P. (1993). Variability of the tropical Atlantic ocean simulated by a general circulation model with two different mixed-layer physics. *Journal of Physical Oceanography*. 23: 1363-1388.

Dee, D.P., Uppala, S.M., Balsamo, G. and Bauer, P. (2011). The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*. 137: 553-597.

Gent, P.R. and McWilliams, J.C. (1990). Isopycnal mixing in ocean circulation models. *Journal of Physical Oceanography*. 20: 150-155.

Locarnini, R.A., Mishonov, A.V. and Baranova, O.K. (2013). World Ocean Atlas Vol 1: Temperature, Technical Ed. *NOAA Atlas NESDIS*. 73: 40.

Madec, G. and NEMO team (2016). NEMO ocean engine. *Note du Pole de modelisation de l'Institut Pierre-Simon Laplace France*. 27: 1288-1619.

Pacanowski, R.C. and Philander, S.G.H. (1981). Parameterization of vertical mixing in numerical models of tropical oceans. *Journal of Physical Oceanography*. 11: 1143-1451.

Reffray, G., Bourdalle-Badie, R. and Calone, C. (2015). Modelling turbulent vertical mixing sensitivity using a 1-D version of NEMO. *Geoscientific Model Development*. 8: 69-86.

Swart, S., Thomella, S.J. and Monteiro, P.M. S. (2015). The seasonal cycle of mixed layer dynamics and phytoplankton biomass in the sub-Antarctic zone: A high resolution glider experiment. *Journal of marine systems*. 147: 103-115.

McDougall, T.J., Jackett, F.J. and Millero, F.J. (2012). A global algorithm for estimating absolute salinity. *Journal of Ocean Science*. 8: 1123-1134

Thorpe, S. A. (2007). An introduction to ocean turbulence. *Cambridge University Press*. 1-293.

Umlauf, L. and Buchard, H. (2003). A generic length-scale equation for geophysical turbulence models. *Journal of Marine Research*. 61: 235-265.

(ii) Web references:

CCI ESA (2017). Ocean colour CCI. European space agency. http://www.esa-oceancolour-cci.org/?q=project. Last accessed 8 February 2017.

GEBCO (2016). General bathymetric charts of the oceans. http://www.gebco.net. Last accessed 18 April 2017.

Japanese Meteorological Society (2016). Japanese 55 year reanalysis. http://jra.kishou.go.jp/JRA-55/index_en.html. Last accessed 11 February 2017.

MERCATOR Editorial team (2008). MERCATOR quarterly newsletter 31. https://www.mercator-ocean.fr/wp-ontent/uploads/2015/06/lettre_31_en.pdf. Last accessed 4 April 2017.

National Aeronautical Space Agency (2016). Goddard earth sciences data and information services centre. http://disc.sci.gsfc.nasa.gov/daac-bin/FTPSubset.pl/. Last accessed 11 April 2017.

National Centre for Environmental Prediction (2016). NCEP/DOE Reanalysis. http://www.rda.ucar.edu/datasets/ds091.0/index.html#!description. Last accessed 11 February 2017.

WOA NOAA (2017). World ocean atlas temperature and salinity data. http://www.nodc.noaa.gov/OC5/indprod.html. Last accessed 20 October 2017.