

Internal Wave Generation in the Gulf of Oman (Outflow of Persian Gulf)

Mohammad Reza Khalilabadi^{*1}, Masoud Sadrinassab¹, Vahid Chegini², Mohammad Akbarinassab³

¹Khorramshahr University of Marine Science and Technology, Khorramshahr, Iran

²Iranian Oceanographic National Center, Tehran, Iran

³University of Mazandaran, Babolsar, Iran

^{*}[E-mail: rezakhalilabadi@gmail.com]

Received 2 October 2013; revised 6 November 2013

Internal waves are a much more complex phenomenon. They are guided by stratification varying with time. From a turbulence modellers point of view, internal wave dynamics must not be neglected, since dissipation of internal waves creates mixing, which is a priori not considered by classical turbulence closure models. In this work, we used GOTM model for calculating and simulating the time series of oceanic parameters related to mixing process and internal waves. The generation of internal waves in the Gulf of Oman (outflow of Persian Gulf) has been investigated by analysis of these parameters. Most important parameters which been analysed for derivation of internal waves are sigma_t variations, bouyancy frequency squared and salinity profiles.

[**Keywords:** Internal wave, stratification, mixing, Gulf of Oman]

Introduction

Internal waves are oscillatory motions whose largest amplitudes occur in the interior of the fluid; they are an ubiquitous phenomenon in the ocean. Here buoyancy acts as the restoring force. Freely propagating internal waves with frequency ω propagate energy at an angle θ to the horizontal given by the dispersion relation given by

$$\omega^2 = N^2 \sin^2 \theta + f^2 \cos^2 \theta \approx N^2 \sin^2 \theta \quad (1)$$

Where the simplification is valid providing the Coriolis parameter f is small compared to the buoyancy frequency N (Sutherland, 2010). Then internal waves in a continuously stratified fluid represented by the stability frequency. The stability of the water column is determined by

$$N^2 = g^2 \left(\frac{\partial \rho}{\partial p} - \frac{1}{C_s^2} \right) \quad (2)$$

Where p is pressure, g the acceleration due to gravity and C_s the speed of sound (which is a function of temperature, salinity and depth). The water column is stably stratified if $N^2 > 0$. The quantity N is called the Brunt-Vaisala or buoyancy frequency; its unit is radians per second (but also

common are cycles per hour, or cycles per day) (Anders, 2011).

The possibility of the generation of the internal waves at the Gulf of Oman shelf-break has been investigated by Small and Martin (2002) using a numerical model.

Materials and Methods

Study region is located in the Gulf of Oman, outflow of Persian Gulf, at 25°N and 57.5° E where oceanographic field measurements alternatively in each season has done.

Compared to surface waves, internal waves are a much more complex phenomenon. They are guided by stratification varying with time in the three-dimensional space. They are three-dimensional themselves with horizontal and vertical modes in contrast to surface waves which are essentially two-dimensional. And, moreover, they interact non-linearly with their wave guide, the stratification of the flow. Various models have been developed for simulating and understanding oceanic internal waves.

From a turbulence modellers point of view, internal wave dynamics must not be neglected, since dissipation of internal waves creates mixing, which is a priori not considered by classical turbulence closure

models. There are two main mechanisms for dissipation of internal waves: Kelvin-Helmholtz instabilities and breaking of internal waves (Burchard, 2002).

In this work we used GOTM model for calculating and simulating time series of the oceanic parameters related to mixing process and internal wave. GOTM stands for General Ocean Turbulence Model and means that the model simulates small-scale turbulence and vertical mixing as far as possible in a general manner and without calibration to specific applications. This general character is underlined by the fact that the model is applied to scenarios in various regions, specifications and scales, such that the model is frequently verified (and unfortunately sometimes falsified as well). The model is modular such that refinements or extensions especially for the turbulence models, but also for the mean flow modeling can easily be carried out. The aim of generality is very ambitious, and there are always situations for which turbulence closures on a higher level would be required. GOTM is a one-dimensional model for the water column, which means that all horizontal gradients have to be either prognostically prescribed, parameterised or neglected (BOLDING and Burchard, 2002).

One weakness of all turbulence models is the reproduction of internal mixing processes which are controlled by the dynamics of internal waves. These are often produced non-locally by various complex processes not properly represented in three-dimensional models. In the GOTM model, the problem solved by limiting the macro length scale by means of the buoyancy length and the turbulent kinetic energy by a constant minimum value, which acts as a tuning parameter. By doing so, background values for the eddy viscosity of the order of $10^{-5} \dots 10^{-4} \text{ m}^2 \text{ s}^{-1}$ are obtained (Wang and Muller, 2002).

In this paper we used a yearlong data of salinity and temperature which measured throughout the water column with the vertical distance of 1 meter. These data had been measured monthly in both warm and cold seasons. The version of GOTM used here is based on the k-ε equations with the second-order turbulence closure scheme proposed by Canuto et al. (2001). This type of model has been tested and used in many studies of the upper ocean mixing layer (e.g. Burchard and Bolding, 2001; Bolding et al., 2002;

Jefrey et al., 2008) and permits that the turbulence properties such as turbulent viscosity, tracer diffusivity, turbulent kinetic energy (TKE), dissipation rate of TKE, and others, be calculated.

Results

The vertical time series of N^2 field (buoyancy frequency squared) in the study region is shown in Figure 1. It shows that the maximum values of N^2 occur between 150-250 m depth. Therefore this zone has a good potential for generation of internal waves. In the following we investigated the formation of these waves by reviewing the time series of salinity and potential density variations in the water column.

Time series data of salinity profiles are presented in Figure 2. From this figure one can say that small subsurface salinity inversions are observed between 150-250 m depth during May to Aug. The existence of a saltier layer in this depth could be the effect of Persian Gulf outflow. The other interesting feature noticed from the time series data of salinity profiles is the sharp salinity fluctuations in this stratified layer during May to Aug which is zoomed in Figure 3. These fluctuations could be associated to the effects of large internal waves during this time. Sharp salinity fluctuations in a highly stratified water column (between 160-180 m depth) during May to Aug show the effects of large internal waves in this layer during this time. As shown in figure 2, this effect is weaker in other months. We can insure the occurrence of internal wave by the study of potential density variations with time. Time series of σ_t variations are presented in Fig. 4. The interesting feature noticed from this figure is the sharp potential density fluctuations between 150-250 m where the layer is highly stratified. These fluctuations are stronger in spring and summer and be weaker by coming the autumn which they vanish at the winter. There is a weaker density variation below the 400 m depth which its form of reducing with time is mostly as same as the density variation in upper layer.

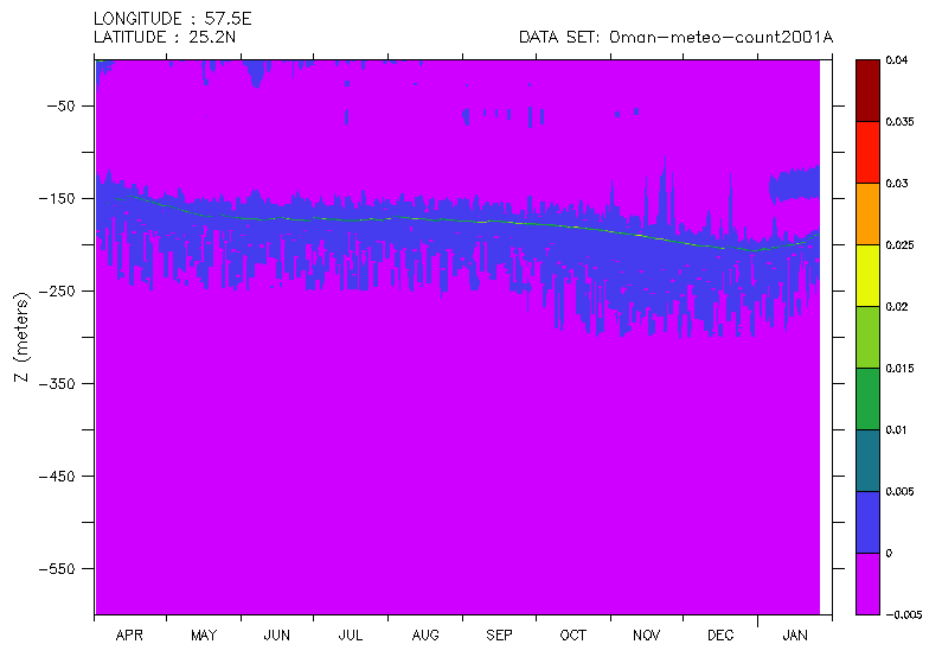


Fig. 1— Time series of Bouyancy frequency squared ($1/s^2$) derived from temperature and salinity profiles in the study region.

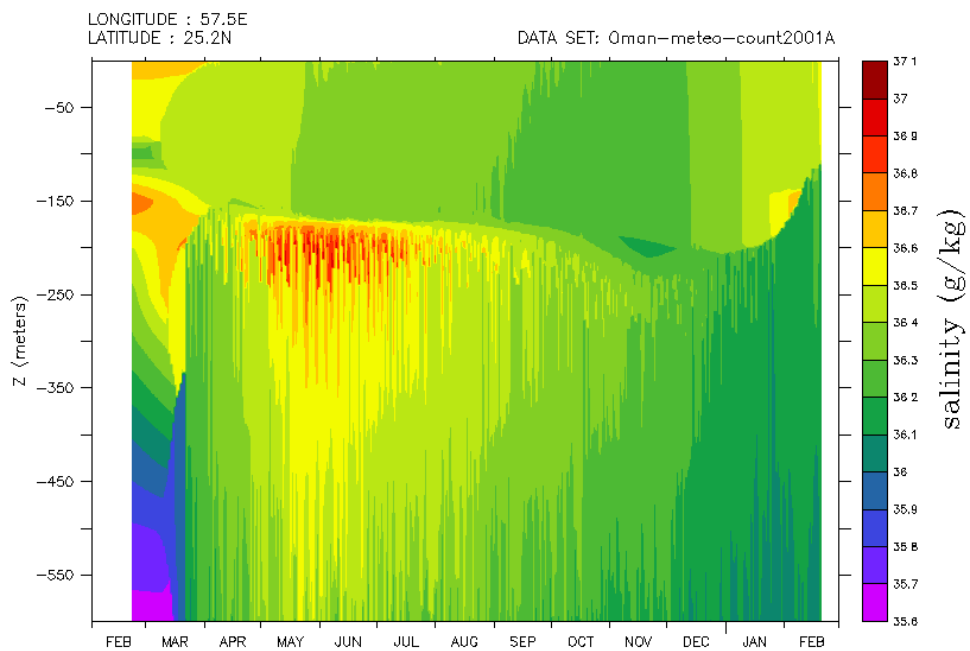


Fig. 2— Time series of salinity profiles.

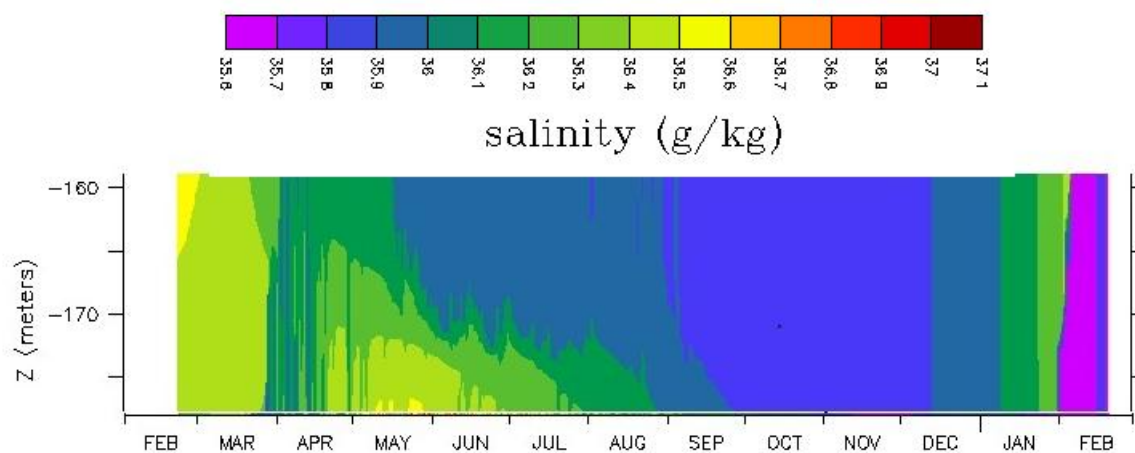


Fig. 3— Sharp salinity fluctuations in a highly stratified water column (between 160-180 m depth) during May to Aug show the effects of large internal waves in this layer during this time.

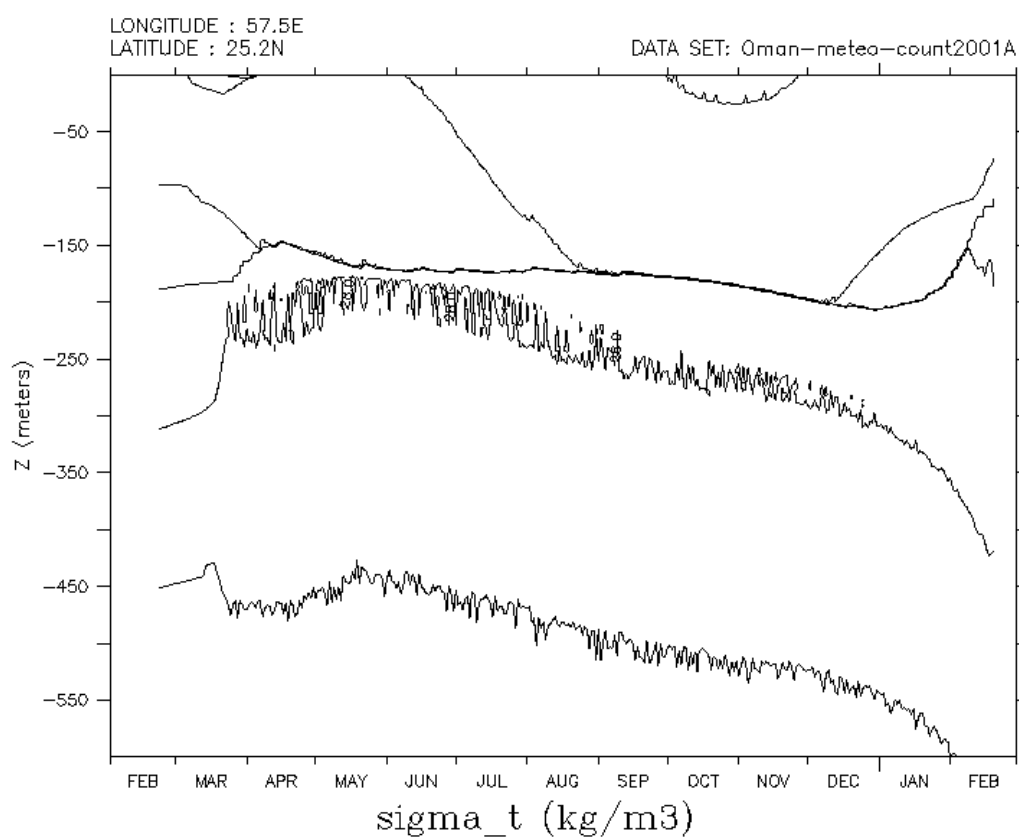


Fig. 4— Time series of σ_t variations

Conclusion

Processing the time series of sigma_t variations in the study region shows two types of internal waves in the water column:

A large internal wave between 150-250 m depth during spring and summer. This wave is weaker in autumn and vanishes in winter. This type of internal wave is matched with time series of Bouyancy frequency and salinity profiles.

Another type of internal wave which is shown by the Time series of sigma_t variations occurred between 450-600m depth. The form of variation of this wave with time and depth is nearly similar to upper layer internal wave. But we can't see the effect of this wave in the time series of Bouyancy frequency squared and salinity profiles.

References

- 1 Anders O., Guide to Process Based Modeling of Lakes and Coastal Seas. Springer-Verlag Berlin Heidelberg, (2011)..
- 2 BOLDING, K., BURCHARD, H.; POHLMANN, T.; STIPS, A. Turbulent mixing in the Northern North Sea: a numerical model study. *Cont. Shelf Res.*, 22(2002): 2707-2724.
- 3 BURCHARD, H., BOLDING, K.; VILLARREAL, M. GOTM – a general ocean turbulence model. Theory, applications and test cases. *Tech.Rep. EUR 18745 EN*, European Commission.
- 4 Burchard, H., Applied Turbulence Modeling in Marine Waters. *Lecture Notes in Earth Sciences* No. 100, Springer-Verlag. (2002).
- 5 BURCHARD, H.; BAUMERT, H. On the performance of a mixed-layer model based on the k-epsilon turbulence closure. *J. Geophys. Res.*, 100(1995): 8523-8540.
- 6 BURCHARD, H.; BOLDING, K. Comparative analysis of four second-moment turbulence closure models for the oceanic mixed layer. *J. Phys. Oceanogr.*, 31(2001): 1943-1968.
- 7 BURCHARD, H., and O. PETERSEN, Models of turbulence in the marine environment - A comparative study of two-equation turbulence models, *J. Mar. Sys.*, 21(1999): 29-53.
- 8 CANUTO, V. M.; HOWARD, A.; CHENG, Y.; DUBOVIKOV, M. S. Ocean turbulence. Part I: One point closure model, momentum and heat vertical diffusivities. *J. Phys. Oceanogr.*, 31(6) (2001): 1413-1426.
- 9 JEFREY, C. D.; ROBINSON, I. S.; WOOLF, D. K.; DONLON, C. J. The response to phase-dependent wind stress and cloud fraction of the diurnal cycle of SST and air-sea CO₂ exchange. *Ocean Modelling*. 23(2008): 33-48.
- 10 Small, J., and J. Martin, The generation of non-linear internal waves in the Gulf of Oman. *Continental Shelf Research*, 22 (8) (2002): 1153-1182.
- 11 Sutherland B. R., Internal gravity waves; *Cambridge university press*, ISBN 978-0-521-83915-0 Hardback, First published 2010.
- 12 Wang, D., and P. Muller, Effects of equatorial undercurrent shear on upper-ocean mixing and internal waves. *J. Phys. Oceanography.*, 32(2002): 1041–1057.