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DEVELOPMENT of OCEAN MODELLING: THE MALAYSIAN PERSPECTIVE

Oleh:

Prof. Dr. Alejandro Livio Camerlengo
Fakulti Sains dan Teknologi
Kolej Universiti Terengganu

INTRODUCTION

The ocean environment has been subjected to severe deterioration in the past few decades. This worsening situation is attributed mainly to the extensive use of pesticides in coastal areas, the rapid expansion of vast metropolitan areas and the displacement of industries to the coastal areas. At the same time, given the rising cost of energy, reckless offshore dumping of industrial wastes has increased. All these have contributed greatly to the fouling of the ocean environment. Concomitantly, harvesting of marine products for providing food to the increasing global population is on the rise. In particular, over-fishing of demersal stocks has been observed in Peninsular Malaysia eastern coast (Ambak et al., 1981; Ambak and Mohsin, 1982; Ambak and Harmin, 1982; Ambak, 2000).

There is an increasing need to manage the ocean environment and to explore for meaningful compromises between the demands of growing industrialization and emergence of prosperous societies and the need to maintain the natural resources. This represents an optimal control problem that can only be addressed by numerical models.

Oceanographers have identified mathematical expressions that represent the most important aspects of the ocean. In this context, ocean models may be viewed as approximations of the complete physics of the ocean. By definition, these models are simplifications of the real ocean.

More often simplifications are introduced to isolate a subset of the physics believed to be essential to the phenomena under study. The task of the ocean modeler is essentially two fold: how to make the correct approximations and how to analyze the results.

The main purpose of numerical ocean modelling is to understand the ocean and to predict or simulate.

By definition, the equations that govern the motion of the atmosphere and the ocean are highly nonlinear. Given the complexity of these mathematical equations, they may not be solved analytically. The solution of these equations necessarily requires approximate numerical methods.

INTRINSIC PROBLEMS IN NUMERICAL WEATHER PREDICTION AND IN OCEAN MODELLING

There are several important physical differences between the large-scale atmospheric flow and the circulation of the ocean as the atmosphere has larger space scales and smaller time scales than the ocean (Jordan, 1964; Orlanski, 1968; Hoskins, 1971). The approximate horizontal length scales of: (a) an extra-tropical cyclone and (b) a hurricane is of the order of 1000 km and 500 km, respectively (Bjerkness, 1919; Reed and Sanders, 1953; Reed, 1955; O' Brien and Reid, 1967; Leipper, 1967; Bleck, 1973). Therefore, these two phenomena may be accurately solved using a resolution of 100 km (Sanders, 1955; Elliassen and Raustein, 1970; Hoskins, 1972; Hoskins and Bretherton, 1972; Shapiro, 1975; Chang and Anthes, 1978). That is, a grid spacing of 1 degree of latitude by 1 degree of longitude.

The situation in the ocean is rather different. A realistic simulation of the ocean requires a horizontal resolution of 1 km. Upper oceanic fronts have a horizontal length scale of 10 km (McNider and O' Brien, 1973; Garvine, 1974, Garvine, 1979; Roden, 1980; Kao, 1980; Camerlengo, 1989a). In particular, a longitudinal resolution of 1 km was used to simulate the response of the sub-arctic oceanic front to atmospheric forcing (Camerlengo, 1982). Consequently, a larger number of grid points are needed in ocean modelling than in atmospheric modelling to accurately simulate a similar area (Roden, 1970; Roden, 1972). Therefore, the requirement of larger computer power is more acute in oceanic modelling than in numerical weather prediction (NWP). In particular, a five-day weather forecast is rather accurate. On the other hand, the situation is completely different as far as ocean forecasting is concerned.

A precise set of initial conditions, also referred to as *initialization*, is crucial for better performance in NWP as well as in oceanic models (Tareyev, 1968). Given the fact that an important number of atmospheric observations are obtained (from satellites, airplanes and radiosonds) at any given time, the meteorologist is able to estimate a set of good initial conditions at all grid points. The situation is radically different in the ocean, as the ocean modeler will rarely have a good set of data on the initial conditions (Roden, 1977). A recent study addresses the initialization problem in ocean modelling (Camerlengo, 1997a).

Due to the lack of a proper initialization the ocean models usually start from rest, whereby the initial velocity is arbitrarily set to zero (Suginohara, 1973; Black and Whitee, 1976; Camerlengo and Nasir, 1996a). The ocean models continue their time integration until there is no significant departure in the currents between two consecutive time steps (Bleck, 1978; MacVean and Woods, 1980; Camerlengo and

Demmler, 1997a). This situation is referred to as either a steady state solution or a stationary solution (Geisler, 1970; Roden, 1975). At this point, the time integration of the ocean model is terminated (Abramov et al., 1972; Roden, 1976; Camerlengo and Demmler, 1996a).

EARLY ATTEMPTS OF MODELLING THE ATMOSPHERE AND THE OCEAN

Right after the Second World War John von Neumann encouraged the meteorological community to use the first general purpose computers for numerical prediction of the atmosphere.

The earliest applications of numerical methods for the purpose of modelling the ocean general circulation were done by Sarkisyan (1955) in the former USSR. Thereafter, Sarkisyan' s research group concentrated their efforts on regional diagnostic studies, such as the North Atlantic.

Ocean modelling activities in the US was started in the early sixties at the University of Princeton by K. Bryan. He applied techniques of NWP for the solution of a vertically integrated ocean model (that is, a 2 dimensional model) enclosed in a rectangular domain (Bryan, 1963). His main concern was to be able to couple his ocean models with atmospheric models. In collaboration with Cox, Bryan moved rapidly to ocean model that address the problem of the time evolution of the internal structure of the ocean, also referred as baroclinic models (Bryan and Cox, 1968). Given the fact that these models study the internal structure of the ocean they are necessarily three-dimensional.

Thereafter, Bryan developed a more general ocean circulation model suitable for cases of irregular coastline (Bryan, 1969). Due to its intrinsic nature, this type of models requires a large amount of computer time. Considerations of the lack of computer power led to the regional applications of Bryan' s model; such as, the Indian Ocean (Cox, 1970), the North Atlantic (Holland and Hirschman; 1972), oceanic tracers (Holland, 1971) and the Southern Ocean (Gill and Bryan, 1971).

For the sake of increasing the time step of the model, the fastest travelling waves (i. e., the external gravity waves), were filtered in Bryan' s (1969) model. For this purpose, a rigid-lid on top of the ocean was implemented. The rigid-lid approximation was later removed upon implementation of the free-surface method (Dukoowicz and Smith; 1994).

The problem of the internal structure of the ocean has been reported recently (Camerlengo, 1997b)

LIMITED AREA MODELS

Limited-area models focus on a small geographical region of the World Ocean. The mathematical formulation of these limited-area models is relativcly straightforward (Camerlengo, 1989b). They are economical and they may be run on personal computers. The main drawback of these kind of models is its limited geographical domain that inhibits the treatment of processes outside its area of integration.

From a computational point of view, one of the most difficult problems of the limited-area models is the mathematical treatment of non-coastal boundaries. This is also referred as the "open boundary condition" problem. An open boundary condition (OBC) is a computational boundary that allows phenomena generated in the interior domain to pass through the artificial boundary without distortion and without affecting the interior solution.

One of the pioneering studies that dealt with this kind of problem was that of Orlanski (1976). Several studies addressed the problem of the evolution of different kinds of waves through different sets of OBC (Camerlengo and O' Brien, 1980; Davies, 1983; Israeli and Orzag, 1981; Wang, 1982; Roed and Smedstad, 1984; Chen, 1973; Bennett and McIntosh, 1982; Beardsley and Haidvogel, 1981; Guo and Zeng, 1995, Roed and Cooper, 1989).

Using a vertically integrated ocean model, Chapman (1985) tested the performance of eleven different sets of OBCs. The results of his study showed conclusively that a modified version of the OBC of Camerlengo and O' Brien (1980) produced better results.

Given the fact that the interior solution of limited-area models depends on the type of OBC implemented, the problem of OBCs is still an area of active research.

GENERAL CIRCULATION MODELS

The coupled general circulation model (GCM) represents the linkage of an atmospheric GCM with an oceanic GCM. This type of model is commonly used to study global warming or cooling scenarios. Given the fact that a considerably amount of time on supercomputers is needed to run these models, they are very expensive.

Quite often modelers have to make a choice between using a model that represents the real world (with all its mathematical complexity) and the cost of using a limited area model for a considerable shorter period of time. In particular, it takes two minutes CPU time for the model developed at UCT to reach a steady state solution (Camerlengo and Demmler, 1996b).

Most of the ocean GCMs requires a coarse grid resolution. These type of model use the Arakawa B lattice (Fig. 1 and 2). Camerlengo and Demmler (1997a) showed that, for this particular lattice, the - CFL - stability criteria is double that for other lattices in a two-dimensional ocean model. Meaning that, given a fixed grid point distance, a double time of integration is needed using this particular lattice as compared to other lattices. This is an additional factor that makes this type of model, GCM, expensive.

As of today no single kind of ocean numerical model is able to capture all aspects of the ocean (circulation, external waves, internal waves, tidal phenomena, etc.). These may be explained by the fact that: (a) ocean modelling activities are quite recent, (b) every model has important shortcomings, and (c) the lack of computer power. It is expected that the performance of these kinds of models will improve considerably during the coming decade and therefore may be used as an important forecasting tool (Figs. 3, 4 and 5).

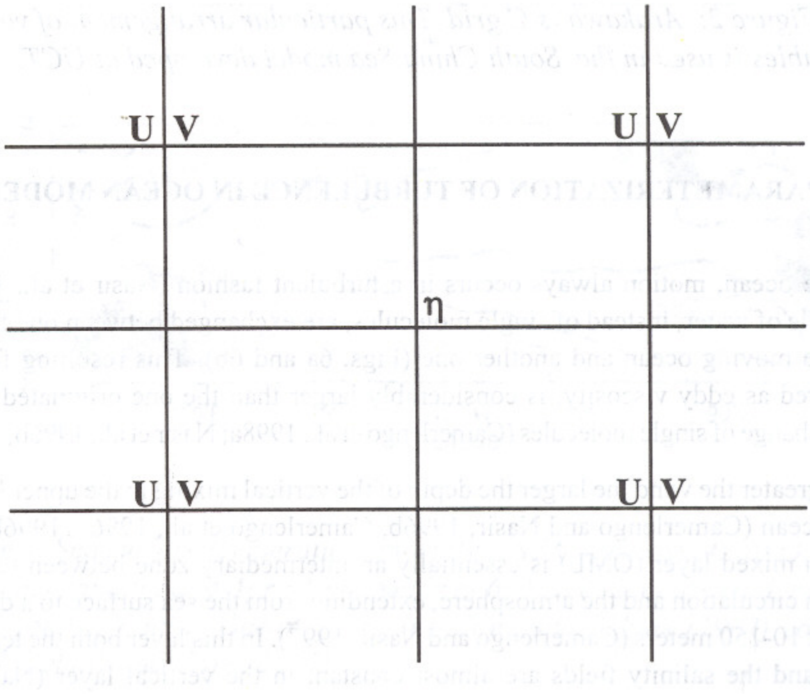


Figure 1: Arakawa' B grid. This particular arrangement of variables is used in Bryan (1969) global ocean model.

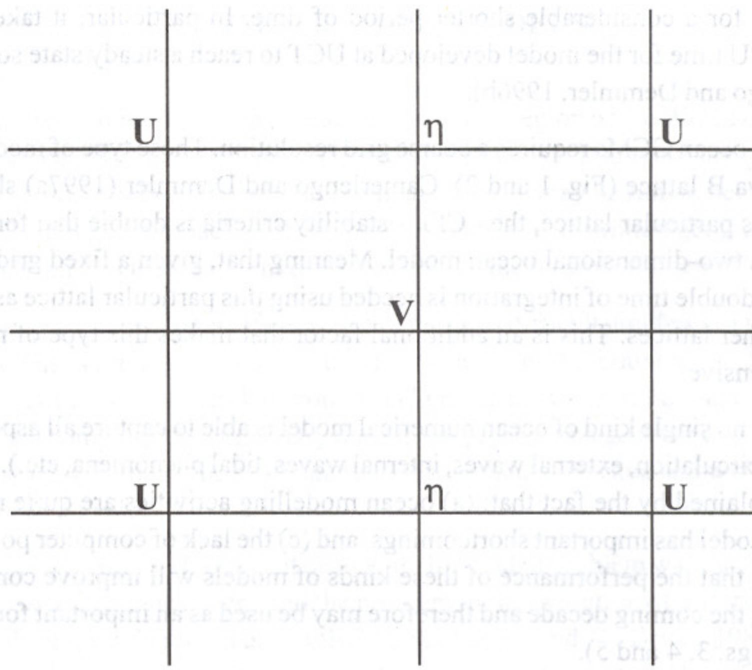


Figure 2: Arakawa' s C grid. This particular arrangement of variables is used in the South China Sea model developed at UCT.

PARAMETERIZATION OF TURBULENCE IN OCEAN MODELS

In the ocean, motion always occurs in a turbulent fashion (Nasir et al., 1996a). Parcels of water, instead of single molecules, are exchanged between one fraction of the moving ocean and another one (Figs. 6a and 6b). This resulting friction, referred as eddy viscosity, is considerably larger than the one originated by the interchange of single molecules (Camerlengo et al., 1998a; Nasir et al., 1996b, 1996c).

The greater the wind the larger the depth of the vertical mixing in the upper layer of the ocean (Camerlengo and Nasir, 1996b, Camerlengo et al., 1996a, 1996b). The ocean mixed layer (OML) is essentially an intermediary zone between the deep ocean circulation and the atmosphere, extending from the sea surface to a depth of about 10-150 meters (Camerlengo and Nasir, 1997). In this layer both the temperature and the salinity fields are almost constant in the vertical layer (Nasir and Camerlengo, 1996). This vertical constancy is due to mixing which again is caused by turbulence (Camerlengo and Nasir, 1996c).

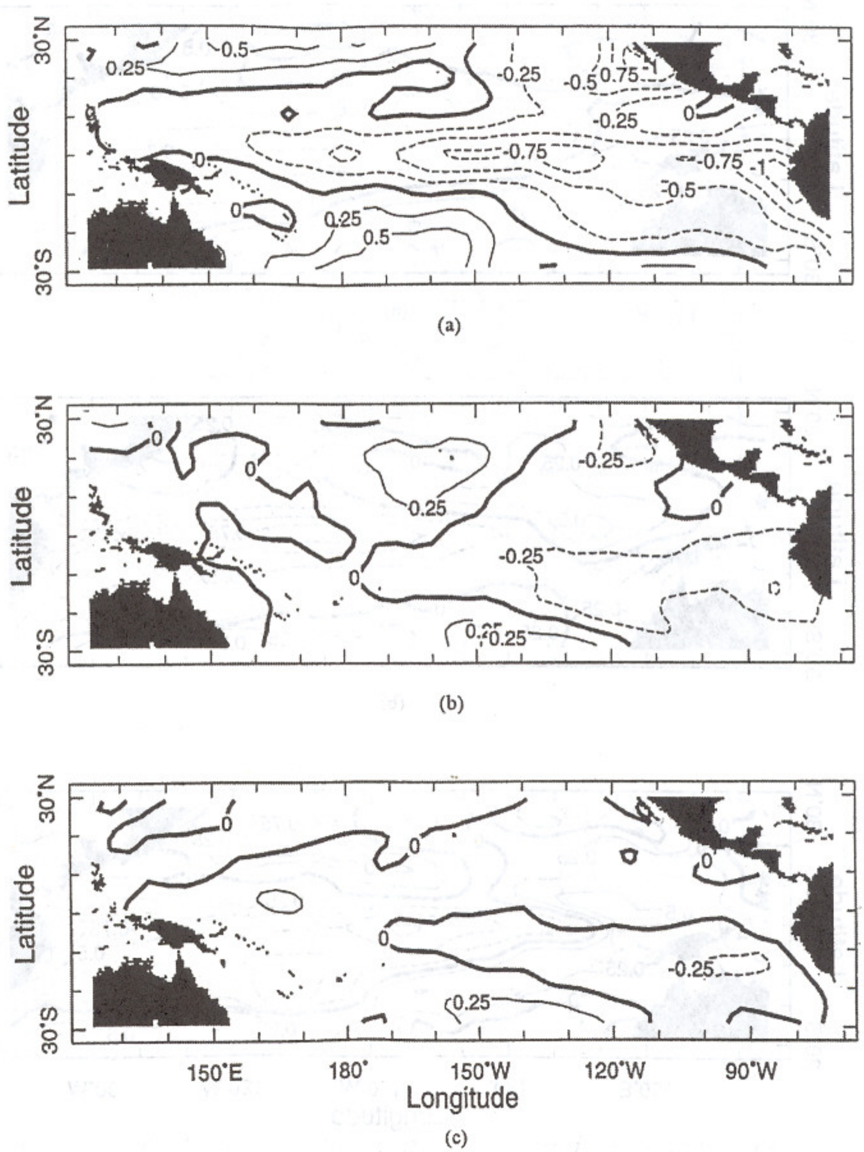
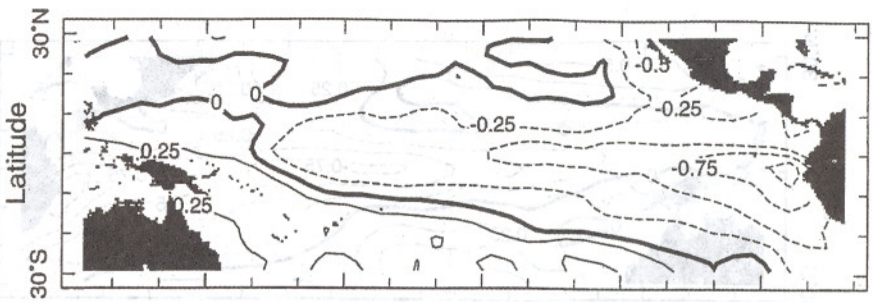
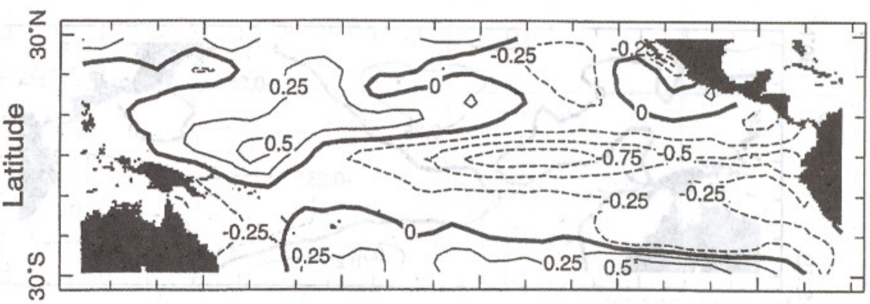


Figure 3: Sea surface temperature anomaly (SSTA) forecast of: (a) October 1997, and January and April 1998, made at 6, 9 and 12 month lead, respectively; for the Pacific Ocean, following Cane and Zebiak (1987) coupled model (Zebiak and Cane, 1987).

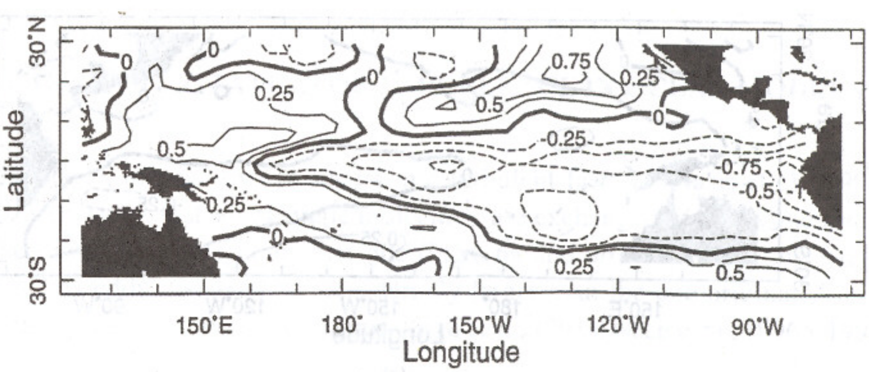
It is interesting to observe that a La Niña event is forecast. However, an El Niño event happen at that particular time.



(a)



(b)



(c)

Figure 4: Same as Figure 4, but using an initialization procedure, following Chen et al. (1995). From Zebiak and Cane (1997).

The proposed initialization enhances the La Niña event.

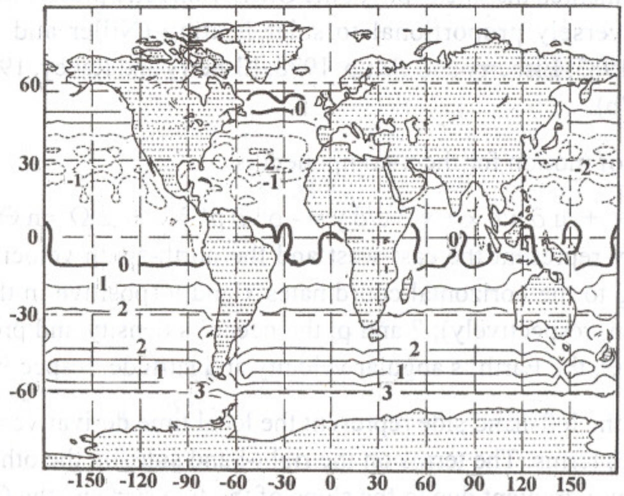


Figure 5: SSTA forecast using Schopf and Cane (1983) ocean model (Camerlengo, 1983).

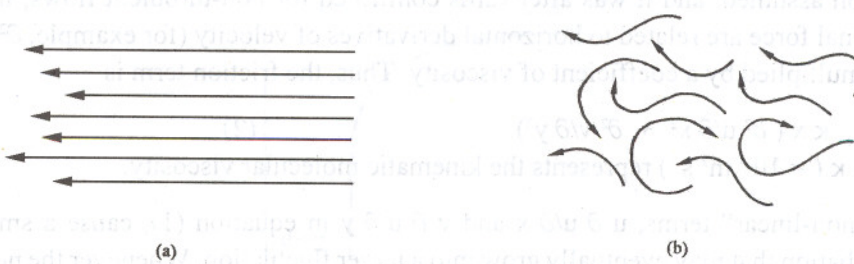


Figure 6: Contrast among (a) a laminar flow and (b) a turbulent flow. The pointer illustrates the trajectory followed by the parcels of water

It is well documented that the depth of the OML is directly proportional to the wind speed and inversely proportional to solar heating (Niiler and Krauss, 1977; Camerlengo, 1983; Elsberry and Camp, 1978; Elsberry and Raney, 1978; Kim, 1976; Figs. 7a and 7b).

The equation of motion for the x-component is:

$$\partial u/\partial t + u\,\partial u/\partial x + v\,\partial u/\partial y = -\rho^{-1}\,\partial p/\partial x + 2\,\Omega \sin \Theta + \text{friction}, \quad (1)$$

where u and v represent the east-west and the north-south velocity components corresponding to the horizontal coordinates x and y (positive in the east and the north direction, respectively); ? and p, the ocean' s density and pressure, respectively; Ω and Θ, the Earth' s angular velocity and latitude, respectively.

The terms on the left-hand side represent the local time derivative and the nonlinear (advective) terms. The terms on the right-hand side, on the other hand, represent the pressure gradient due to the slope of the free surface, the Coriolis deflection and the friction terms (Camerlengo and Nasir, 1996a).

Frictional forces in a moving fluid result from the transfer of momentum (mass x velocity) between different vertical layers of the fluid. In the real ocean the effect of wind stress is transported down as a result of internal friction within the uppermost layer of the ocean. This internal friction is due to the turbulent flow produced by the variable wind (Camerlengo and Demmler, 1996c).

Newton assumed, and it was afterwards confirmed for non-turbulent flows, that frictional force are related to horizontal derivatives of velocity (for example, $\partial^2 v/\partial x^2$) multiplied by a coefficient of viscosity. Thus, the friction term is

$$\kappa \times (\partial^2 u/\partial x^2 + \partial^2 v/\partial y^2) \quad (2)$$

where κ ($= 10^{-6}\ m^2\ s^{-1}$) represents the kinematic molecular viscosity.

The "non-linear" terms, $u\,\partial u/\partial x$ and $v\,\partial u/\partial y$ in equation (1), cause a small perturbation that may eventually grow into a larger fluctuation. Whenever the nonlinear terms are larger than the frictional terms, instability - due to turbulence - occurs.

It is convenient to consider u and ∂u to be of order U (a typical velocity magnitude) and ∂x of order L (L a typical length magnitude over which the velocity varies by U). To determine what is meant by "large" the ratio:

$$(u\,\partial u/\partial x) / (\partial x\,\partial^2 u/\partial x^2) \quad (3)$$

is evaluated (Rayleigh, 1880). After some algebraic manipulations the ratio, also referred as the Reynolds number (Re), is of order:

$$U \times L/\kappa. \quad (4)$$

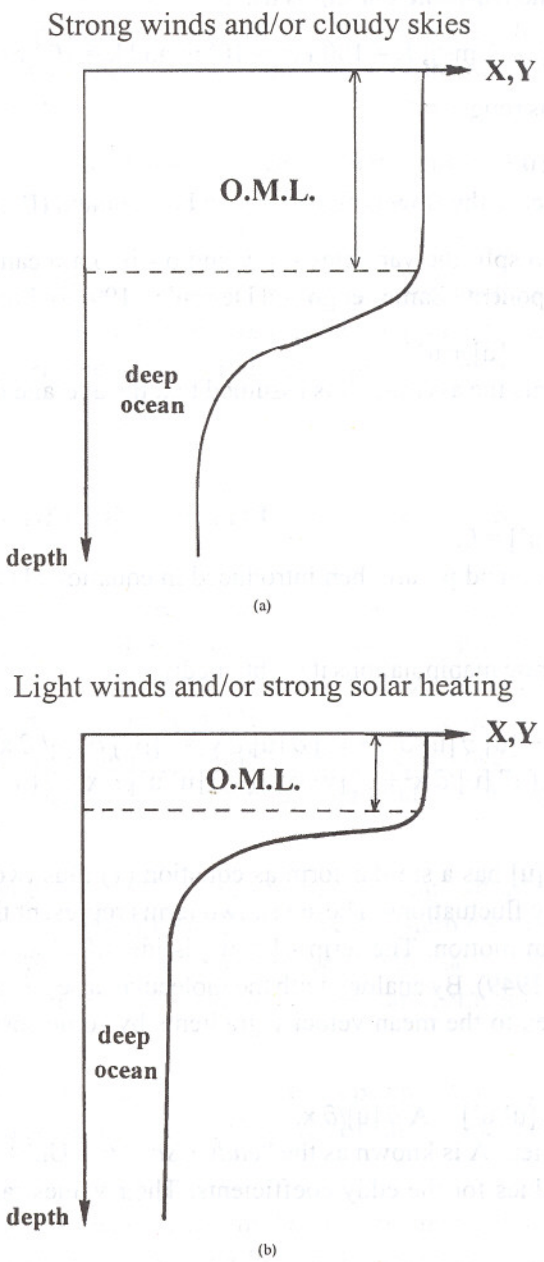


Figure 7: The OML is deeper whenever (a) there is either strong winds and/ or cloudy skies. The reverse is also true. (b) Light and variable winds and/or cloudless skies are responsible for the retreat of the OML

For example, if the Kuroshio current is used:

$$U = 1\ ms^{-1},\ L = 100\ km = 10^5\ m \text{ and } k = 10^{-6}\ m^2\ s^{-1}. \qquad (5)$$

The resulting Re is roughly:

$$10^{11}. \qquad (6)$$

In this particular case the flow is considered to be turbulent (Bergeron, 1928).

It is convenient to split the variables - u, v and p - into a mean component and a perturbation component (Camerlengo and Demmler, 1996d). For example:

$$u = [u] + u' \qquad (7)$$

where [ ] represents the average. It is assumed that the average of the perturbation is zero.

That is,

$$[u'] = 0. \qquad (8)$$

The variables - u, v and p - are then introduced in equation (1) and the average is taken.

After some algebraic manipulations it is obtained:

$$\partial [u]/\partial t + [u]\, \partial [u]/\partial x + [v]\, \partial [u]/\partial y = - [\rho^{-1}]\, \partial [p]/\partial x + 2 \times \Omega \times \sin \Theta \times [v] + \kappa \times (\partial^2 [u]/\partial x^2 + \partial^2 [v]/\partial y^2) - \partial [u'\ u']/\partial x - \partial [u'\ v']/?\ y \qquad (9)$$

Equation (9) for [u] has a similar form as equation (1) plus two additional terms involving velocity fluctuations. These last two terms represent the effect of turbulence on the mean motion. The term - [u' u'] is identified as a stress due to the turbulence (Kuo, 1949). By analogy with the molecular case it is assumed that these stresses are related to the mean velocity gradients by some sort of viscosity. For example:

$$- [u'\ u'] = A\, \partial [u]/\partial x, \qquad (10)$$

where the coefficient A is known as the "*eddy viscosity*". Unlike κ, there is a garden variety of values for the eddy coefficients. Their values range from 1 to 10^5 m^2s^{-1}.

In ocean models the turbulent terms tend to "smooth" the numerical solution. In other words, the larger the value of the eddy viscosity, A, a larger smoothing of the model results is attained.

Given the particular arrangement of variables in Bryan's (1969) model, also referred to as Arakawa' s B grid, one is forced to use an extremely large value of A (=

10^5 m^2s^{-1}). Using a different arrangement of variables (Arakawa' s C grid) the South China Sea model that has been developed at UCT requires a value of A not larger than 10 m^2s^{-1}. Therefore, no unnecessary smoothing of the numerical solutions of the latter model is needed.

Although it is convenient to consider the eddy coefficients, A, to be constant it is well known that this may not be the case (Roden, 1974; Camerlengo and Demmler, 1997b).

The "state of the art" indicates that the correct parameterization of the turbulent terms has not been achieved yet. This is one of the additional problems that need to be vercome before a reliable forecast of the ocean is achieved by numerical means.

MODELLING ACTIVITIES IN MALAYSIA

Ocean modelling is in its infancy in Malaysia. Gouy (1989), using a two dimensional linear model, observed that the M_2 tidal component is predominant in the Malacca Straits while the diurnal tides are predominant in Peninsular Malaysia's eastern continental shelf. Azmi et al. (1991), using a two dimensional non linear model, confirmed that a piling up of water (of tens of cm) occur during the boreal winter while a lowering of water (of similar magnitude) occurs during the boreal summer at the east coast.

Camerlengo and Demmler (1997c) developed a nonlinear hydrodynamic, vertically integrated ocean model for Peninsular Malaysia's eastern continental shelf. Field observations in the South China Sea have been undertaken by Wyrtki (1961). Camerlengo and Demmler's (1997c) model results are comparable with Wyrtki's observations.

An interesting feature of the ocean model developed at UCT is the new methodology for the evaluation of viscous terms close to the coast (Camerlengo and Demmler, 1995).

Qualitatively, our results are able to simulate the two maximum currents flowing along the Vietnamese coast and along Peninsular Malaysia's eastern continental shelf during both the monsoon seasons (Figs. 8 to 14).

Qualitatively, our model results, for December, show a mass transport of 4.7 Sv (1 Sv =10^6 m^3s^{-1}) and 4.1 Sv along the Vietnamese coast and along Peninsular Malaysia's eastern continental shelf, respectively. Wyrtki's observations are 5.0

Sv and 4.0 Sv, respectively, for these two locations, during the same month. The model results, for August, show a mass transport of 2.8 Sv and 2.6 Sv for these two locations. These results compare favourably with Wyrtki' s values (3.0 Sv) for the same two locations.

It has been determined that the gyre located in the South China Sea, during the two monsoon seasons, is only due to topographic effects (Figs.15 and 16).

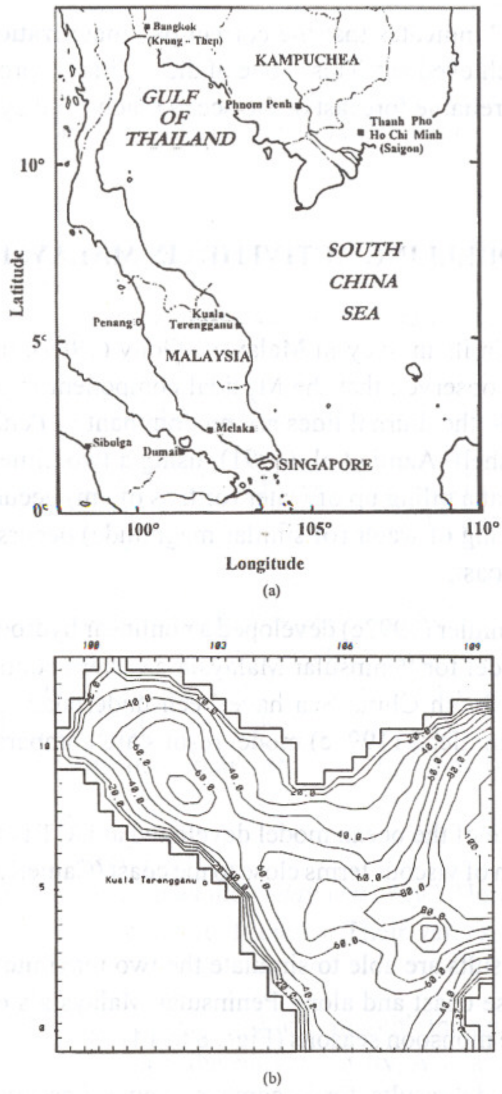


Figure 8: Illustration of: (a) the area and (b) the bottom topography numerically simulated using the ocean model developed at UCT.

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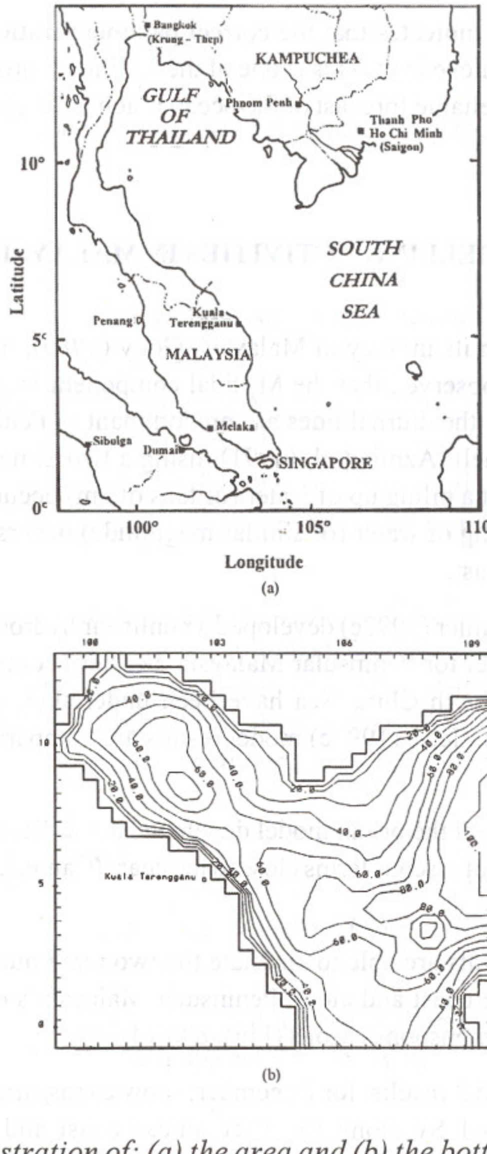

Figure 8: Illustration of: (a) the area and (b) the bottom topography numerically simulated using the ocean model developed at UCT.

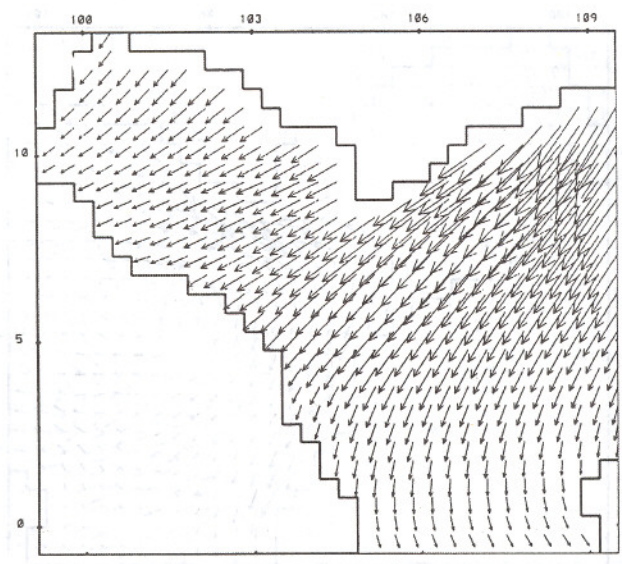

Figure 9: December Hellerman and Rosenstein's (1983) wind stress.

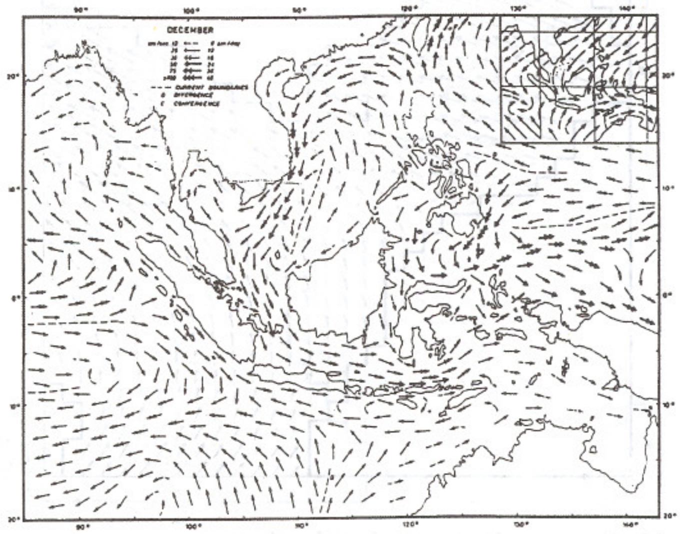

Figure 10: Wyrtki's (1961) surface currents for December.

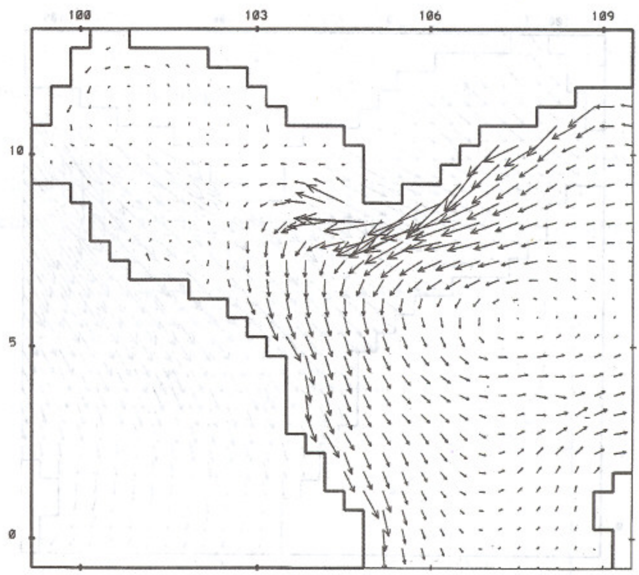

Figure 11: December surface currents simulation given the ocean model developed at UCT.

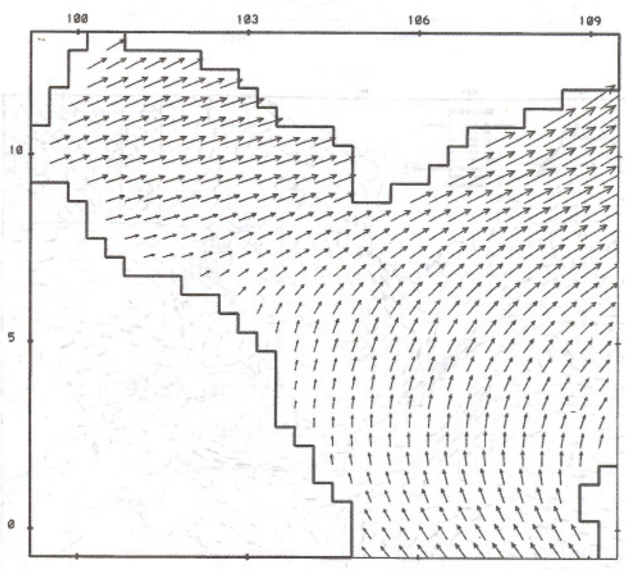

Figure 12: Same as Figure 9, but for August.

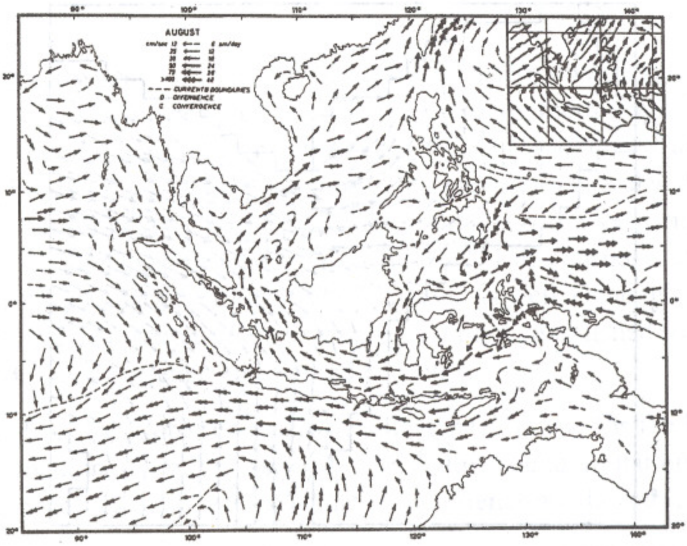

Figure 13: Same as Figure 10, but for August.

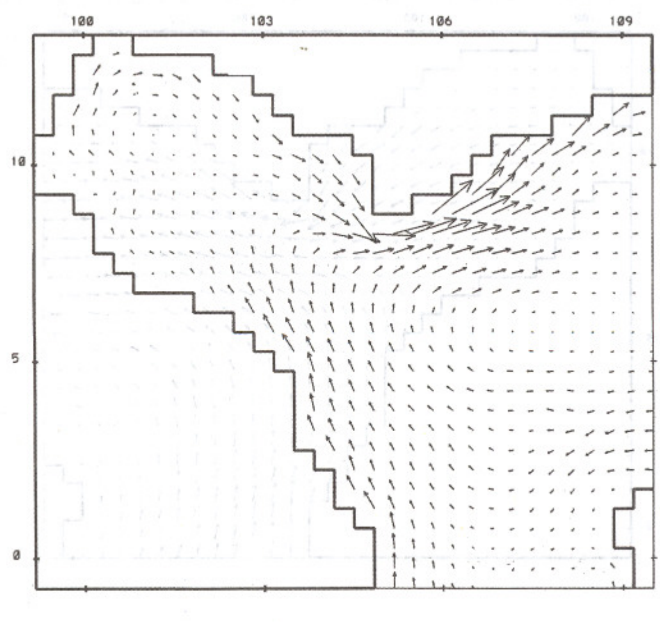

Figure 14. Same as Figure 11, but for August.

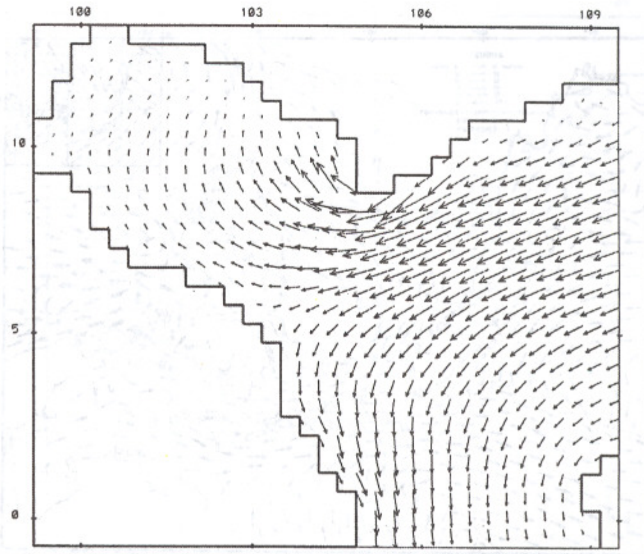

Figure 15: Numerical simulation of the December surface currents using a flat bottom topography.

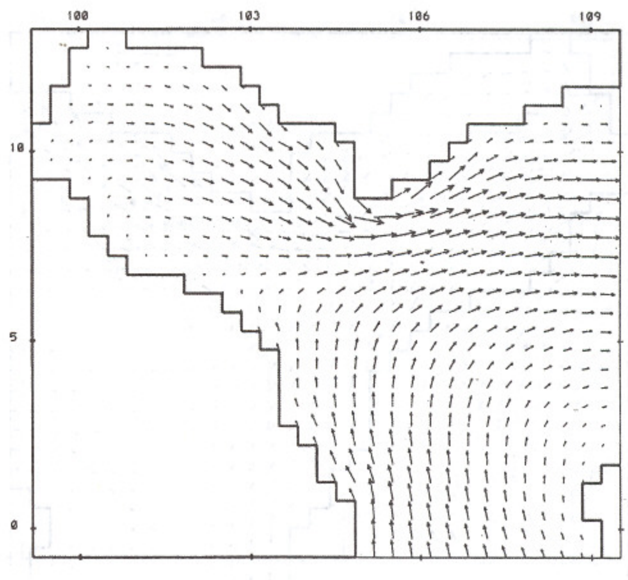

Figure 16: Same as Figure 15, but for August.

CONCLUSIONS

Oil exploration activities in Peninsular Malaysia' s eastern continental shelf are expected to increase in the next few years. Consequently, there is a danger of a major oil spill catastrophe as has been witnessed in the Malacca Straits (Camerlengo et al., 1998b). Research in Malaysia into different aspects of removal and containment of oil spill under adverse meteorological conditions will necessarily have to undergo an accelerated expansion in the near future. For this purpose, a good understanding of the circulation of the South China Sea as well as the oil spill path, driven by the wind, is essential. This task may only be accomplished by usage of numerical models (Camerlengo and Demmler, 1998).

In spite of the fact that global ocean models have been in use for the last thirty years, advancement in ocean forecasting has been slow due to limitations in computer power and the lack of observational data (Camerlengo and Demmler, 1997d).

Ocean models are recent research tools. As such, it is expected that they will undergo improvements in their performance during this decade.

I feel it is necessary to step up ocean modelling activities and research in Malaysia. The purpose is two-fold. On one hand, there is a need to upgrade the performance of the existing ocean models. On the other hand, the emergence of a core of ocean modelers is very much needed.

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