

The evolution of temperature and salinity fields in a global ocean model

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A three dimensional Ocean General Circulation Model in stretched coordinate with zoom capability over an area of interest has been used to study the evolution of the meridional and vertical structure of temperature, salinity and density of the ocean. In this study 9 discrete vertical levels with flat bottom topography and horizontal resolution of 2.5° (N-S) $\times$ 5° (E-W) has been considered. The lateral boundaries are set at 30° S and 30° N for the channel ocean surrounding the earth. The model simulation run is forced by analytic wind stress, heat and salinity fluxes from initial steady state to a stable state of ocean. For the final steady state, the longitudinal average of above fields are taken at all the levels. Finally best fit relations have been obtained from their latitudinal and vertical variation.

Coupled modelling is a rapidly progressing field because of the large scientific and public interest in predictions of potential anthropogenic climate changes and climate variations. Both issues require a proper representation of both oceanic and atmospheric circulation. Most of the coupled models do not employ same type of numerical techniques for treating the dynamics in the atmosphere and ocean. The computations for atmospheric dynamics are generally performed by spectral/grid point method and the ocean dynamics by the grid point method. Even the schemes used in the grid point methods for the ocean and atmosphere may differ. Hence there is a chance to transfer of numerical errors from atmospheric simulation to ocean simulation and vice-versa¹. In view of this problem, a three dimensional (3-D) Ocean General Circulation Model (OGCM) in stretched coordinates with zoom capability over an area of interest has been developed, which is being reported for the first time. This model will be eventually coupled to the stretched coordinate AGCM to study the dynamics of climate and its variations, intraseasonal and interannual variability of monsoon and for El-Nino/Southern Oscillation (ENSO) predictions. The coordinate stretching has its own advantage of diminishing the grid size in an area where finer

resolution is required². Now, there are important technical questions that arise related to this kind of OGCM. For instance, could this OGCM be able to produce the mean structure of temperature and salinity fields? Or is the evolution of the mean meridional and vertical structure of above fields appear realistic from such a model simulation? This paper examines these questions by analysing the mean vertical and meridional distribution of temperature, density and salinity of the global ocean from the simulation run in the tropical belt.

Materials and Methods

Model's governing equations

The ocean is considered as an incompressible fluid described by Navier-Stokes equations formulated in spherical coordinates λ , ϕ and z , where λ is longitude, ϕ latitude and z depth. The vertical coordinate z is positive upward with the ocean surface coincide with $z=0$. Both the hydrostatic and Boussinesq approximations are used in simplifying the governing equations. The linearized equation of state has been considered to save computer time. The subgrid-scale processes are parameterized by the down gradient mixing hypothesis, where the exchange co-efficients are assumed to be constant.

If u, v , and w are the zonal, meridional and vertical velocity components respectively and $x = x(X)$, $y = y(Y)$, where X and Y are model coordinates along x and y directions then defining covariant components (u^* , v^*) and contravariant components (u_* , v_*) as

$$u_* = u a x' \cos \phi \quad u^* = \frac{u}{a x' \cos \phi}$$

$$v_* = v a y' \quad v^* = \frac{v}{a y'}$$

where,

$$x' = \frac{\partial x}{\partial X}, \quad y' = \frac{\partial y}{\partial Y}, \quad \text{and area (A)} = a^2 x' y' \cos \phi,$$

one can write the governing model equations in stretched coordinate^{3,6} as:

$$\frac{\partial u_*}{\partial t} + \frac{\partial B}{\partial X} v^* Z + w \frac{\partial u_*}{\partial z} = A_m \nabla_H^2 u_* + K_m \frac{\partial^2 u_*}{\partial z^2} \quad \dots (1)$$

$$\frac{\partial v_*}{\partial t} + \frac{\partial B}{\partial Y} u^* Z + w \frac{\partial v_*}{\partial z} = A_m \nabla_H^2 v_* + K_m \frac{\partial^2 v_*}{\partial z^2} \quad \dots (2)$$

$$\frac{\partial T}{\partial t} + \frac{\partial (u^* T)}{\partial X} + \frac{\partial (v^* T)}{\partial Y} + \frac{\partial (w T)}{\partial z} = A_h \nabla_H^2 T + K_h \frac{\partial^2 T}{\partial z^2} \quad \dots (3)$$

$$\frac{\partial S}{\partial t} + \frac{\partial (u^* S)}{\partial X} + \frac{\partial (v^* S)}{\partial Y} + \frac{\partial (w S)}{\partial z} = A_s \nabla_H^2 S + K_s \frac{\partial^2 S}{\partial z^2} \quad \dots (4)$$

$$\frac{\partial u_*}{\partial X} + \frac{\partial v_*}{\partial Y} + \frac{\partial w}{\partial z} = 0 \quad \dots (5)$$

$$\frac{\partial P}{\partial z} = -\rho g \quad \dots (6)$$

$$\rho = \rho_0 [1 - \alpha(T - T_0) + \beta(S - S_0)] \quad \dots (7)$$

where,

$$B = \frac{P}{\rho_0} + \frac{1}{2} (u_* u^* + v_* v^*), \quad Z = [fA + (\frac{\partial v_*}{\partial X} \frac{\partial u_*}{\partial X})],$$

$$\nabla_H^2 = \frac{\partial^2}{\partial X^2} + \frac{\partial^2}{\partial Y^2}$$

and $f = 2\Omega \sin \phi$. T and S are temperature and salinity respectively of the model ocean. All constant terms are described in Table 1.

Model domain and boundary conditions

The physical domain in the ocean model is the tropical channel going around the earth without any boundary in the east or west. The northern and southern boundaries are at 30°N and 30°S respectively. It has a flat bottom of 5 km depth.

Lateral boundary conditions are :

$$\frac{\partial u}{\partial Y} = 0, \quad v = 0 \quad \text{at} \quad \phi = 30^\circ, -30^\circ \quad (\text{no slip condition}).$$

$$\frac{\partial T}{\partial Y} = \frac{\partial S}{\partial Y} = 0, \quad \text{at} \quad \phi = 30^\circ, -30^\circ \quad (\text{no heat or salinity flux condition}).$$

Periodicity is applied for u, v, T and S at $\lambda = 0^\circ$ and 360° .

Surface boundary condition is:

$$\left(w, K_m \frac{\partial u}{\partial z}, K_m \frac{\partial v}{\partial z}, K_h \frac{\partial T}{\partial z}, K_s \frac{\partial S}{\partial z} \right) \Big|_{z=0} = (0, \frac{\tau_x}{\rho_0}, \frac{\tau_y}{\rho_0}, \frac{Q_T}{\rho_0 C_p}, Q_S)$$

where, Q_T and Q_S are heat and salinity fluxes respectively, and $w=0$ corresponds to rigid lid condition.

Bottom boundary conditions is :

$$\left(w, K_m \frac{\partial u}{\partial z}, K_m \frac{\partial v}{\partial z}, K_h \frac{\partial T}{\partial z}, K_s \frac{\partial S}{\partial z} \right) \Big|_{z=-H} = (0, 0, 0, 0, 0)$$

that is, there is no stress at and heat and salinity fluxes from bottom surface.

Dynamic and thermodynamic forcings

The model ocean is driven by analytic wind-stress, heat and salinity fluxes through the sea-surface. The longitudinal and meridional wind stresses are calculated from atmospheric wind components as:

$$(\tau_x, \tau_y) = \left\{ \begin{aligned} & \left[\rho_a \cdot C_d \cdot |(u_a^2 + v_a^2)|^{\frac{1}{2}} \cdot u_a \right] \\ & \left[\rho_a \cdot |(u_a^2 + v_a^2)|^{\frac{1}{2}} \cdot v_a \right] \end{aligned} \right\}, \quad \dots (8)$$

where, ρ_a is the density of air near surface and C_d is drag coefficient. The wind components u_a and v_a are calculated with the help of geostrophic balance,

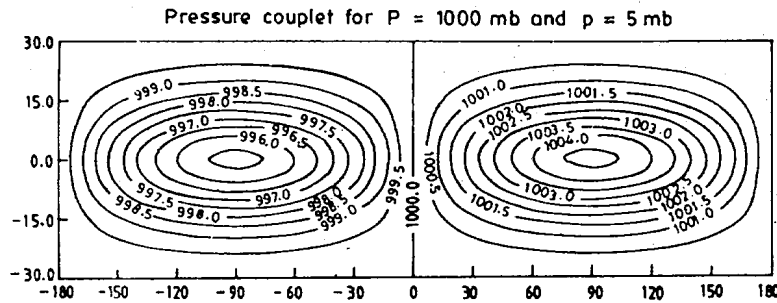


Fig. 1—Plot of pressure contours.

$$(u_a, v_a) = \left(-\frac{1}{\rho_a f} \frac{\partial P_s}{\partial x}, \frac{1}{\rho_a f} \frac{\partial P_s}{\partial y} \right) \quad \dots (9)$$

where P_s is the atmospheric surface pressure which is taken in the form of a couplet consisting of a low and a high pressure centre^{7,8}(see Fig.1) and expressed as:

$$P_s(x, y) = P_o + \Delta P \left[\tanh^2(2) - \tanh^2\left(\frac{4y}{YM}\right) \right] \sin\left(\frac{2\pi x}{XM}\right) \quad \dots (10)$$

In the above expression, P_o is the reference sea surface pressure, ΔP is the departure from the reference pressure and XM is the length of the channel and YM is the width. The thermal forcing in the model is specified by using an approximate formula proposed by Haney⁹. The heat flux through the surface is calculated from,

$$Q_T(\lambda, \phi, t) = Q_0 [T_a^*(\phi) - T_l(\lambda, \phi, t)] \quad \dots (11)$$

$$T_a^*(\phi) = 13.0 + 17.0 \cos\left(\frac{\phi}{40} \times \frac{\pi}{2}\right) \quad \dots (12)$$

where T_l is the temperature of the top layer of the model ocean and $T_a^*(\phi)$ is the apparent atmospheric equilibrium temperature.

The salinity flux through the surface is calculated from

$$Q_S(\lambda, \phi, t) = S_l(\lambda, \phi, t) [P(\phi) - E(\phi)] \quad \dots (13)$$

where, S_l is the salinity of the top model layer, $E(\phi)$ the evaporation and $P(\phi)$ the precipitation. $E(\phi)$ is taken from the zonal mean annual evaporation for the Pacific Ocean estimated by Wyrki¹⁰ and $P(\phi)$ is taken from the zonal mean annual precipitation for the Pacific Ocean estimated by Dorman & Bourke¹¹. The $[P(\phi) - E(\phi)]$ meridional profile is shown in

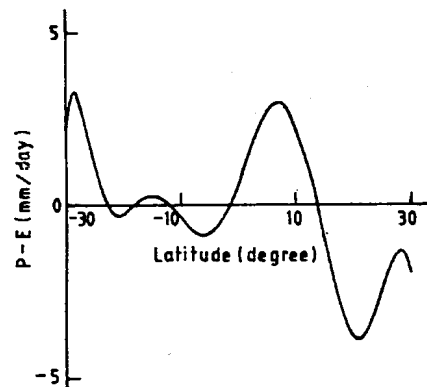


Fig. 2—The prescribed external forcing function: latitudinal variation of precipitation minus evaporation (P-E).

Fig.2, which is a best fit polynomial of degree 9 and reads as :

$$[P(\phi) - E(\phi)] = \sum_{i=0}^9 a_i \phi^i$$

The numerical values of the coefficients a_i in the above polynomial are found to be,

$$a_0 = 0.59036; a_1 = 0.444199; a_2 = 0.0159951; a_3 = -1.5991 \times 10^{-2}; a_4 = -1.47113 \times 10^{-4}; a_5 = 1.12358 \times 10^{-5}; a_6 = 2.93977 \times 10^{-7}; a_7 = -1.30377 \times 10^{-8}; a_8 = -1.67895 \times 10^{-10} \text{ and } a_9 = 5.44151 \times 10^{-12}.$$

The numerical method

The set of governing equations (Eqs 1-7) are resolved numerically on a staggered grid of Arakawa C-type. The model ocean has 9 layers of different thickness (20.0 m, 30.02 m, 50.67 m, 140.44 m, 71.61 m, 560.13 m, 740.11 m, 444.15 m and 1942.87m). In the middle of each layer u , v , T , S , ρ and P are defined while the vertical velocity is

defined at its bounding surfaces (Fig. 3A). The variables in a horizontal plane are defined in rectangular grid boxes of dimension ΔX and ΔY . The T , S , P and ρ are located at the corners of the grid boxes, while u and v are assigned a location in the middle of meridional and zonal edges of each box respectively (Fig. 3B). The time integration scheme for the evolution equations is a combination of one Matsuno step followed by four leap frog steps. Diffusive terms are evaluated at the same way. The grid spacing of $\Delta X=5^\circ$ and $\Delta Y=2.5^\circ$ in the horizontal and a time step $\Delta t = 1.2$ hr have been selected for this model simulation run.

Parameter choices

The values of different parameters used in this model are listed in Table 1. They are physically realistic and numerically sensitive choices. The numerical solutions of the governing equations are not particularly sensitive to most of them although the effects of varying some of these parameters are remarkable. These parameters have been chosen from the literatures^{12,13}.

Results and Discussion

The model simulation begins from a state of rest ($u=v=w=0$), with initial temperature, salinity and density stratification as given in Fig. 4 (A,B,C) (also see Table 2 for their values). The forcing consists of

an analytical constant wind stress and time dependent, latitudinally varying heat and salinity fluxes given by Eqs (8-13) respectively. The model is integrated forward in time for a period of 120

Table 1—A list of parameters used in the model run

Parameter	Notation	Value
Angular velocity of earth	Ω	$7.292 \times 10^{-2} \text{ sec}^{-1}$
Radius of the earth	a	$6.375 \times 10^6 \text{ m}$
Gravitational acceleration	g	9.8 m/sec^2
Coefficient of vertical eddy viscosity	K_m	$1.6 \times 10^{-4} \text{ m}^2/\text{sec}$
Coefficient of vertical eddy diffusivity for heat/salt	$K_h=K_s$	$0.109 \times 10^{-4} \text{ m}^2/\text{sec}$
Coefficient of horizontal eddy viscosity	A_m	$2.4 \times 10^{-4} \text{ m}^2/\text{sec}$
Coefficient of horizontal eddy diffusivity for heat/salt	$A_h=A_s$	$1.8 \times 10^{-3} \text{ m}^2/\text{sec}$
Reference density	ρ_0	1025 kg/m^3
Specific heat of seawater	C_p	10^3 cal/kg/K
Density of air	ρ_a	1.175 kg/m^3
Drag coefficient	C_d	1.5×10^{-3}
Reference surface pressure	P_0	1013 mb
Departure of pressure from P_0	ΔP	55 mb
Coupling coefficient	Q_0	$500 \text{ kcal/m}^2/\text{day/K}$
Total ocean depth	H	5000 m
Thermal coefficient of seawater	α	$2 \times 10^{-4} \text{ K}^{-1}$
Salinity co-efficient of seawater	β	1.5×10^{-7}
Length of the channel	XM	$2\pi a \text{ m}$
Width of the channel	YM	$0.5\pi a \text{ m}$

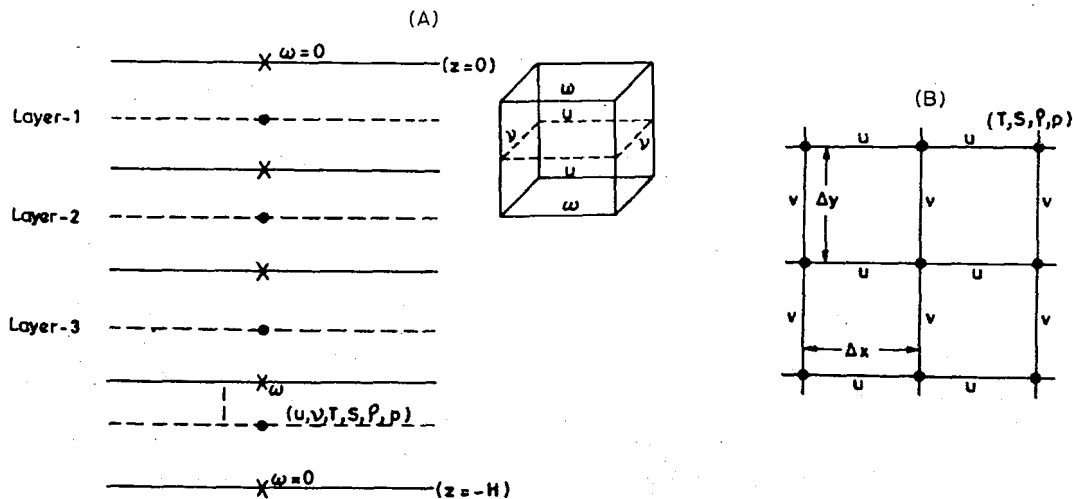


Fig. 3—Placement of the variables: (A) vertical and (B) horizontal.

days when the dynamical variables approach a stationary state. From this quasi steady state, the longitudinal average temperature, salinity and density are calculated at all the levels.

The latitudinal distribution of mean temperature, salinity and density in the top layer (designated as level 1 of the model) are shown in Fig. 5. The general patterns of temperature and salinity distributions are principally governed by the external parameters T_a^* and $[P(\phi)-E(\phi)]$ are clearly

seen. The minimum in the salinity seen in Fig. 5B at about 10°N due to excess precipitation in this region (see Fig. 2 also). Moreover, a minimum in the density of seawater may also be noticed in Fig. 5C, as expected, in the same region. The vertical profiles of mean temperature, salinity and density at the equator are shown in Fig. 6. It may be observed that the mean temperatures at depths 312.74 m (level 5) and 872.87 m (level 6) increase at a very small rate of $0.009 - 0.018^\circ\text{C}/\text{year}$. It therefore reflects that the thermohaline structure prescribed as an initial state diffuses slowly with time. It may also be noticed that the density and temperature fields is quite similar. The model has therefore reproduced the observed structure of above fields¹⁴ to some extent but not satisfactorily. This discrepancy may be partly attributed to the structure of the imposed wind stress forcing, heat and salinity fluxes to drive the circulation or the model integration for 120 days is not sufficient to produce satisfactory observed structure of the above fields from a state of rest. The following best fit relations are obtained from this model study;

Table 2—Initial profiles

Depth (m)	Temperature ($^\circ\text{C}$)	Salinity (‰)	Density (σ_t , kg/m^3)
20.00	21.0	35.60	25.0
50.02	21.0	35.60	25.0
100.69	21.0	35.60	25.0
241.13	12.0	35.40	27.0
312.74	12.0	35.40	27.0
872.87	12.0	35.40	27.0
1612.98	2.0	35.66	27.5
2057.13	2.0	35.66	27.5
5000.00	2.0	35.66	27.5

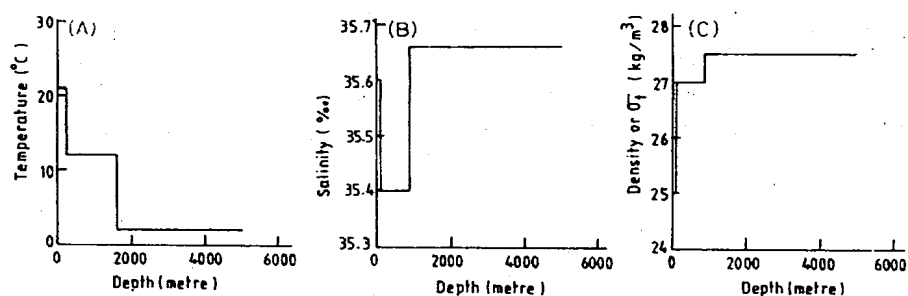


Fig. 4—Initial stratification: A) temperature B) salinity and C) density.

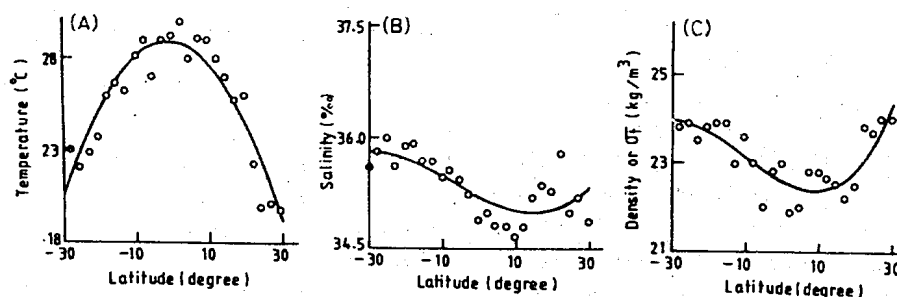


Fig. 5—Model output of latitudinal variation of A) mean temperature, B) salinity and C) density.

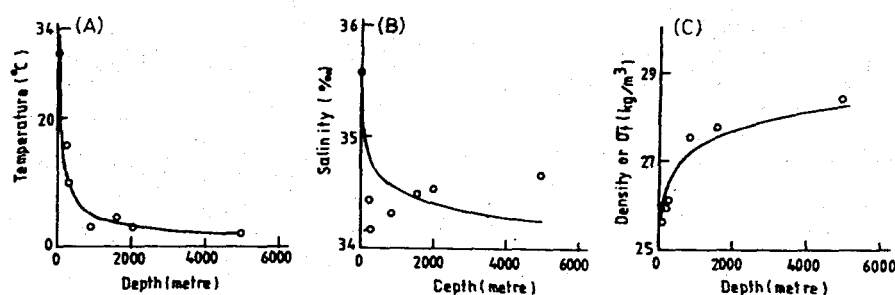


Fig. 6—Vertical profile of mean A) temperature, B) salinity and C) density at the equator from the model run.

$$\begin{aligned}
 T(\phi) &= a_0 + a_1\phi + a_2\phi^2 & T(z) &= 2.56.31 \times z^{-0.570227} \\
 S(\phi) &= b_0 + b_1\phi + b_2\phi^2 + b_3\phi^3 & S(z) &= 35.795 \times z^{-0.00519659} \\
 \sigma_t(\phi) &= c_0 + c_1\phi + c_2\phi^2 + c_3\phi^3 & \sigma_t(z) &= 23.5011 \times z^{0.0216934}
 \end{aligned}$$

where, $a_0 = 28.9066$; $a_1 = -1.97031 \times 10^{-2}$; $a_2 = -1.00361 \times 10^{-2}$; $b_0 = 35.2017$; $b_1 = -2.56291 \times 10^{-2}$; $b_2 = 4.24595 \times 10^{-4}$; $b_3 = 2.00853 \times 10^{-5}$; $c_0 = 22.5982$; $c_1 = -4.22257 \times 10^{-2}$; $c_2 = 1.73188 \times 10^{-3}$; $c_3 = 5.4352 \times 10^{-5}$.

A global ocean general circulation model has been developed which has feature like zooming and refining resolution over an area of interest. A simulation run of 120 day has been accomplished for a continuous tropical channel and evolution of different parameters such as temperature, salinity and density have been computed where model has been forced by wind-stress, heat and salinity fluxes. From this OGCM simulation, following inferences may be made:

- The model has shown the capability to reproduce the structure of temperature, salinity and density fields quite well.
- The analytic profiles of wind field, heat and salinity fluxes are very useful in testing the model response by examining the evolution of the above fields as a first step in numerical experimentation and development of the OGCM.
- Best fit relations could be used to generate temperature and salinity fields data for initialization of the OGCM where the observations are sparse.

Finally one can conclude that the structure of temperature and salinity fields, which are not very different from real distribution can be generated from this model simulation and this may be helpful for the ocean modelers to initialize their models.

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References

- 1 Huang B & Schneider E E, *J Amer Met Soc*, 123 (1995) 3059.
- 2 Sharma O P, Upadhyaya H, Braine-Bonnaire Th & Sadourny R, in *Short and medium range numerical weather prediction*, edited by T Matsuno, (Meteorological Society of Japan, Tokyo) 1987, 263.
- 3 Sadourny R, *J Atmos Sci*, 32 (1975) 680.
- 4 Blanke B & Delecluse P, *J Phys Oceanogr*, 23 (1993) 1363.
- 5 Cox M D, *A primitive equation 3-dimensional model of the ocean*, GFDL Ocean Group Tech. Rep.1, (GFDL/NOAA, Princeton), 1984, pp. 143.
- 6 Bryan K, *J Comput Phys*, 4 (1969) 347.
- 7 Upadhyaya H C & Sadourny R, *Proc. Indian Acad. Sci.(Earth Planet Sci.)*, 101 (1992) 35.
- 8 Shapiro M A, *Mon Weather Rev*, 103 (1975) 591.
- 9 Haney R L, *J Phys Oceanogr*, 1 (1971) 241.
- 10 Wyrtki K, *J Geophys Res*, 70 (1965) 4547.
- 11 Dorman C E & Bourke R H, *Mon Weather Rev*, 107 (1979) 896.
- 12 Holton J R, *An introduction to dynamical meteorology*, (Academic Press, London) 1992, 116.
- 13 Schwind J J Von, *Geophysical fluid dynamics for oceanographers*, (Prentice-Hall, London) 1980, pp. 134.
- 14 Pickard G L & Emery W J, *Descriptive physical oceanography*, (Pergamon Press, Oxford) 1984, 29.