A New Ocean GCM for Tropical Ocean and ENSO Studies

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ABSTRACT

A new reduced gravity, primitive equation model of the upper equatorial ocean has been developed by Gent and Cane (1989). It has been configured to simulate the annual cycle in the tropical Pacific Ocean. It is forced by the monthly winds from Rasmusson and Carpenter (1982) and a new heat flux formulation from Seager et al. (1988). The coefficients of vertical eddy viscosity and conductivity depend upon the Richardson number of the flow. With this mixing a deep warm pool forms in the Western Pacific, increasing the west-east gradient of the thermocline and equatorial undercurrent. The model has been diagnosed as to what factors maintain this deep warm pool.

1. Heat flux parameterization.

Heat Flux = Incoming Solar - Latent - (Sensible + Longwave)

* Incoming Solar Flux = $(1 - A)\,(1 - 0.62\,C + 0.0019\,\theta)\,Q_0$
A is albedo, C is % cloud cover, θ is solar altitude, Q_0 is clear sky flux

* Latent Heat Flux = $\rho_a\, C_E\, L\, |\mathbf{u}|\, (1-\delta)\, q_s(SST)$
$|\mathbf{u}|$ is wind speed with minimum of 4 m s^{-1}, $q_s(SST)$ is saturation humidity, and humidity factor δ is related to relative humidity, δ_{rh},

$$\delta\, q_s(SST) = \delta_{rh}\, q_s(T_a)$$

* Sensible + Longwave Flux = $\alpha\,(SST - T^*)$

$$[A = 0.06,\ \delta = 0.78,\ \alpha = 1.8\ \mathrm{m\ s^{-1}},\ T^* = 2.8^\circ\mathrm{C}]$$

2. Vertical mixing coefficients.

* Diffusivity: $\nu = 10^3\,(1+10R_i)^{-2} + \nu_B \qquad \mathrm{cm^{-2}\ s^{-1}}$

* Conductivity: $K = 10^3\,(1+10R_i)^{-3} + K_B \qquad 0 < R_i < 3$

$\nu_B\,(z)$ varies between 1 and 2 $cm^2\ s^{-1}$
$K_B\,(z)$ varies between 1/2 and 1 $cm^2\ s^{-1}$

In the COARE volume, R_i is nearly always > 3, so that the vertical mixing is done solely by the background values ν_B and K_B.

Sections of average temperature and zonal velocity in January along the equator down to 400 m and along 160° E down to 500 m are shown in Figures 1-4.

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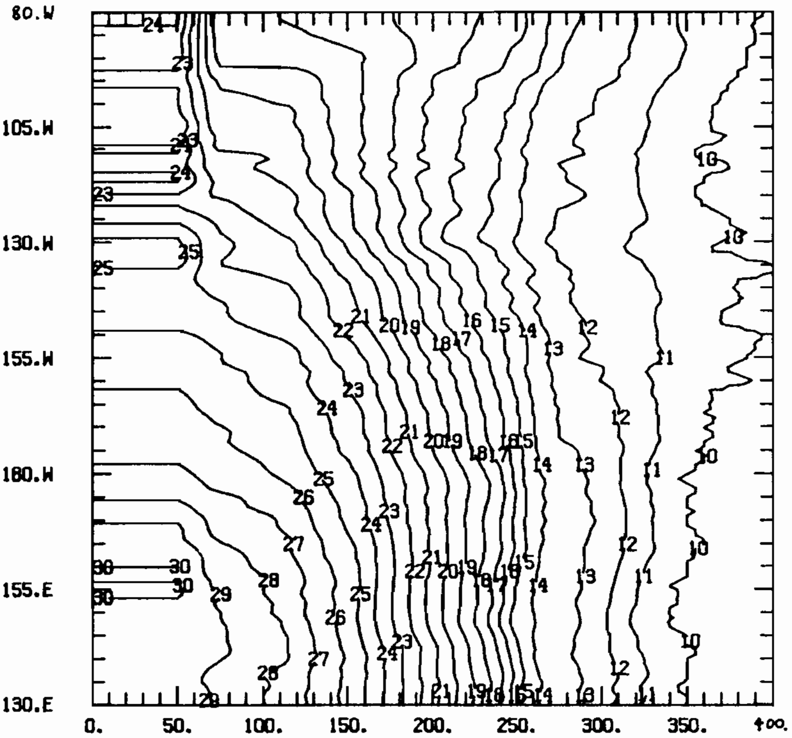

FIG.1. Average January Temperature (°C) along Equator.

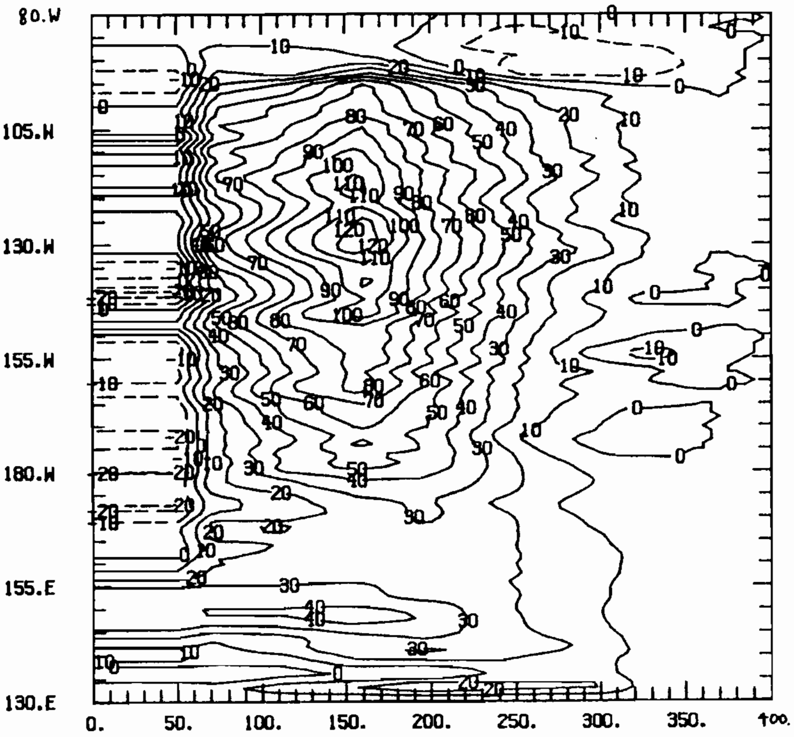

FIG.2. Average January Zonal velocity (cm.s^{-1}) along Equator.

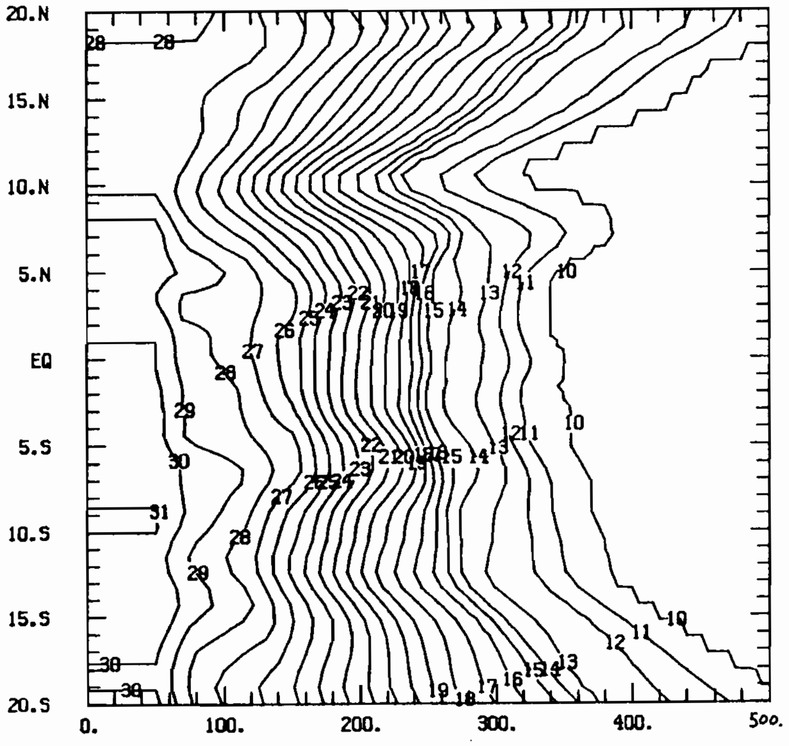

FIG.3. Average January Temperature (°C) along 160°E.

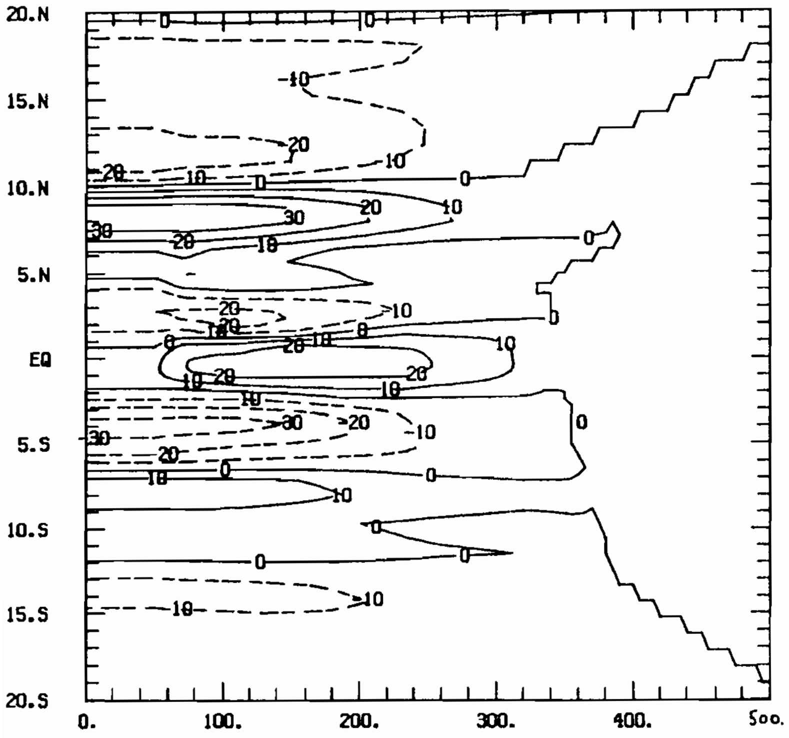

FIG.4. Average January Zonal Velocity (cm.s^{-1}) along 160°E.

3. Heat balance over the TOGA-COARE domain.

140°E-180°E; 10°S-10°N; 0-150 m (average)

Advection and temperature gradients in the domain are small, and the advection tends to be parallel to the isotherms, so that the 3-D heat advection in the domain is small. Thus, if the vertical heat diffusion is small, then the heat flux must also be small. This is confirmed in the model, where over the COARE domain Ri mixing and horizontal diffusion are negligible. Thus, over a year

$$\begin{array}{lllll} \partial/\partial t(hT) = & \text{-3-D Advection} & + \text{Heat Flux} & - \text{Vertical diffusion} & \\ 0 \quad \approx & -3.9 & + \ 13.5 & - \ 9.4 \text{ W m}^{-2} & \end{array}$$

The model SST for January and the SST such that $Q \approx O$ (Figures 5 and 6) show that, over the COARE area, SST is set by $Q(SST) \approx 0$.

$$\begin{array}{llll} \text{Heat Flux} = & \text{Incoming Solar} & - \text{Latent} & - (\text{Sensible} + \text{Longwave}) \\ 13{,}5 \quad = & 189{,}8 & - \ 117{,}6 & - \quad 58{,}7 \text{ W m}^{-2} \end{array}$$

$$\begin{array}{llllll} \nabla.(huT) & = & \partial/\partial x(huT) & + \partial/\partial y(hvT) & + \partial/\partial s(wT) & \\ 3.9 & = & -246.3 & + \ 202.1 & + \ 48.1 & \text{W m}^{-2} \end{array}$$

Thus the 3-D heat advection is a small residual of large component terms and, therefore, will be very difficult to measure. Alternatively, a small error in the very small angle between velocity and isotherms will cause a large error in the 3-D advective heat flux estimate. Quantitatively

$$|\nabla.(huT)| / \{ \Sigma[\partial/\partial x_i(hu_iT)]^2 \}^{1/2} = 0.012$$

4. What sets the SST and depth of the warm pool?

The hypothesis that $0 < Q(SST) < 20$ W m^{-2} was confirmed by setting the minimum value of $|u|$ to 3 m s^{-1} (not 4) in the latent flux. This increases the temperature, such that $Q = O$, from about 29.5 → 30°C (min = 4) to about 33 → 33.5°C (min = 3) on the equator between 130°E and 150°E. The actual model SST in this region increases from about 29.5°C (min = 4) to about 32°C (min = 3). When the minimum is set to 3 m.s^{-1}, the outgoing latent flux is reduced by 1/4 in the region, or about 30 W m^{-2}. Thus, the sensitivity of SST in this region to errors in the heat flux is

$$\mathit{Sensitivity} \equiv dT/dQ = 2.5/30 = 1/12 \ ^\circ\text{C W}^{-1} \text{ m}^{-2}$$

Thus, an error of 16 W m^{-2} in Q will lead to an error of 1°C in SST in this region of the model. With $|u|$ min = 3 m s^{-1}, the heat balance over a year is

$$0 \approx -5.5 \ (3 - D \ A) + 17.7 \ (H \ F) - 10.5 \ (V \ D) \quad \text{W m}^{-2}$$

This similar to the min = 4m s^{-1} case, but is not so close to equilibrium.

The depth of the warm pool in this model is set by K_B. In a run where K_B and ν_B were increased by factors of 2 and 10, with no R_i mixing, the depth of the warm pool (water>27°C) was reduced by about 50m. Thus the run with smaller K_B, which can sustain a sharper thermocline, has a deeper warm pool. With a larger K_B, there is more vertical diffusion of heat, so that the COARE region SST is reduced by close to 1°C to produce a larger heat flux. With increased ν_B and K_B, the heat balance over a year is

$$0 \approx 3.2 \ (3 - D \ A) + 25.0 \ (H \ F) - 21.3 \ (V \ D) \quad \text{W m}^{-2}.$$

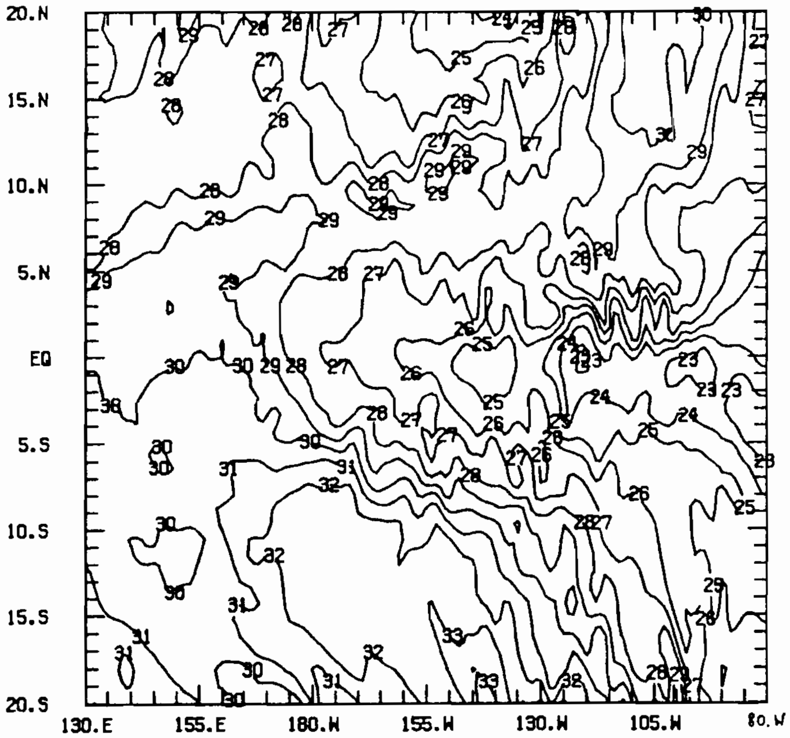

FIG.5. Average January Sea Surface Temperature (°C).

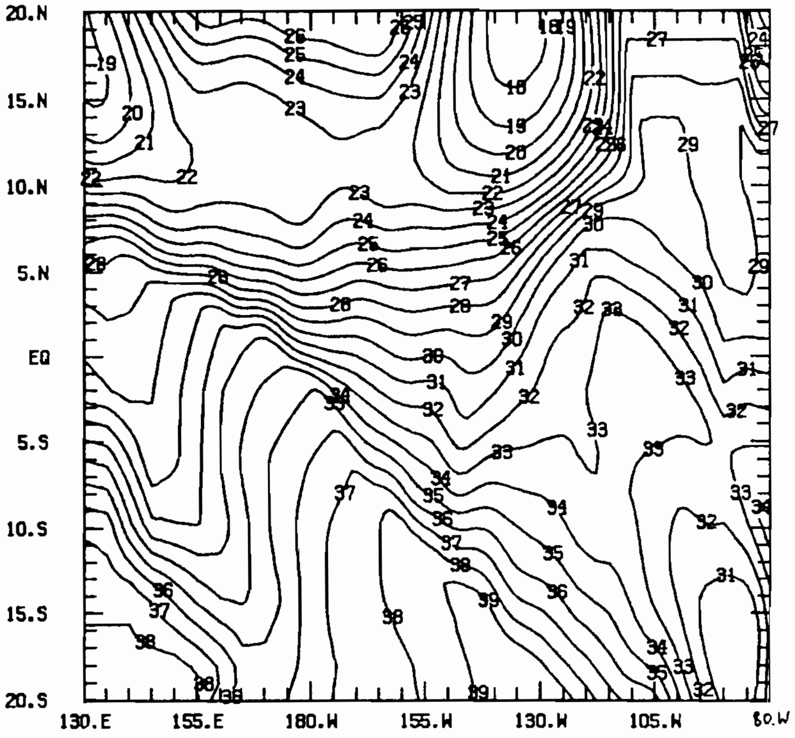

FIG.6. Average January Temperature (°C) such that Q = 0.

REFERENCES

Gent, P.R. and M.A. Cane, 1989: A reduced gravity, primitive equation model of the upper equatorial ocean. *J. Comp. Phys.*, **81**, 444-480.

Rasmusson, E.M. and T.H. Carpenter, 1982: Variations in tropical sea surface temperature and surface wind fields associated with the Southern oscillation/El Nino. *Mon. Wea. Rev.*, **110**, 354-384.

Seager, R., S.E. Zebiak and M.A. Cane, 1988: A model of the tropical Pacific sea surface temperature climatology. *J. Geophys. Res.*, **93**, 1265-1280.

WESTERN PACIFIC INTERNATIONAL MEETING AND WORKSHOP ON TOGA COARE

Nouméa, New Caledonia
May 24-30, 1989

PROCEEDINGS

edited by

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