Why are there Such Strong Steric Height Gradients off Western Australia ?

John S. GODFREY[1] and A. WEAVER[2]

(1)CSIRO Division of Oceanography, GPO Box 1538, Hobart, TAS 7001, Australia
(2)University of Washington, Seattle, Washington 98195 - U.S.A.

ABSTRACT

The Indonesian channel permits equatorial Pacific winds to maintain a bank of very warm (28°C) water along Australian's Northwest Shelf. This leads to net ocean cooling south of 20°S off Western Australia (compared to 40° or 50°S in the eastern Atlantic of Pacific). It is suggested that this convective cooling towards the latitude-dependent Haney equilibrium temperature in turn generates meridional pressure gradients and the onshore geostrophic flows that drive the Leeuwin Current; in this sense the equatorial Pacific winds drive the Leeuwin Current. Preliminary results from a numerical model support this hypothesis.

1. Annual mean flow patterns in the Leeuwin Current.

Steric height maps of the Western Australian region show a strong onshore geostrophic flow at the surface, that turns polewards near the coast. This polewards flow - the Leeuwin Current - moves directly into the prevailing equatorward wind, from 22°S to the southwest tip of Australia at 36°S (fig. 1a; from Godfrey and Ridgway, 1985). Below about 250m there is deep, slow equatorward flow along the coast feeding an offshore geostrophic flow - the Leeuwin Undercurrent. (Fig. 1b). Neither feature has any analogue in the Pacific or Atlantic.

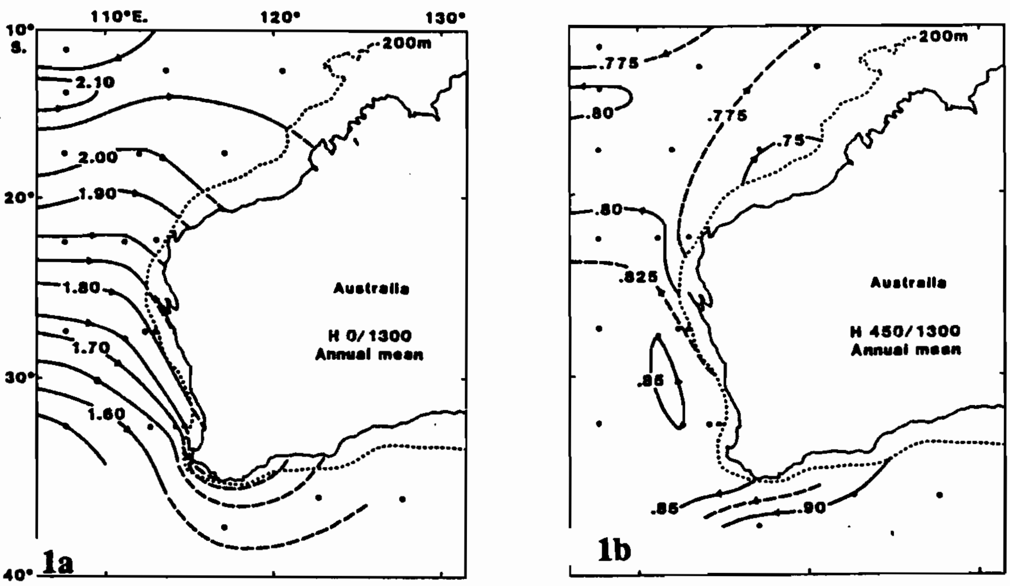


FIG.1. Annual mean steric sea level at (a) the surface and (b) 450 db, relative to 1300db, off Western Australia.

2. Longshore steric height gradients in the Leeuwin Current.

The meridional gradients of steric height found offshore from Western Australia are much greater than those off other eastern boundaries and extend much deeper; and they reverse with depth. This is seen in Figure 2, which compares the annual mean steric height difference relative to 1500 db between 17.5°S and 32.5°S off Western Australia (open squares) with that off South America (diamonds). The data are 5°x5° averages from Levitus (1982). Recent modelling studies (McCreary et al., 1986; Weaver and Meddleton, 1989) have shown, that these large steric height gradients off Western Australia are responsible for driving the Leeuwin Current polewards, into the prevailing wind - and for the observed equatorwards undercurrent. However, why do these large, reversing gradients occur off Western Australia and not off any other subtropical eastern boundaries such as South America ?

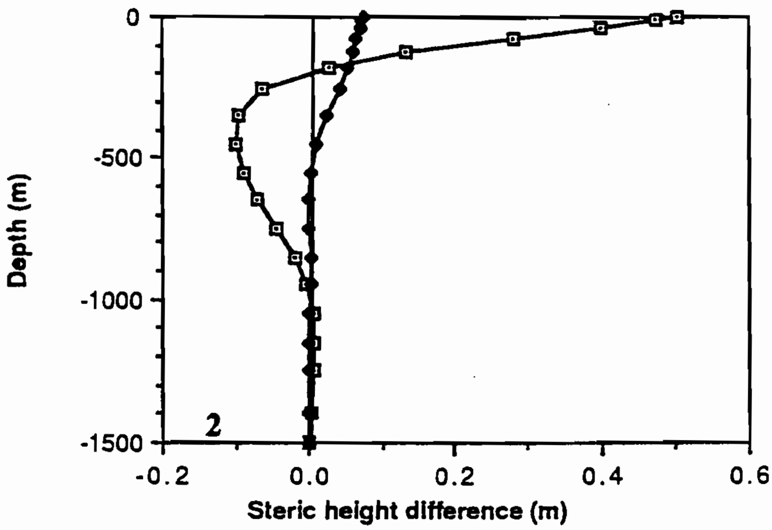


FIG.2. Differences in annual mean steric height relative to 1300 db, between 17.5°S and 32.5°S in 5°x5° squares along the coasts of Western Australian coast (open squares) and South America (diamonds).

3. Kelvin and Rossby wave propagation from the Pacific.

The large steric height differences of Fig.2 mostly reflect the fact that near-surface waters are much warmer off Northwestern Australia than off other eastern boundaries. We therefore begin by examining the reason for these warm northwest Australian temperatures. Below 100 m, the vertical profile of Specific Volume Anomaly (SVA) off northwestern Australia at 17.5°S (open diamonds in Fig.3a) is essentially identical to that in the western equatorial Pacific, just west of Irian Jaya (open squares). Both profiles are very different to those off other eastern boundaries such as South America (closed diamonds, squares with dots). It is suggested that internal Kelvin waves propagate with little dissipation or forcing from the western equatorial Pacific through the Indonesian archipelago along the northwestern Australasian shef edge, and that internal Rossby waves then propagate westwards, bringing SVA profiles off northwestern Australia close to that off Irian Jaya. As a result, annual mean water temperatures in the top 200 m are much warmer at 17.5°S off Western Australia than at the same latitude off South America (Fig. 3b).

4. Models forced by heat fluxes.

If the Kelvin and Rossby waves continued their poleward and westward propagation

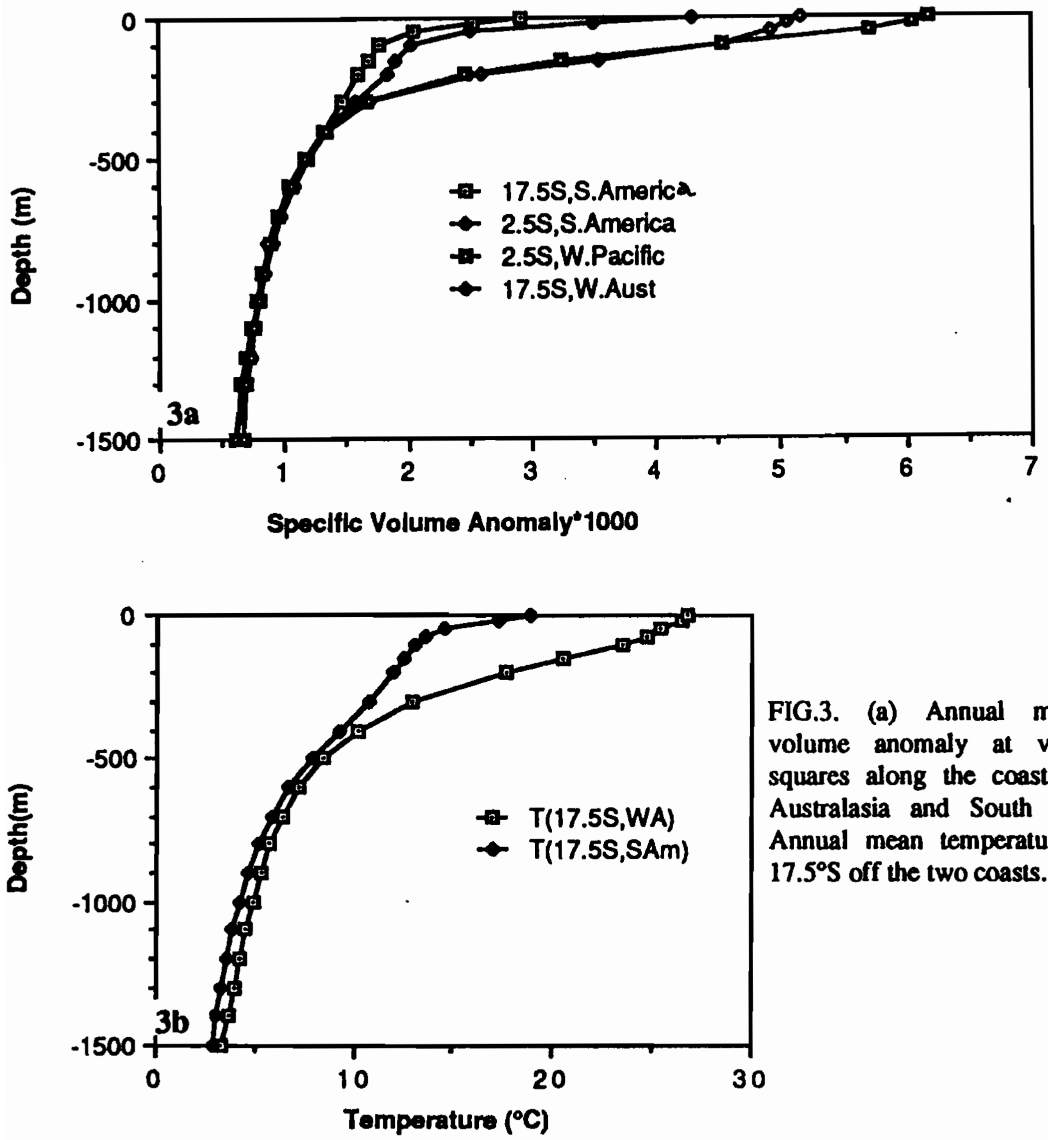


FIG.3. (a) Annual mean specific volume anomaly at various 5°x5° squares along the coasts of Western Australasia and South America. (b) Annual mean temperature profiles at 17.5°S off the two coasts.

without dissipation or forcing from 17.5°S to 32.5°S, the annual mean SVA profile off Western Australia at 32.5°S, would be like the SVA profiles of the equatorial west Pacific and at 17.5°S and 32.5°S seen in Fig. 3a; thus the large steric height differences between 17.5°S and 32.5°S seen in Fig.2 would not occur. Very strong forcing must occur off Western Australia between 17.5°S to 32.5°S to create the observed longshore gradients of Fig.2; much stronger than can be provided by the wind stress. The forcing between these latitudes is *not* primarily due to the wind - the Leeuwin Current flows into the wind.

McCreary, Shetye and Kundu (1986) introduced vertical heat diffusion into a linear model of the Leeuwin Current, and imposed a boundary condition that surface temperatures have the observed north-south gradient. Their vertical heat flux was unrealistically parameterized by $(\kappa T)_z$ rather than by κT_z, where K is the eddy diffusivity and T is the temperature at depth z; and away from the eastern boundary this heat flux was constant vertically from the surface through the ocean floor. Nevertheless they obtained a realistic-looking solution, both offshore and in the Leeuwin Current, as can be seen by comparing their steric height maps (Fig. 4a-b) with the observations of Fig.1. In particular they obtained both a poleward surface current and an equatorward subsurface undercurrent,

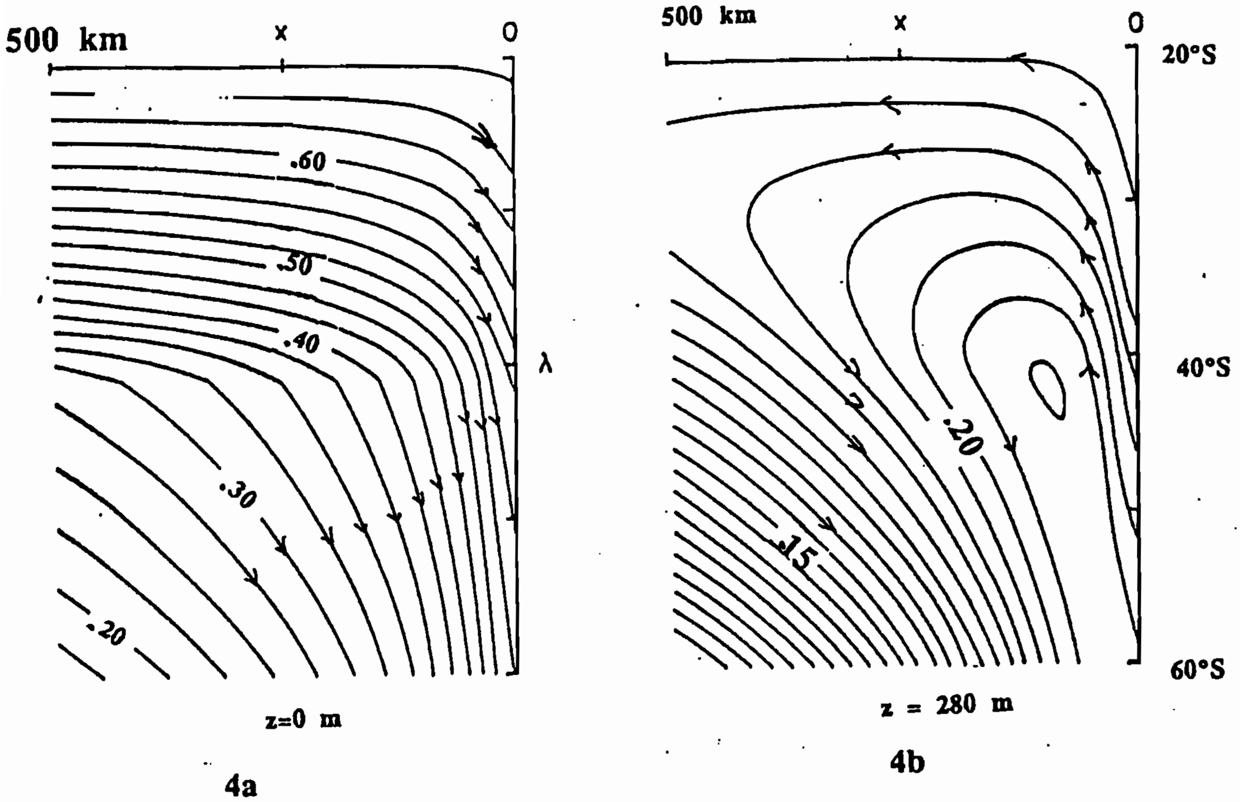


FIG.4. Predicted pressure pattern in the model of McCreary et al(1986) at the surface and 280m, for comparison with Fig.1.

at about the observed depths. This success suggests that the anomalous features of the Leeuwin Current relate to forcing by heat fluxes rather than by winds.

However, we can now restate the earlier question : Why should Western Australia be subject to heat flux effects so strong that they overwhelm the usual wind forcing, between 17.5°S and 32.5°S ? And why does this not occur off any other subtropical eastern boundary ?

5. Haney cooling.

Haney (1971) showed that annual mean heat fluxes into the ocean could be fairly well parameterized as $\lambda(T_e(y)-T)$, where T is annual mean sea surface temperature, $T_e(y)$ is and "equilibrium temperature" that is a function only of latitude and λ is a constant. Fig. 5a shows temperatures at various depths just offshore from the west Australasian continental shelf, compared to the Haney equilibrium temperature. Fig. 5b shows a similar comparison of South American temperatures with the Haney equilibrium temperature.

Annual mean temperatures in the top 50 m off Western Australia lie slightly above the Haney equilibrium temperature from about 15°S southwards: thus mean surface cooling and convective overturn can be expected. The temperatures of Fig. 5a appear to be constrained to follow the Haney equilibrium temperature, at least near the surface and possibly to as deep as 200m. By contrast, surface and subsurface temperatures are all well below the Haney equilibrium temperature off South America, to as far south as 40°S; and there is no apparent relation between the Haney temperature, and ocean temperatures there. The reason may be that when SST lies below the Haney temperature, the net heat flux is into the ocean, and the heat is trapped near the surface where it can be carried offshore by the Ekman flux.

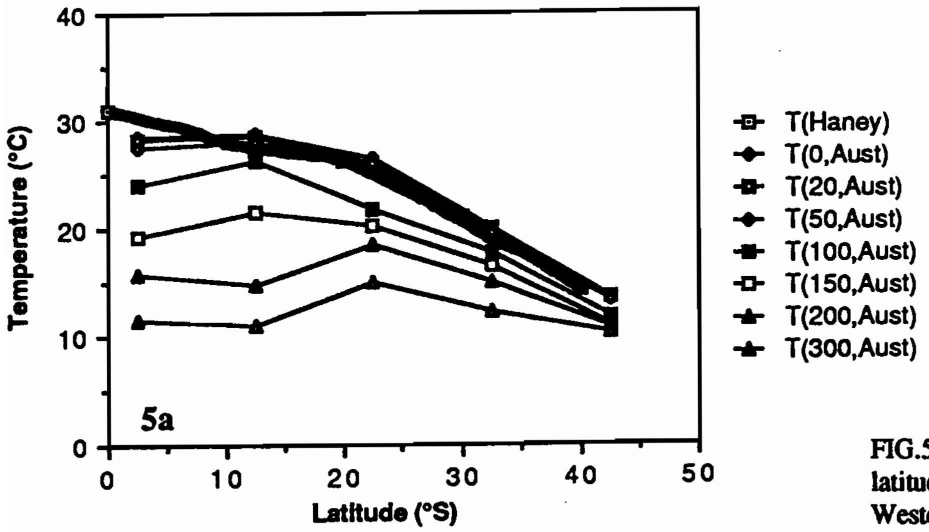
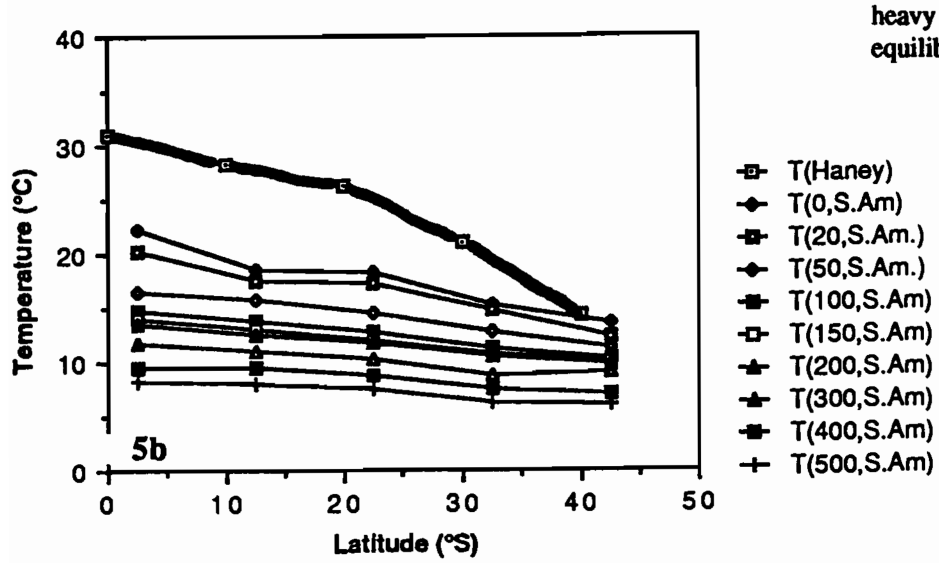


FIG.5. Temperature versus latitude at various depths, off Western Australasia (top) and South America (bottom). The heavy line shows Haney equilibrium temperature.



By contrast, when SST lies above the Haney temperature, convective overturn takes place: water will cool towards $T_e(y)$, no just at the surface but to substantial depths beneath. This in turn creates large meridional steric height gradients.

Looking at Fig.5 in a different way, the large meridional temperature gradients in the top 200 m of Western Australia (Fig. 5a) are also the reason for the strong onshore geostrophic flow there, and hence for the Leeuwin Current.

6. A Numerical experiment.

It is therefore thought that the near-equatorial temperatures off Western Australia are high enough so that poleward propagation of higher-mode Kelvin waves must induce convective overturn everywhere south of 20°S; by contrast, convective overturn will not occur till about 40°S for a South American equatorial SVA profile.

To test the idea that this convective overturn may help create the meridional SVA gradients that drive the Leuwin Current, some numerical experiments are being run with a Bryan and Cox model (which contains a good representation of convective overturn). Results are preliminary : one run only will be shown here. An idealized "Indian Ocean" basin extends from the equator to 40°S, and is 30° wide: it is joined at its northeast corner to a "Pacific Ocean" which in our model serves simply as a reservoir of warm water for the Indian Ocean.

At the initial instant the SVA profile throughout the model domain is given by the western equatorial Pacific profile of Fig. 3a (open squares), with the corresponding temperature and salinity profiles: thus surface temperatures are 29°C everywhere. Cooling to the Haney equilibrium temperature is then started in the "Indian Ocean". A strong artificial forcing term brings temperature and salinity profiles in the "Pacific" back to the initial values with a 2.5-day time scale. A northward wind stress is applied between 22.5° and 32.5°S with a maximum strenght of 0.05 $N.m^{-2}$ (much like the observed winds off Western Australia).

7. Preliminary Results.

After 700 days of surface cooling, the Kelvin and Rossby wave adjustment is probably complete for a substantial distance from the eastern boundary; and convective cooling is nearly complete. Temperature at 20m has fallen below 16°C at 40°S (Fig. 6a). Temperature also shows a strong southward decrease at 60 and 110 m (not shown). Poleward advective effects can be seen along the eastern boundary, as observed off Western Australia, despite the imposed equatorward winds. A reversed meridional temperature gradient occurs at 295m throughout the ocean, but particularly along the eastern boundary (Fig. 6b), presumably as a results of downwelling where the induced zonal flows encounter the boundary. The surface steric height difference between 17.5°S and 32.5°S is about 25 cm - less than that observed (Fig.2), but of the right order of magnitude.

The corresponding flow patterns are seen in Figs. 6c-d. There is a vigorous surface flow into the "Indian" from the "Pacific" Ocean (Fig. 6c), connecting into a western boundary current that supplies the eastward geostrophic flow in the interior. Notice in Fig. 6c that the Ekman transport, which is greatest near 25°S, reduces the geostrophic flow to zero at this latitude; but at other latitudes the net flow is eastward - i.e. the convectively-induced flow overwhelms the Ekman drift. Flow is also onshore at 60 and 110 m (not shown), but at 295m (Fig.6d), the interior geostrophic flows are reversed. Note that these depths are well below the direct influence of surface convective overturn. Along the northern boundary, at 295m, the flow is *into* the Pacific, i.e. opposite to the surface flow: the net mass flux from the Pacific to the Indian Ocean is exactly zero in our model, but there is evidently a large net heat flux into the indian Ocean.

So far we do have a poleward Leeuwin Current, but it is much weaker than observed: Fig. 6c and d suggest that the geostrophic inflow sinks directly into the geostrophic outflow. Further numerical experimentation is planned to see if the reason for this can be found.

First results from coarser-grid runs with similar equatorward winds, but an equatorial SVA profile like that off South America (Fig.3) suggest that no significant convection-driven flows develop in this case: the familiar eastern-boundary upwelling occurs instead.

8. Connection with Pacific winds.

The model seems to demonstrate that continuity with the warm west Pacific causes convective cooling to the Haney (latitude-dependent) temperature, and hence leads to onshore geostrophic flow towards Western Australia. This flow in turn drives the path shown in Fig.7a, from the Hellerman and Rosenstein (1983) wind stresses; these are shown in Fig.7b (full line). Depth-integrated steric height is some 60-80 m^2 higher off Western Australia than in the east Pacific. Observed depth-integrated steric heiths relative to 1000

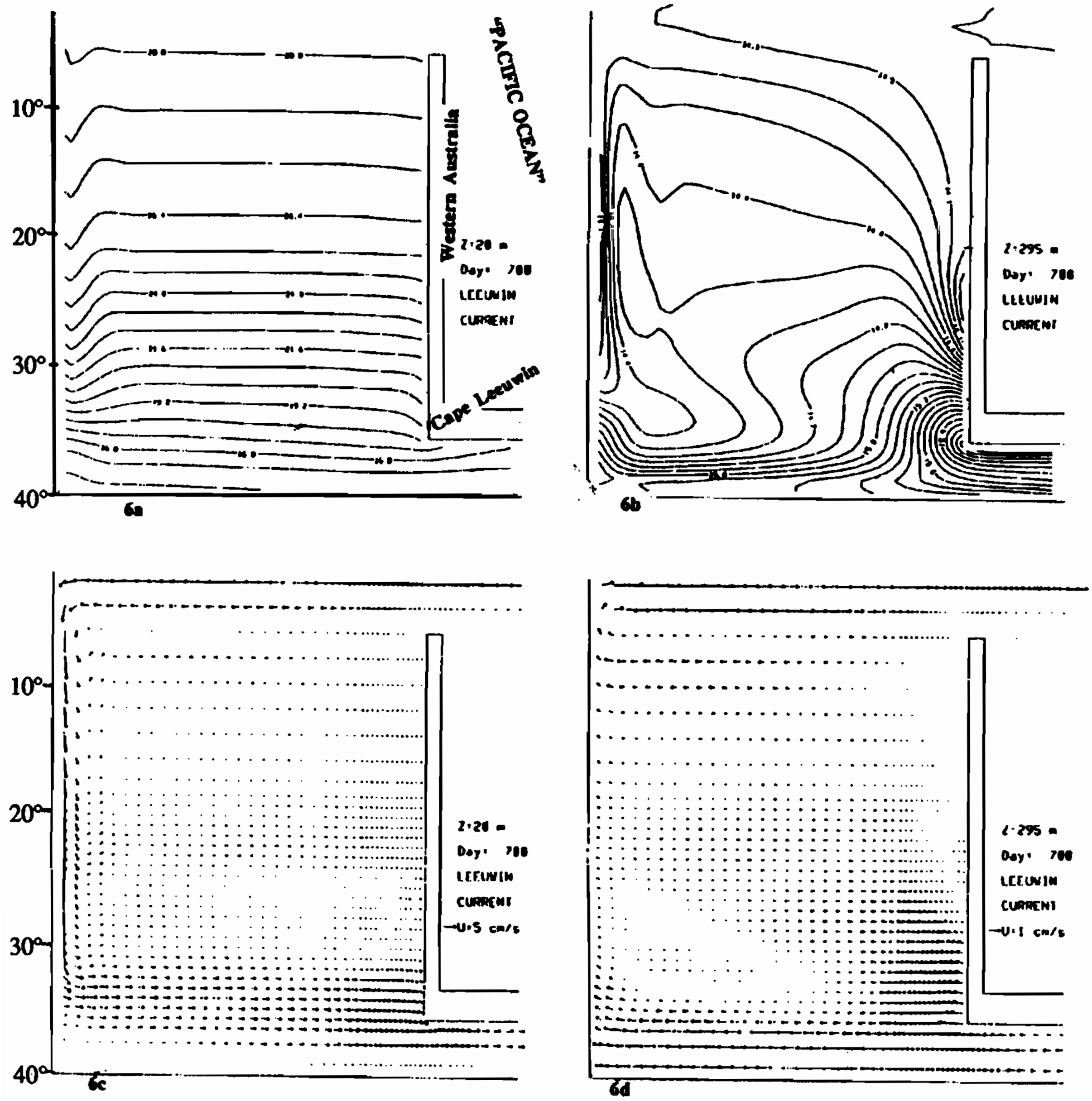
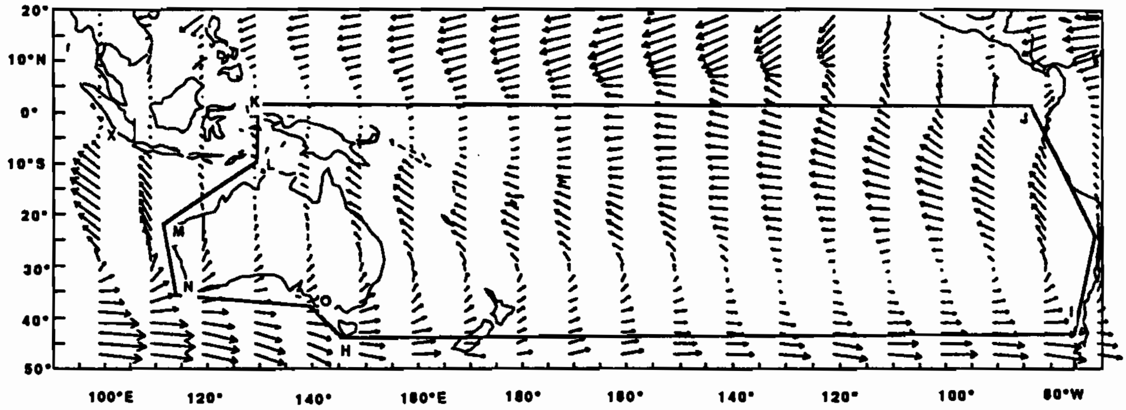


FIG.6. Temperature and velocity at 20m and 295m, in an idealized model of the Leeuwin Current, Western Australia.

db follow the Sverdrup prediction reasonably well, (squares in Fig. 8b), both along the equatorial Pacific and along the South American and Western Australian coasts (though with considerable noise along the latter two segments). The 60 m^2 difference in depth-integrated steric height (or double-depth-integrated SVA) across the Pacific is reflected in the difference between the east Pacific and the west Pacific-east Indian SVA profiles seen in Fig. 3.

In conclusion, the equatorial Pacific winds may be said to drive the Leeuwin Current, by maintaing the high near-equatorial temperatures that lead (throught convection) to the zonal geostrophic flows south of 20°S in the Indian Ocean.



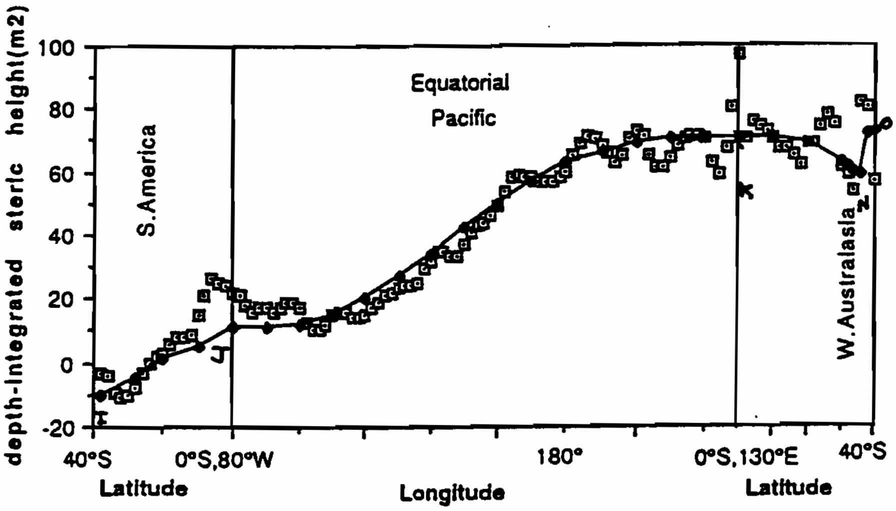


FIG.7. (a) Integration path for calculating depth-integrated steric height from the wind field. (b) The full line shows calculated depth -integrated steric heights along the legs IJKLMNO of Fig.7a; the squares are observed depth-integrated steric heights, relative to 1000 db.

REFERENCES

Godfrey, J.S. and K.R.R. Ridgway, 1985: The large-scale environment of the poleward-flowing Leeuwin Current, Western Australia: longshore steric height gradients, wind stresses and geostrophic flow. *J. Phys. Oceanogr.*, **15**, 481-495.

Haney, R.L., 1971: Surface thermal boundary condition for ocean circulation models. *J. Phys. Oceanogr.*, 1, 241-248.

Hellerman S. and M. Rosenstein, 1983: Normal monthly wind stress over the world ocean with error estimates. *J. Phys. Oceanogr.*, 13, 1093-1104.

Levitus, S., 1982: Climatological Atlas of the World Ocean. *NOAA Professional Paper*, 13.

McCreary, J.P., S.R. Shetye and P.K. Kundu, 1986: Thermohaline forcing of eastern boundary currents: with application to the circulation off the west coast of Australia. *J. Mar. Res.*, **44**, 71-92.

Weaver, A.J. and J.H. Middleton, 1989: Poleward boundary current off Western Australia. *J. Phys. Oceanogr.*, **19**, (in press).

WESTERN PACIFIC INTERNATIONAL MEETING AND WORKSHOP ON TOGA COARE

Nouméa, New Caledonia
May 24-30, 1989

PROCEEDINGS

edited by

Joël Picaut *
Roger Lukas **
Thierry Delcroix *

* ORSTOM, Nouméa, New Caledonia
** JIMAR, University of Hawaii, U.S.A.

INSTITUT FRANÇAIS DE RECHERCHE SCIENTIFIQUE
POUR LE DÉVELOPPEMENT EN COOPÉRATION

ORSTOM

Centre de Nouméa

TABLE OF CONTENTS

MEETING COLLECTED PAPERS

WATER MASSES, SEA SURFACE TOPOGRAPHY, AND CIRCULATION

EL NINO/SOUTHERN OSCILLATION 1986-87

THEORETICAL AND MODELING STUDIES OF ENSO AND RELATED PROCESSES

MOMENTUM, HEAT, AND MOISTURE FLUXES BETWEEN ATMOSPHERE AND OCEAN

EMPIRICAL STUDIES OF ENSO AND SHORT-TERM CLIMATE VARIABILITY