

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

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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.

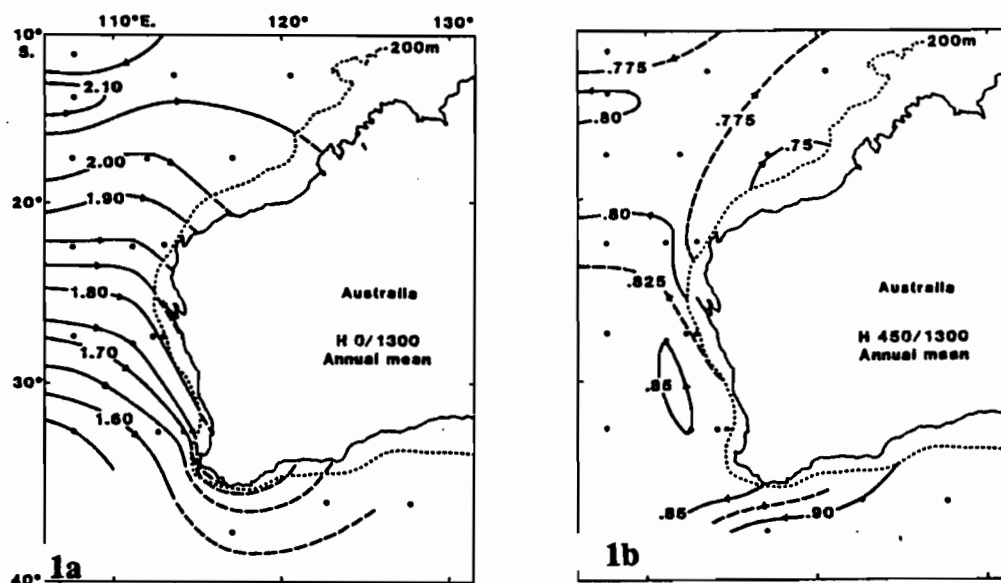


FIG.1. Annual mean steric sea level at (a) the surface and (b) 450 db, relative to 1300db, off Western Australia.

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?

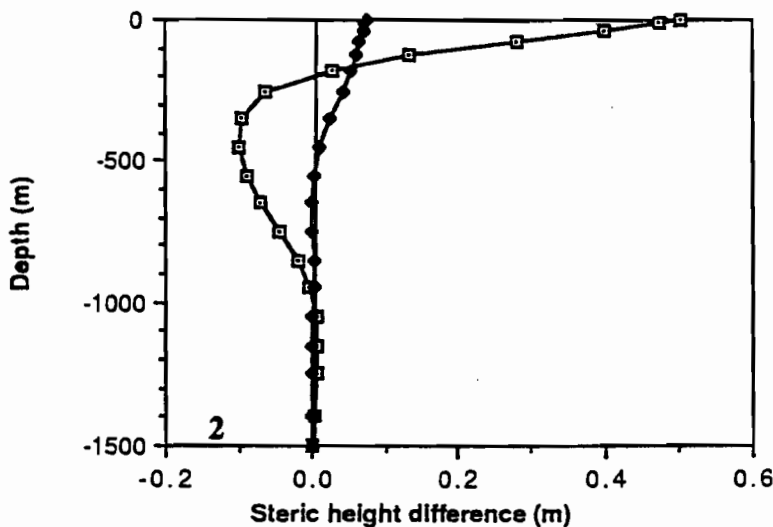


FIG.2. Differences in annual mean steric height relative to 1300 db, between 17.5°S and 32.5°S in 5°x5° squares along the coasts of Western Australian coast (open squares) and South America (diamonds).

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 shelf 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

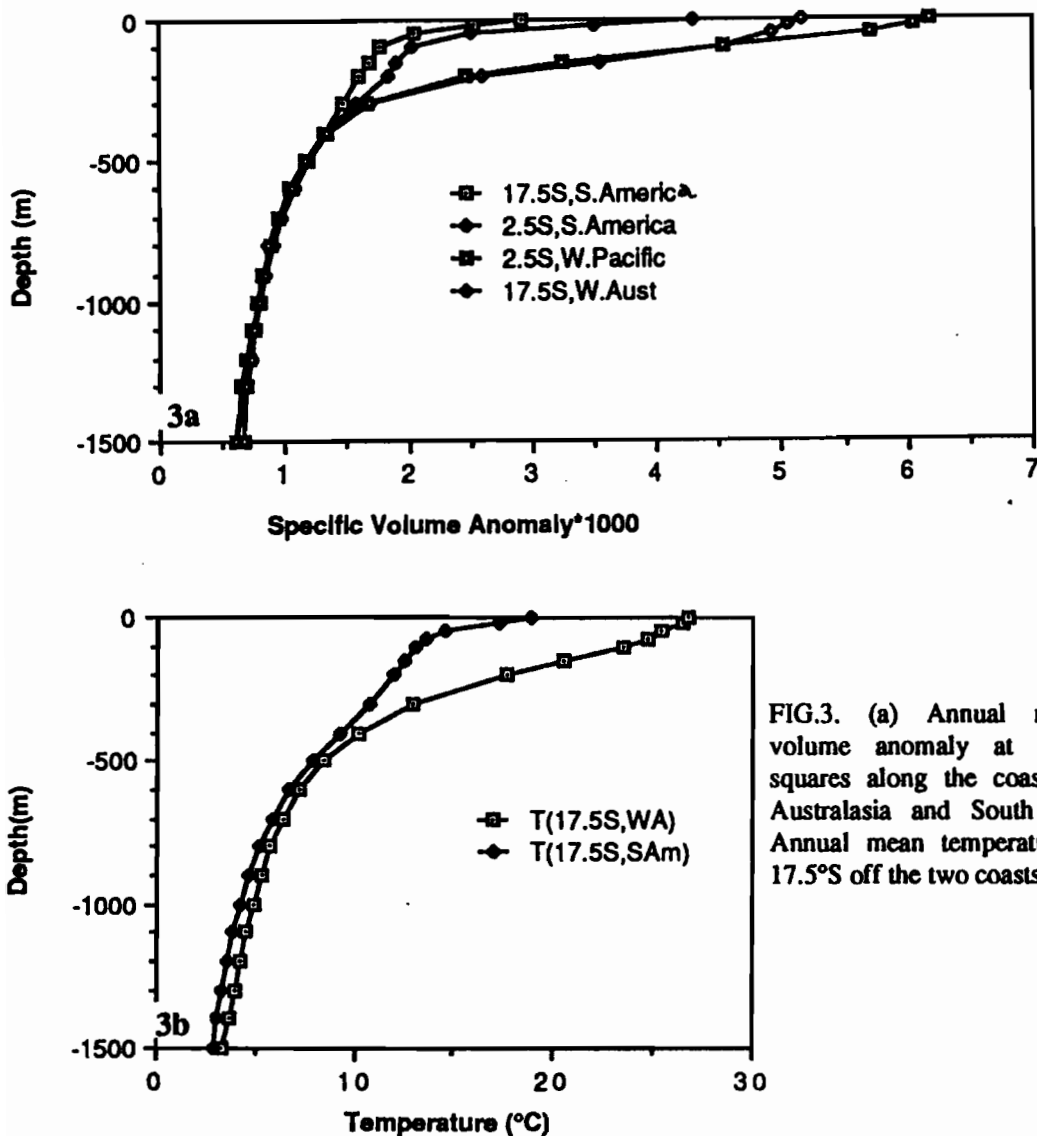


FIG.3. (a) Annual mean specific volume anomaly at various $5^{\circ} \times 5^{\circ}$ squares along the coasts of Western Australasia and South America. (b) Annual mean temperature profiles at 17.5°S off the two coasts.

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,

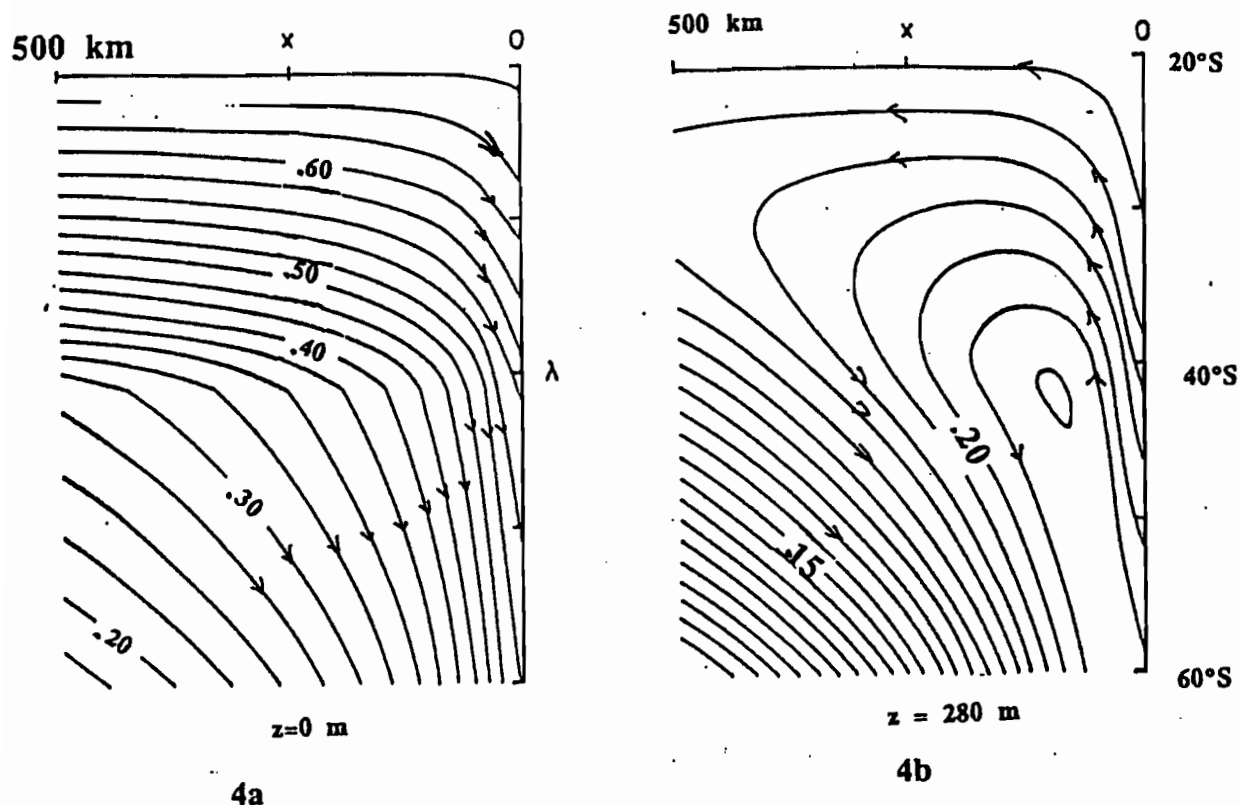


FIG.4. Predicted pressure pattern in the model of McCreary et al(1986) at the surface and 280m, for comparison with Fig.1.

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.

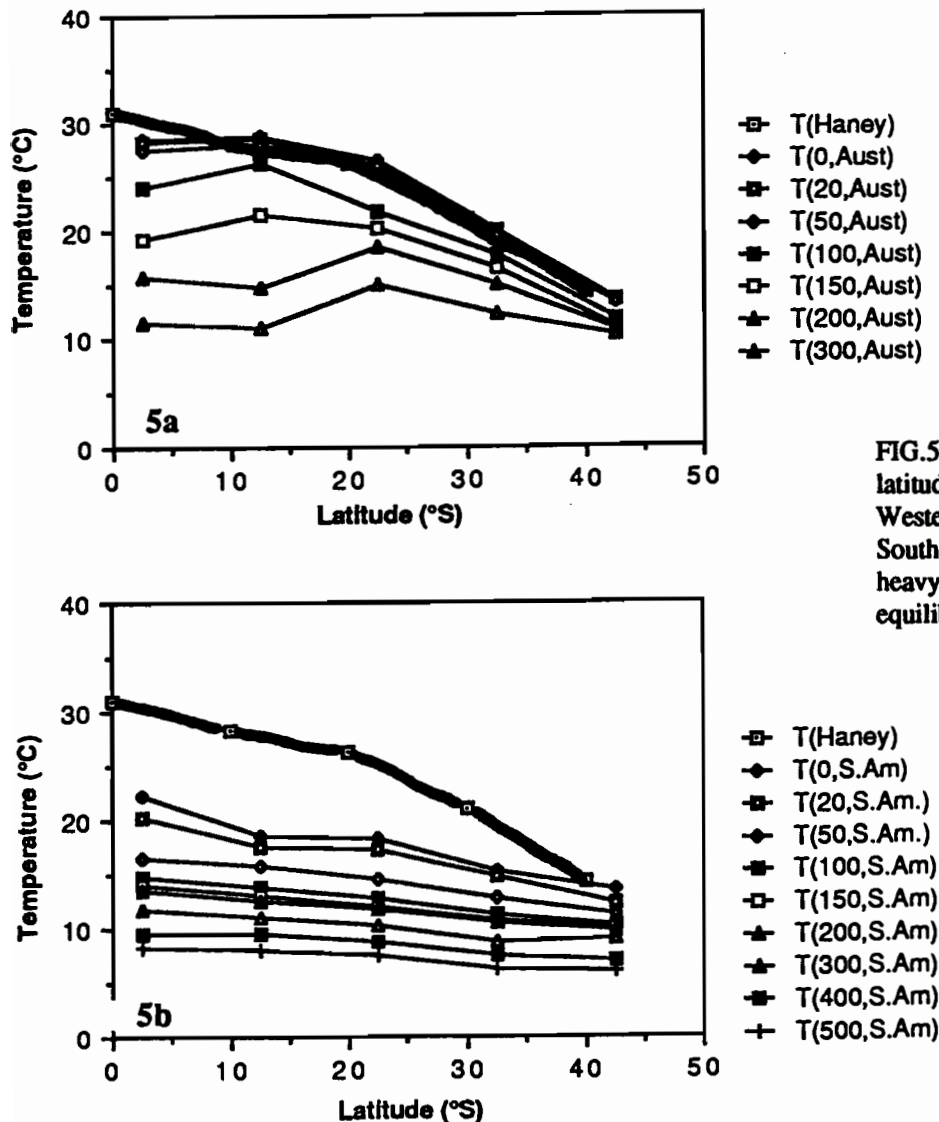


FIG.5. Temperature versus latitude at various depths, off Western Australasia (top) and South America (bottom). The heavy line shows Haney equilibrium temperature.

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 Leeuwin 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 strength 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 result 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 m² higher off Western Australia than in the east Pacific. Observed depth-integrated steric heights relative to 1000

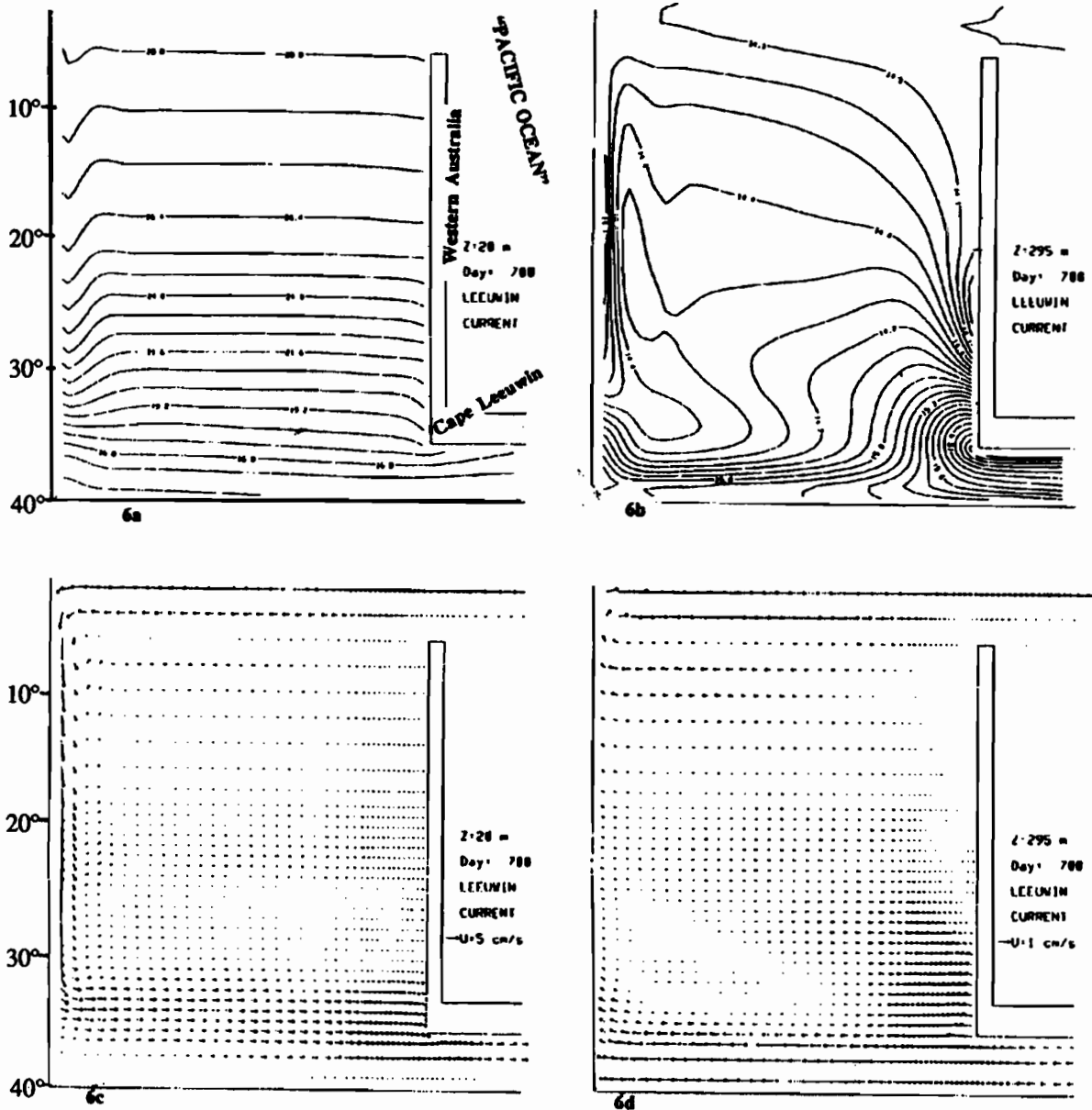


FIG.6. Temperature and velocity at 20m and 295m, in an idealized model of the Leeuwin Current, Western Australia.

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 maintaining the high near-equatorial temperatures that lead (through convection) to the zonal geostrophic flows south of 20°S in the Indian Ocean.

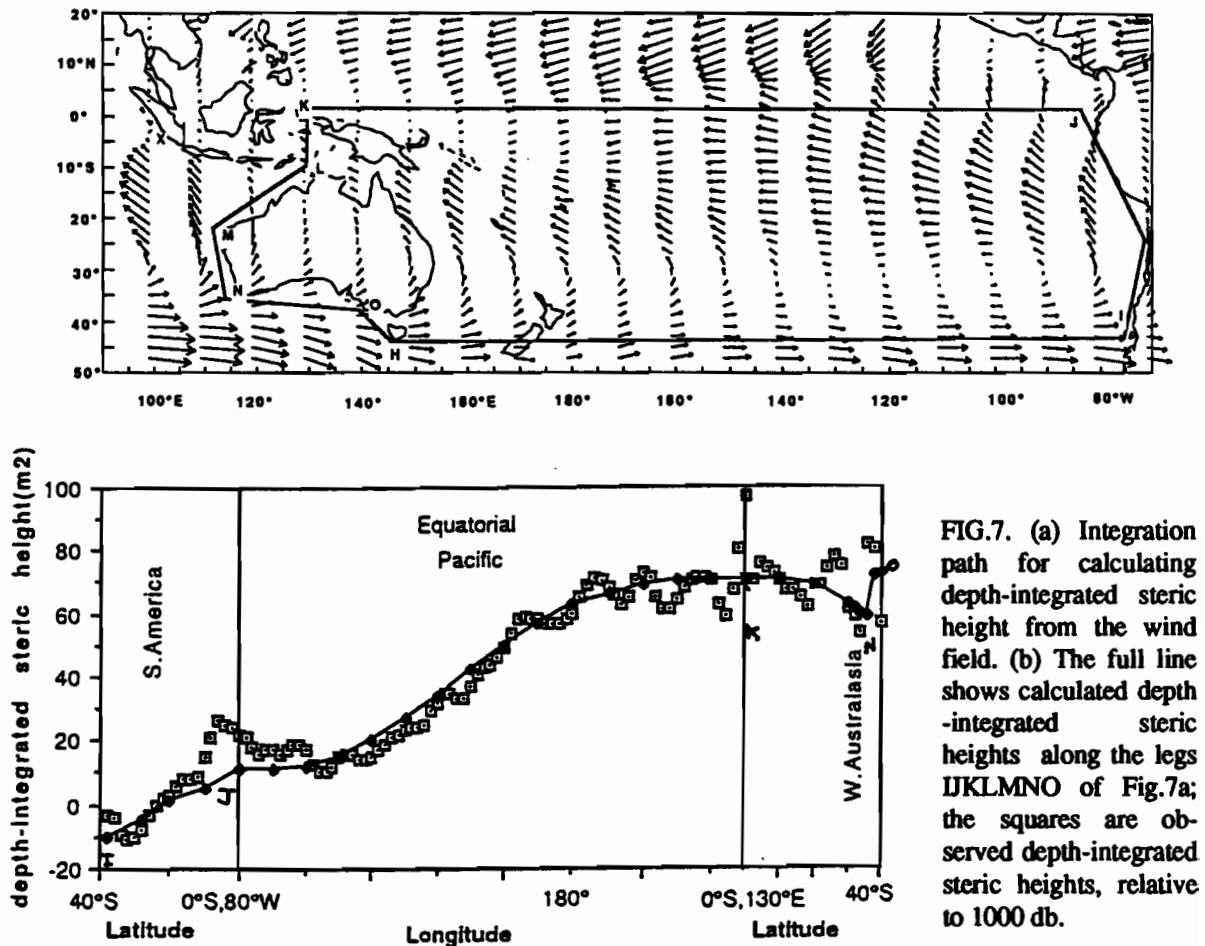


FIG.7. (a) Integration path for calculating depth-integrated steric height from the wind field. (b) The full line shows calculated depth-integrated steric heights along the legs JKLMNO of Fig.7a; the squares are observed depth-integrated steric heights, relative to 1000 db.

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**WESTERN PACIFIC INTERNATIONAL MEETING
AND WORKSHOP ON TOGA COARE**

Nouméa, New Caledonia

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PROCEEDINGS

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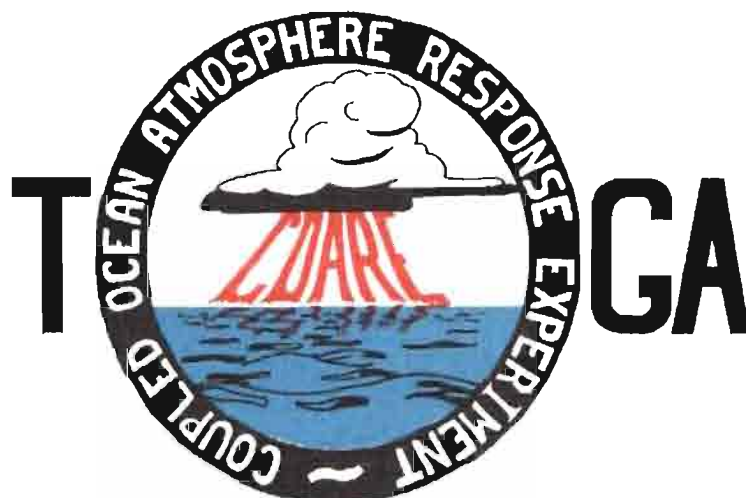


TABLE OF CONTENTS

ABSTRACT	i
RESUME	iii
ACKNOWLEDGMENTS	vi
INTRODUCTION	
1. Motivation	1
2. Structure	2
LIST OF PARTICIPANTS	5
AGENDA	7
WORKSHOP REPORT	
1. Introduction	19
2. Working group discussions, recommendations, and plans	20
a. Air-Sea Fluxes and Boundary Layer Processes	20
b. Regional Scale Atmospheric Circulation and Waves	24
c. Regional Scale Oceanic Circulation and Waves	30
3. Related programs	35
a. NASA Ocean Processes and Satellite Missions	35
b. Tropical Rainfall Measuring Mission	37
c. Typhoon Motion Program	39
d. World Ocean Circulation Experiment	39
4. Presentations on related technology	40
5. National reports	40
6. Meeting of the International Ad Hoc Committee on TOGA COARE	40
APPENDIX: WORKSHOP RELATED PAPERS	
Robert A. Weller and David S. Hosom: Improved Meteorological Measurements from Buoys and Ships for the World Ocean Circulation Experiment	45
Peter H. Hildebrand: Flux Measurement using Aircraft and Radars	57
Walter F. Dabberdt, Hale Cole, K. Gage, W. Ecklund and W.L. Smith: Determination of Boundary-Layer Fluxes with an Integrated Sounding System	81

MEETING COLLECTED PAPERS

WATER MASSES, SEA SURFACE TOPOGRAPHY, AND CIRCULATION

Klaus Wyrtki: Some Thoughts about the West Pacific Warm Pool	99
Jean René Donguy, Gary Meyers, and Eric Lindstrom: Comparison of the Results of two West Pacific Oceanographic Expeditions FOC (1971) and WEPOCS (1985-86)	111
Dunxin Hu, and Maochang Cui: The Western Boundary Current in the Far Western Pacific Ocean	123
Peter Hacker, Eric Firing, Roger Lukas, Philipp L. Richardson, and Curtis A. Collins: Observations of the Low-latitude Western Boundary Circulation in the Pacific during WEPOCS III	135
Stephen P. Murray, John Kindle, Dharma Arief, and Harley Hurlburt: Comparison of Observations and Numerical Model Results in the Indonesian Throughflow Region	145
Christian Henin: Thermohaline Structure Variability along 165°E in the Western Tropical Pacific Ocean (January 1984 - January 1989)	155
David J. Webb, and Brian A. King: Preliminary Results from Charles Darwin Cruise 34A in the Western Equatorial Pacific	165
Warren B. White, Nicholas Graham, and Chang-Kou Tai: Reflection of Annual Rossby Waves at The Maritime Western Boundary of the Tropical Pacific	173
William S. Kessler: Observations of Long Rossby Waves in the Northern Tropical Pacific	185
Eric Firing, and Jiang Songnian: Variable Currents in the Western Pacific Measured During the US/PRC Bilateral Air-Sea Interaction Program and WEPOCS	205
John S. Godfrey, and A. Weaver: Why are there Such Strong Steric Height Gradients off Western Australia ?	215
John M. Toole, R.C. Millard, Z. Wang, and S. Pu: Observations of the Pacific North Equatorial Current Bifurcation at the Philippine Coast	223

EL NINO/SOUTHERN OSCILLATION 1986-87

Gary Meyers, Rick Bailey, Eric Lindstrom, and Helen Phillips: Air/Sea Interaction in the Western Tropical Pacific Ocean during 1982/83 and 1986/87	229
Laury Miller, and Robert Cheney: GEOSAT Observations of Sea Level in the Tropical Pacific and Indian Oceans during the 1986-87 El Nino Event	247
Thierry Delcroix, Gérard Eldin, and Joël Picaut: GEOSAT Sea Level Anomalies in the Western Equatorial Pacific during the 1986-87 El Nino, Elucidated as Equatorial Kelvin and Rossby Waves	259
Gérard Eldin, and Thierry Delcroix: Vertical Thermal Structure Variability along 165°E during the 1986-87 ENSO Event	269
Michael J. McPhaden: On the Relationship between Winds and Upper Ocean Temperature Variability in the Western Equatorial Pacific	283

John S. Godfrey, K. Ridgway, Gary Meyers, and Rick Bailey: Sea Level and Thermal Response to the 1986-87 ENSO Event in the Far Western Pacific	291
Joël Picaut, Bruno Camusat, Thierry Delcroix, Michael J. McPhaden, and Antonio J. Busalacchi: Surface Equatorial Flow Anomalies in the Pacific Ocean during the 1986-87 ENSO using GEOSAT Altimeter Data	301

THEORETICAL AND MODELING STUDIES OF ENSO AND RELATED PROCESSES

Julian P. McCreary, Jr.: An Overview of Coupled Ocean-Atmosphere Models of El Nino and the Southern Oscillation	313
Kensuke Takeuchi: On Warm Rossby Waves and their Relations to ENSO Events	329
Yves du Penhoat, and Mark A. Cane: Effect of Low Latitude Western Boundary Gaps on the Reflection of Equatorial Motions	335
Harley Hurlburt, John Kindle, E. Joseph Metzger, and Alan Wallcraft: Results from a Global Ocean Model in the Western Tropical Pacific	343
John C. Kindle, Harley E. Hurlburt, and E. Joseph Metzger: On the Seasonal and Interannual Variability of the Pacific to Indian Ocean Throughflow	355
Antonio J. Busalacchi, Michael J. McPhaden, Joël Picaut, and Scott Springer: Uncertainties in Tropical Pacific Ocean Simulations: The Seasonal and Interannual Sea Level Response to Three Analyses of the Surface Wind Field	367
Stephen E. Zebiak: Intraseasonal Variability - A Critical Component of ENSO ?	379
Akimasa Sumi: Behavior of Convective Activity over the "Jovian-type" Aqua-Planet Experiments	389
Ka-Ming Lau: Dynamics of Multi-Scale Interactions Relevant to ENSO	397
Pecheng C. Chu and Roland W. Garwood, Jr.: Hydrological Effects on the Air-Ocean Coupled System	407
Sam F. Iacobellis, and Richard C.J. Somerville: A one Dimensional Coupled Air-Sea Model for Diagnostic Studies during TOGA-COARE	419
Allan J. Clarke: On the Reflection and Transmission of Low Frequency Energy at the Irregular Western Pacific Ocean Boundary - a Preliminary Report	423
Roland W. Garwood, Jr., Pecheng C. Chu, Peter Muller, and Niklas Schneider: Equatorial Entrainment Zone : the Diurnal Cycle	435
Peter R. Gent: A New Ocean GCM for Tropical Ocean and ENSO Studies	445
Wasito Hadi, and Nuraini: The Steady State Response of Indonesian Sea to a Steady Wind Field	451
Pedro Ripa: Instability Conditions and Energetics in the Equatorial Pacific	457
Lewis M. Rothstein: Mixed Layer Modelling in the Western Equatorial Pacific Ocean	465
Neville R. Smith: An Oceanic Subsurface Thermal Analysis Scheme with Objective Quality Control	475
Duane E. Stevens, Qi Hu, Graeme Stephens, and David Randall: The hydrological Cycle of the Intraseasonal Oscillation	485
Peter J. Webster, Hai-Ru Chang, and Chidong Zhang: Transmission Characteristics of the Dynamic Response to Episodic Forcing in the Warm Pool Regions of the Tropical Oceans	493

MOMENTUM, HEAT, AND MOISTURE FLUXES BETWEEN ATMOSPHERE AND OCEAN

W. Timothy Liu: An Overview of Bulk Parametrization and Remote Sensing of Latent Heat Flux in the Tropical Ocean	513
E. Frank Bradley, Peter A. Coppin, and John S. Godfrey: Measurements of Heat and Moisture Fluxes from the Western Tropical Pacific Ocean	523
Richard W. Reynolds, and Ants Leetmaa: Evaluation of NMC's Operational Surface Fluxes in the Tropical Pacific	535
Stanley P. Hayes, Michael J. McPhaden, John M. Wallace, and Joël Picaut: The Influence of Sea-Surface Temperature on Surface Wind in the Equatorial Pacific Ocean	543
T.D. Keenan, and Richard E. Carbone: A Preliminary Morphology of Precipitation Systems In Tropical Northern Australia	549
Phillip A. Arkin: Estimation of Large-Scale Oceanic Rainfall for TOGA	561
Catherine Gautier, and Robert Frouin: Surface Radiation Processes in the Tropical Pacific	571
Thierry Delcroix, and Christian Henin: Mechanisms of Subsurface Thermal Structure and Sea Surface Thermo-Haline Variabilities in the South Western Tropical Pacific during 1979-85 - A Preliminary Report	581
Greg. J. Holland, T.D. Keenan, and M.J. Manton: Observations from the Maritime Continent : Darwin, Australia	591
Roger Lukas: Observations of Air-Sea Interactions in the Western Pacific Warm Pool during WEPOCS	599
M. Nunez, and K. Michael: Satellite Derivation of Ocean-Atmosphere Heat Fluxes in a Tropical Environment	611

EMPIRICAL STUDIES OF ENSO AND SHORT-TERM CLIMATE VARIABILITY

Klaus M. Weickmann: Convection and Circulation Anomalies over the Oceanic Warm Pool during 1981-1982	623
Claire Perigaud: Instability Waves in the Tropical Pacific Observed with GEOSAT	637
Ryuichi Kawamura: Intraseasonal and Interannual Modes of Atmosphere-Ocean System Over the Tropical Western Pacific	649
David Gutzler, and Tamara M. Wood: Observed Structure of Convective Anomalies	659
Siri Jodha Khalsa: Remote Sensing of Atmospheric Thermodynamics in the Tropics	665
Bingrong Xu: Some Features of the Western Tropical Pacific: Surface Wind Field and its Influence on the Upper Ocean Thermal Structure	677
Bret A. Mullan: Influence of Southern Oscillation on New Zealand Weather	687
Kenneth S. Gage, Ben Basley, Warner Ecklund, D.A. Carter, and John R. McAfee: Wind Profiler Related Research in the Tropical Pacific	699
John Joseph Bates: Signature of a West Wind Convective Event in SSM/I Data	711
David S. Gutzler: Seasonal and Interannual Variability of the Madden-Julian Oscillation	723
Marie-Hélène Radenac: Fine Structure Variability in the Equatorial Western Pacific Ocean	735
George C. Reid, Kenneth S. Gage, and John R. McAfee: The Climatology of the Western Tropical Pacific: Analysis of the Radiosonde Data Base	741

Chung-Hsiung Sui, and Ka-Ming Lau: Multi-Scale Processes in the Equatorial Western Pacific	747
Stephen E. Zebiak: Diagnostic Studies of Pacific Surface Winds	757

MISCELLANEOUS

Rick J. Bailey, Helene E. Phillips, and Gary Meyers: Relevance to TOGA of Systematic XBT Errors	775
Jean Blanchot, Robert Le Borgne, Aubert Le Bouteiller, and Martine Rodier: ENSO Events and Consequences on Nutrient, Planktonic Biomass, and Production in the Western Tropical Pacific Ocean	785
Yves Dandonneau: Abnormal Bloom of Phytoplankton around 10°N in the Western Pacific during the 1982-83 ENSO	791
Cécile Dupouy: Sea Surface Chlorophyll Concentration in the South Western Tropical Pacific, as seen from NIMBUS Coastal Zone Color Scanner from 1979 to 1984 (New Caledonia and Vanuatu)	803
Michael Szabados, and Darren Wright: Field Evaluation of Real-Time XBT Systems	811
Pierre Rual: For a Better XBT Bathy-Message: Onboard Quality Control, plus a New Data Reduction Method	823