On the reflection and Transmission of Low Frequency Energy at the Irregular Western Pacific Ocean Boundary - a Preliminary Report

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ABSTRACT

The western boundary of the tropical Pacific is not continuous and leakage of low frequency energy from the Pacific to the Indian Ocean is possible. At low frequencies equatorial Kelvin and Rossby waves have very large east-west scales compared with the east-west scale of the land masses in the region. Consequently, these land masses may be treated as islands that are infinitesimally thin in the east-west direction. By generalizing previous theory for a single island, the leakage of low frequency energy through the seven major 'islands" forming the boundary of the western Pacific can be studied. The major results are as follows.

(1) When a mode 1 low frequency Rossby wave is reflected at the discontinuous western Pacific boundary, the eastward reflected Kelvin wave energy flux is about one third of the incoming energy flux or about two thirds of that expected for a solid meridional wall.
(2) In phase interannual sea levels should occur along Australia's western coast.
The latter prediction is in agreement with observation.
(3) Negligible low frequency Kelvin wave energy from the Indian Ocean is transmitted into the Pacific.
(4) Strong narrow currents are predicted to occur westward of some island tips.

1. Introduction

The western 'boundary' of the tropical Pacific is discontinuous. The reflection of low frequency energy from this western boundary may be crucial to interannual coupled ocean-atmosphere dynamics (Battisti, 1988). But present models assume that the boundary is a solid wall when it clearly is not. Just how well does the gappy western Pacific reflect low frequency energy compared to a solid wall?

In order to answer this question, it is important to realize that because low frequency westward propagating energy has such a large east-west scale, land masses forming the western tropical Pacific boundary can dynamically be treated as being infinitesimally thin east-west. The single 'island' results of Cane and du Penhoat (1982) then apply. These results can be generalized to the several island case and the multiple reflection and transmission of low frequency energy in the western tropical Pacific can be analyzed.

Theory for low frequency flow near a single irregularly shaped island is discussed in the next section and this is generalized in section 3 to the several island case. Section 4 presents some results for the west Pacific.

2. Theory for a Single Island

I will suppose that the large-scale, low-frequency flow is linear. The linear equations for perturbations to a continuously stratified constant depth ocean at rest can be separated into vertical modes (e.g., Gill and Clarke, 1974; Moore and Philander, 1977) and in the following I will consider a single baroclinic mode. The horizontal equations for each vertical mode are nondimensionalized in standard equatorial fashion, viz., $(c/\beta)^{1/2}$ for length and $(c\beta)^{-1/2}$ for time. (In these expressions β is the northward gradient of the Coriolis parameter and c is the Kelvin wave speed for the vertical mode). The coordinates x and y will represent non dimensional distance eastward from the origin and northward from the equator.

At the very low frequencies of interest here, large scale waves carrying energy westward are Rossby waves while those carrying energy eastward are equatorial Kelvin waves. At low frequencies these waves have very large east-west scales and the motion can be assumed to be independent of x. By geostrophy,

$$v(\text{large scale}) = p_{x/y} = 0 \tag{2.1}$$

Consider now an irregularly shaped island with a well defined single eastern and a single western boundary. The island's northern most and southern most points are defined by y=a and y=b respectively. Analysis to be reported elsewhere shows that the boundary conditions for that island, together with (2.1) and p and u independent of x imply that the irregular island is dynamically equivalent to an island which extends from y=b to y=a and is infinitesimally thin from east to west. Specifically, the infinitesimally thin island results of Cane and du Penhoat (1982) are valid for an irregular island provided

$$\varepsilon\omega << 1 \quad \text{and} \quad k\,\Delta x << 1 \tag{2.2}$$

where ε, Δx and k are, respectively, the nondimensional width of the boundary layer east of the island, half of the east-west extent of the island and the largest wave number of all large scale motion of significant amplitude near the island.

The Cane and du Penhoat (1982) results for an incident unit amplitude equatorial Kelvin wave striking a north south island are shown in Figure 1. The transmitted Kelvin wave has amplitude α and so by continuity the p and u fields west of the island for y > a and y < b have the form

$$p_W = \alpha\psi_0 \tag{2.3a}$$

$$u_W = \alpha\psi_0 \tag{2.3b}$$

where ψ_0 is the zeroth order Hermite function. West of the island and in its latitude range b < y < a, the boundary condition at the island and u and p independent of x imply

$$u_W = 0 \tag{2.4a}$$

$$p_W = D = \text{constant} \tag{2.4b}$$

As pointed out by Cane and du Penhoat, (2.4b) and (2.3a) cannot simultaneously hold without there being a discontinuity in pressure at y=a or y=b or both. By geostrophy, this leads to a δ function behaviour for u and so (2.3b) can be written as

$$u_W \begin{cases} = \alpha\psi_0 + A\delta(y-a) & \text{for } y \geq a \\ = \alpha\psi_0 + B\delta(y-b) & \text{for } y \leq b \end{cases} \tag{2.5}$$

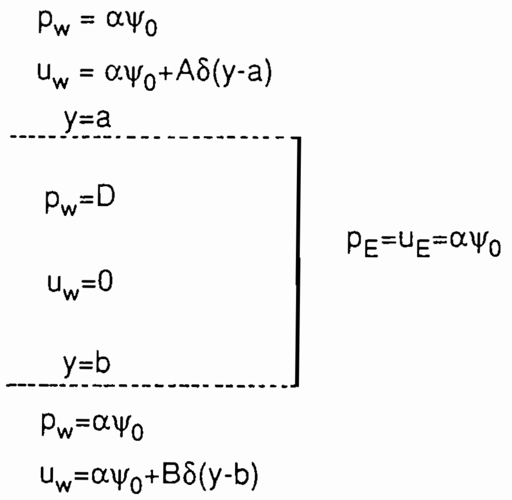

Figure 1

p and u fields for a low frequency equatorial Kelvin wave striking an island extending from y=b to y=a. The incoming Kelvin wave has $u=p=\psi_0$. P_E and u_E are given for the large-scale field outside the narrow western boundary layer east of the island. δ is the Dirac delta function.

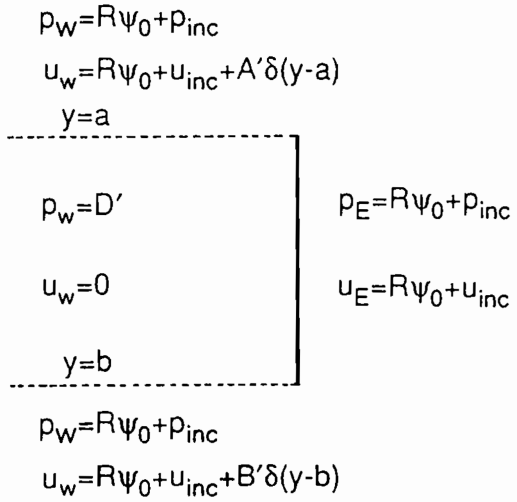

Figure 2

p and u fields for a low frequency Rossby wave striking an island extending from y=b to y=a. The incoming Rossby wave has $u=u_{inc}$ and $p=p_{inc}$. P_E and u_E are given for the large-scale field outside of the narrow boundary layer east of the island.

The transports A and B supply the western boundary current on the eastern side of the island. This boundary current redistributes mass to allow the transmitted Kelvin wave with amplitude α to leave the island. Cane and du Penhoat provide formulae for α, A, B and D.

A similar analysis can be carried out for the case of a Rossby wave striking a north-south island (see Fig. 2). Formulae for the amplitude R of the reflected Kelvin wave and A', B' and D' are provided by Cane and du Penhoat.

3. Several Island Theory

To examine the reflection and transmission at the western Pacific 'boundary', theory must be developed for the interaction of low frequency fields with several islands. Proceeding westward from the easternmost island, number the islands i = 1, 2, ... The western Pacific Ocean boundary appears to consist of seven major islands (see Figs. 3 and 4).

Consider low frequency transmission and reflection occurring at island i (see Fig. 5). Define T_i to be the amplitude of the Kelvin wave transmitted past island i due to the Kelvin wave coming into the island from the west and R_i as the amplitude of the Kelvin wave reflected from island i due to an incoming Rossby wave field from the east. Represent this Rossby wave field as

$$u = u^R_{i-1} , \qquad p = p^R_{i-1} \tag{3.1}$$

If α_i is the transmission coefficient for island i, then since $(R_{i+1}+T_{i+1})$ is the amplitude of the incoming Kelvin wave it follows that

$$T_i = \alpha_i \, (R_{i+1} + T_{i+1}) \tag{3.2}$$

where, from Cane and du Penhoat's single island results

$$\frac{1}{\alpha_i} = \frac{2(a_i-b_i)(1-I_i) + 2J_i[a_i\Psi_0(b_i) - b_i\Psi_0(a_i)] - [\Psi_0(a_i) - \Psi_0(b_i)]^2 - a_ib_i(J_i)^2}{2(a_i-b_i)} \tag{3.3}$$

In (3.3)

$$I_i = \int_{b_i}^{a_i} \Psi_0^2 \, dy \tag{3.4}$$

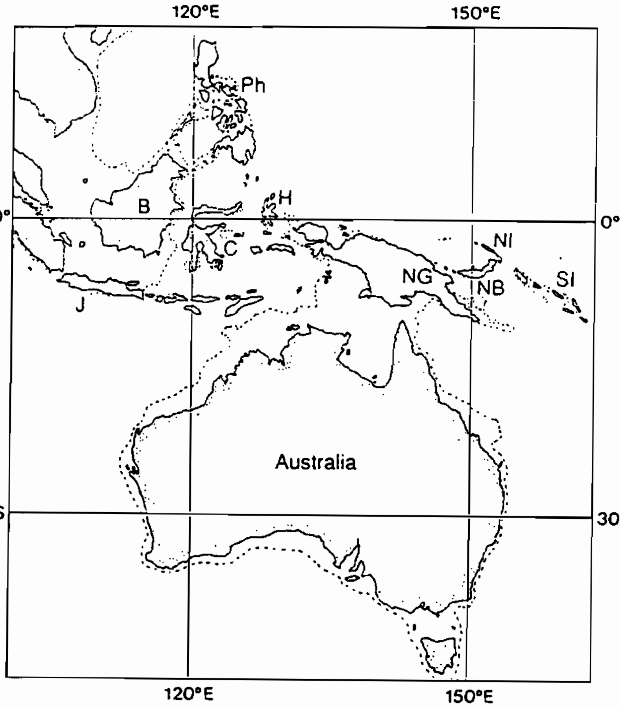

Figure 3

The western Pacific region under study. The dashed line is the 200 m isobath. SI=Solomon Islands, NB=New Britain, NI=New Ireland, NG=New Guinea, H=Halmahera, C=Celebes, Ph=Philippines, B=Borneo and J=Java.

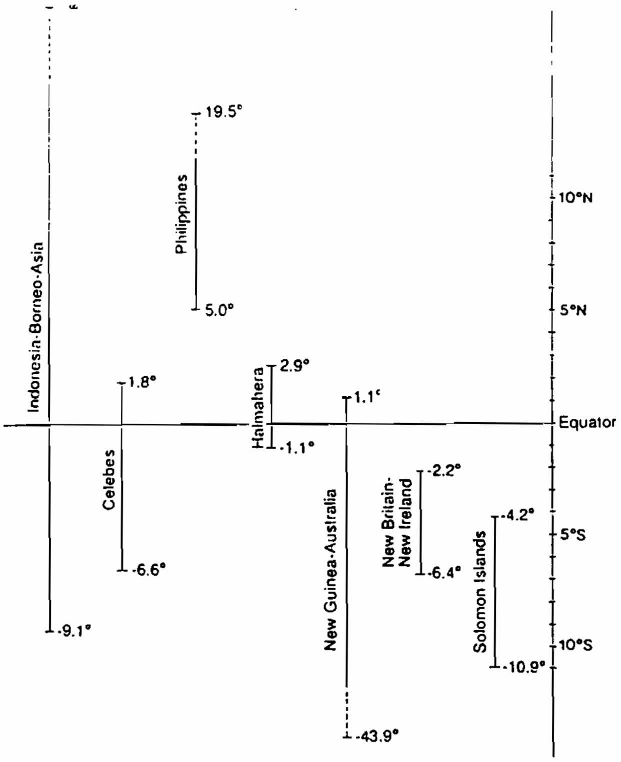

Figure 4

Thin island approximation to the western Pacific boundary. The northern and southern latitudes were based on the northern and southern limits of the 200 m isobath for each island.

and

$$J_i = \int_{b_i}^{a_i} \Psi_0 \, dy \tag{3.5}$$

Define A_i and B_i to be transport around the northern and southern tips of island i due to the incoming Kelvin wave and A_i' and B_i' to be similar transports for the incoming Rossby wave. The pressure D_i west of island i is associated with the incoming Kelvin wave and the pressure D_i' with the incoming Rossby wave. Then from the single island results of Cane and du Penhoat,

$$A_i = \lambda_i T_i \tag{3.6}$$

$$B_i = \mu_i T_i \tag{3.7}$$

$$D_i = \nu_i T_i \tag{3.8}$$

$$R_i \Psi_0(a_i) - D_i' + a_i A_i' + P^R_{i-1}(a_i) = 0 \tag{3.9}$$

$$-R_i \Psi_0(b_i) + D_i' + b_i B_i' - P^R_{i-1}(b_i) = 0 \tag{3.10}$$

$$2R_i[1-I_i] + D_i' J_i + A_i' \Psi_0(a_i) + B_i' \Psi_0(b_i) - K_i = 0 \tag{3.11}$$

$$-R_i J_i + A_i' + B_i' - U_i = 0 \tag{3.12}$$

where

$$\lambda_i = -\frac{1}{a_i - b_i} \left| \Psi_0(a_i) - \Psi_0(b_i) + b_i J_i \right| \tag{3.13}$$

$$\mu_i = \frac{1}{a_i - b_i} \left| \Psi_0(a_i) - \Psi_0(b_i) + a_i J_i \right| \tag{3.14}$$

$$\nu_i = a_i \lambda_i + \Psi_0(a_i) \tag{3.15}$$

and the K_i and U_i are known in terms of P^R_{i-1} and u^R_{i-1} as

$$K_i = \int_{b_i}^{a_i} \left(u^R_{i-1} + p^R_{i-1}\right) \Psi_0 \, dy \tag{3.16}$$

$$U_i = \int_{b_i}^{a_i} u^R_{i-1} \, dy \tag{3.17}$$

Fig. 5 shows the p and u fields east and west of island i.

To solve the problem posed by (3.2) and (3.6)-(3.12) for the unknowns A_i, B_i, D_i, T_i, R_i, A_i', B_i' and D_i' (i=1,2,...,7), I must find expressions for the Rossby wave fields $u^R{}_{i-1}$ and $p^R{}_{i-1}$ so that the K_i and U_i can be evaluated. The p and u fields west of island i consist of the required long Rossby wave field and the incoming Kelvin wave field with amplitude $T_{i+1}+R_{i+1}$. Thus we can obtain $p^R{}_i$ and $u^R{}_i$ by subtracting off the Kelvin wave field. From Figure 5 and Eqs. (3.2) and (3.6)-(3.12), the Rossby wave field west of island i is given by

$$p^R_i = \left[T_i\left(1-\frac{1}{\alpha_i}\right) + R_i\right] \Psi_0 + p^R_{i-1} \tag{3.18a}$$

$$y \geq a_i$$

$$u^R_i = \left[T_i\left(1-\frac{1}{\alpha_i}\right) + R_i\right]\Psi_0 + u^R_{i-1} + (A_i' + \lambda_i T_i)\delta(y-a_i) \tag{3.18b}$$

$$p^R_i = \nu_i T_i + D_i' - T_i \Psi_0/\alpha_i \qquad b_i<y<a_i \tag{3.18c}$$

$$u^R_i = -T_i\Psi_0/\alpha_i \tag{3.18d}$$

$$p^R_i = \left[T_i\left(1-\frac{1}{\alpha_i}\right)+R_i\right]\Psi_0 + p^R_{i-1} \tag{3.18e}$$

$$y \leq b_i$$

$$u^R_i = \left[T_i\left(1-\frac{1}{\alpha_i}\right)+ R_i\right]\Psi_0 + u^R_{i-1} + (B_i' + \mu_i T_i)\delta(y-b_i) \tag{3.18f}$$

In (3.18) p^R_{i-1} and u^R_{i-1} can be similarly written in terms of T_{i-1}, R_{i-1}, D_{i-1}, A'_{i-1}, B'_{i-1}, p^R_{i-2} and u^R_{i-2}. This process can be repeated until i=1 when p^R_0 and u^R_0 are known incoming Rossby wave fields from the Pacific interior. Thus equations (3. 9)-(3.12) and (3.2) are all linear equations in terms of the 35 variables T_i, R_i, D_i', A_i' and B_i' (i=1,...,7). The form of the equations will differ depending on the relative positions of the islands. Note that since there is no eighth island, $(R_8 + T_8)$ is the given amplitude of the incoming Kelvin wave from the Indian Ocean.

The 35 linear equations can be written in terms of the 35 unknowns as a matrix problem

$$Ex = q \tag{3.19}$$

where x is the column vector consisting of elements T_1, R_1, D_1', A_1', B_1', ... A_7', B_7', q is a known vector with elements derived from T_8 and the incoming known Rossby p and u fields and E is the appropriate 35x35 matrix associated with the linear equations. E consists mainly of zeros and its structure is influenced by the relative positions of the islands. Equations (3.9)-(3.12) for i=1 indicate that A_1', D_1', A_1' and B_1' can be found separately but for structural convenience I kept the problem in the 35x35 form and solved it by standard techniques.

4. Application of the Theory to the Western Pacific

4.1 Validity of the theory

To apply the theory to the western Pacific, the criteria in (2.2) must first be checked. For $\beta = 2.29\mathrm{x}10^{-11}\mathrm{m}^{-1}\mathrm{s}^{-1}$, $c = 2.74\mathrm{ms}^{-1}$, an ENSO frequency of $2\pi/3$ years, k corresponding to a Kelvin wave or first mode Rossby wave and Δx corresponding to 2900km (half of total east-west distance occupied by the 7 island 'boundary'), the maximum magnitude of $k\Delta x$ and $\omega\epsilon$ is 0.2. Thus the requirement that this maximum magnitude be small compared with unity is marginally satisfied.

A further theoretical restriction is that the motion be linear and inviscid. While this is reasonable for the large scale Kelvin and westward propagating Rossby wave fields, it will break down for the strong currents at the island tips and east of the island. As noted by Cane and du Penhoat, friction and nonlinear effects will broaden these strong currents. The large scale balances on which the theory is based will be neglegibly affected, however.

4.2 Results

I briefly discuss some of the major results below. A more detailed discussion will be given in a future report.

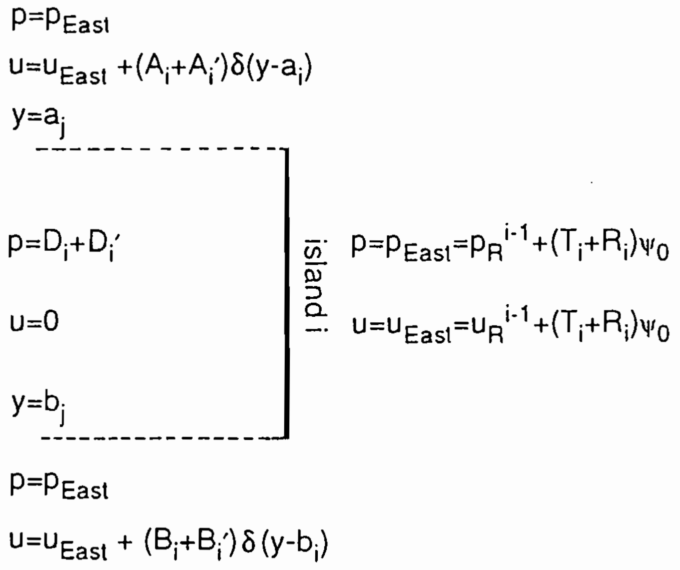

Figure 5

The u and p fields for reflection and transmission at island *i* due to an incident Rossby wave from island *i*-1 and an incident equatorial Kelvin wave from island *i*+1.

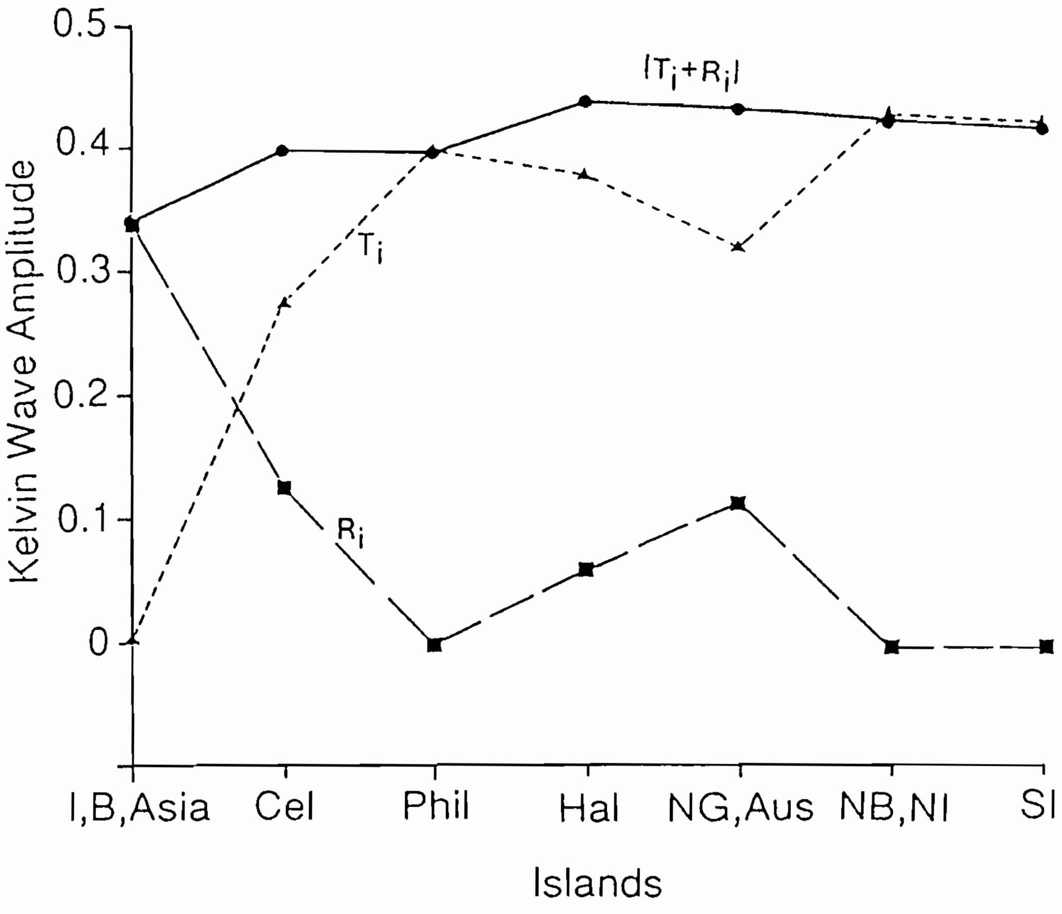

FIG.6. Kelvin wave amplitudes R_i, T_i and R_i+T_i for the seven islands forming the west Pacific boundary. I, B, Asia=indonesia, Borneo, Asia; Cel=Celebes, Phil=Philippines, Hal=Halmahera, NG=New Guinea, Aus=Australia, NB=New Britain, NI=New Ireland, SI=Solomon Islands.

a. Reflection and transmission of a model Rossby wave

Figure 6 shows the transmitted and reflection Kelvin wave amplitudes plotted for each island. The large value of R_7 compared to the other R_i indicates that the mode 1 Rossby wave energy is mainly reflected at the western most island (Indonesia/Borneo/Asia). The total Kelvin wave amplitude does not vary much from island to island because all islands are good to excellent transmitters of the Kelvin wave reflected at Indonesia/Borneo/Asia.

If the western Pacific boundary were a solid north-south wall then the magnitude of the Kelvin wave energy flux reflected back into the Pacific compared to the incident mode 1 Rossby wave energy flux would be 0.5 (Clarke, 1983). The ratio for the 7 island model is 0.34, i.e., about two-thirds of that expected for a solid wall.

The solution also indicates that $D_3 + D_3'$ is substantial and that therefore interannual sea level fluctuations should be observed along Australia's western coast. These sea level fluctuations should be in phase and of constant amplitude. This is in good agreement with observation (Pariwono et al, 1986).

Strong jets occurring westward of some island tips are suggested by the model. These have been observed in numerical models (Luther, personal communication) and recent observations near the Philippines suggest a westward jet from the southern tip [Lukas (1988), Hacker and Firing (1988)]. For the model incoming mode 1 Rossby wave the strongest jet is predicted at the southern end of the Philippines. If this mode were to have a sea level amplitude of 7 cm at the equator, then the upper layer transport in a 1½ layer model with upper layer depth of 100 m would be about 6 Sverdrups at the southern end of the Philippines.

b. Reflection and transmission of an Indian Ocean equatorial Kelvin wave

The western most island (Indonesia/Borneo/Asia) prevents transmission of almost all of an incoming Indian Ocean Equatorial Kelvin wave. Only small transmission is expected because this island extends further north and south than the north-south scale of the incoming Kelvin wave. A Kelvin wave eventually reaches the Pacific by proceeding past the other islands, but its energy flux is less than 5% of the original energy flux.

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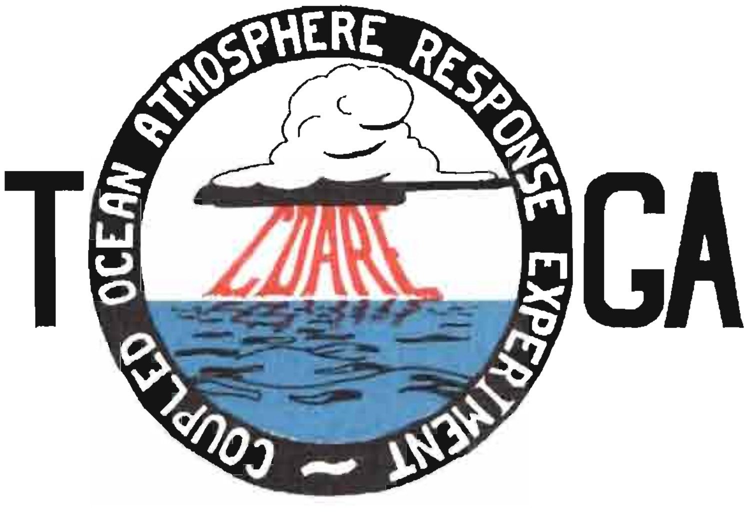

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