

On the Dynamics of the Celebes and Sulu Seas

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SUMMARY As part of a much larger investigation of the waters of South East Asia, preliminary results are given of a study designed to determine the influence of the wind stress and the oceanic pressure difference between the Pacific Ocean and the South China Sea on the circulation of the Mindanao Current meander within the Celebes and Sulu Seas. These results indicate how the Mindanao Current meander is fundamentally related to the flow through the Makassar Strait.

1 INTRODUCTION

The waters of South East Asia are of great importance to many of the countries of Australasia. Countries local to these seas are interested in the fisheries of the region. Countries less local are interested in the climatic importance of these seas. Nicholls (1978, 1979) using observations, has suggested a basic interaction between the sea surface temperature of the area and large scale climatic variability. Unfortunately, there is a scarcity of data which makes it necessary to rely strongly on mathematical modelling in understanding the behaviour of these seas.

The seas of South East Asia appear to be strongly influenced by the behaviour of the Mindanao Current. This current with a strength of about $10^7 \text{ m}^3 \text{ s}^{-1}$, meanders into the Celebes Sea. Part of the current returns to the Pacific Ocean, while part of it flows southward into the Flores Sea through the Makassar Strait. The purpose of the present study is to consider the behaviour of the Mindanao Current within the Celebes Sea and to determine the influence of a wind stress and a pressure gradient across the Celebes and Sulu Seas on the current.

2 THE BASIC MODEL

Observations from the Snellius Expedition 1929-1930 reported by Van Riel, Groen and Weenink (1957), suggest that for studying the surface water behaviour, the waters of South East Asia may be represented by a two layer model. In accordance with observations, the surface layer depth, H , is characteristically 200 m while the lower layer may be taken to be infinitely deep and passive. Variations in the depth of the upper layer are observed to be small compared to the depth of the layer. The reduced gravity, g' , between the layers may be taken to be of order $1.5 \times 10^{-2} \text{ m s}^{-2}$.

Suppose that the Coriolis parameter, f , is constant at $1 \times 10^{-5} \text{ s}^{-1}$. Further suppose that all the water in the upper layer is of

tranquil origin and that there is no wind stress on the ocean in the region. Then the frictionless nonlinear vorticity equation for the upper layer stream function, ψ , is given by Hughes (1980) as

$$\nabla^2 \psi = -F(\nabla \psi)^2 \quad (1)$$

where $F = f/2Hg'$ is a constant of order $2 \times 10^{-6} \text{ m}^{-2} \text{ s}$ and ψ is defined by

$$u = -\frac{\partial \psi}{\partial y} \quad v = \frac{\partial \psi}{\partial x} \quad (2)$$

Hughes has noted that the general solution to (1) of the form

$$\psi = \frac{1}{F} \ln(1 + F\xi) \quad (3)$$

can be obtained from a knowledge of the solution of Laplace's equation

$$\nabla^2 \xi = 0 \quad (4)$$

in the region with ξ constant on those boundaries where ψ is constant. If no analytical solution to (4) is available, then a solution to (4) can be obtained by numerical relaxation.

Now it is observed that the inflows and outflows of the Celebes and Sulu Seas system to the South China Sea and through the Philippines to the Pacific Ocean are small compared with the inflow associated with the Mindanao Current. It is thus convenient to ignore these flows. The water exchanges between the Celebes and Sulu Seas with the surrounding oceans are then to the east between the Celebes Sea and the Pacific Ocean and to the south through the Makassar Strait. On land boundaries between these outlets the stream function ψ and also the variable ξ are constant.

The general solution to (4) in this basin is composed of two parts ξ_1 and ξ_2 where

$$\xi = \alpha_1 \xi_1 + \alpha_2 \xi_2 \quad (5)$$

where α_1 and α_2 are arbitrary real constants.

These parts are plotted separately in Figures 1 and 2. The flow is chosen to asymptote to channel flow conditions at the open boundaries.

Combining (3) and (5) gives a general solution to (1) for arbitrary flow rates. From (3) it follows that on curves for which ξ is constant ψ is also constant. Hence Figure 1, which gives ξ when $\alpha_1=1$ and $\alpha_2=0$, represents lines of constant ψ when there is no flow through the Makassar Strait. Note how the Mindanao Current meanders within the Celebes Sea before leaving it by flowing eastwards. Figure 2, which gives ξ when $\alpha_1=0$ and $\alpha_2=1$,

represents lines of constant ψ when there is no meandering of the Mindanao Current. All of the current flows out of the Celebes Sea by southwards flow into the Makassar Strait.

Wyrski (1961) has presented maps of the topography of the sea level in the region. These maps show that there is very little change in the surface layer pressure between the Sulu and South China Sea where they meet through the Balabac Strait. Now it is hypothesised here that even though the inflows and outflows from the Sulu Sea to the South China Sea are small, they are sufficient to equalise the pressure in the Sulu Sea at that of the South China Sea. This hypothesis can only be proven or disproven by more field observations which unfortunately are lacking at the moment. However it seems a reasonable assumption to make. To the author's knowledge no other control mechanism for the Mindanao Current has been proposed. Even if this hypothesis is incorrect, it would be interesting to know how the behaviour of the currents in the area are related to the pressure in the Sulu Sea.

Using (2), (3), (5) and Bernoulli's equation it follows that the pressure, p , is given by

$$p = -\frac{1}{2} \rho \frac{(\alpha_1 \nabla \xi_1 + \alpha_2 \nabla \xi_2)^2}{(1 + F(\alpha_1 \xi_1 + \alpha_2 \xi_2))^2} \quad (6)$$

where ρ is the density of water and the pressure is measured relative to the pressure associated with the tranquil state in the Pacific Ocean to the east where the flow is small. p is negative throughout the flow. Denoting a variable () applicable to the Balabac Strait region of the Sulu Sea by ()_S and that applicable to the channel of the Makassar Strait where $\xi_2 = -0.5$ by ()_M, it follows that a specification of the negative pressures p_S and p_M is sufficient to determine α_1 and α_2 using (6). From the numerical results

$$\nabla \xi_{1S} = -2 \times 10^{-8} \text{ m}^{-1}, \nabla \xi_{2S} = -7 \times 10^{-8} \text{ m}^{-1}, \xi_{1S} = 0, \xi_{2S} = 0$$

$$\nabla \xi_{1M} = 0, \nabla \xi_{2M} = -7 \times 10^{-6} \text{ m}^{-1}, \xi_{1M} = 0, \xi_{2M} = -0.5 \quad (7)$$

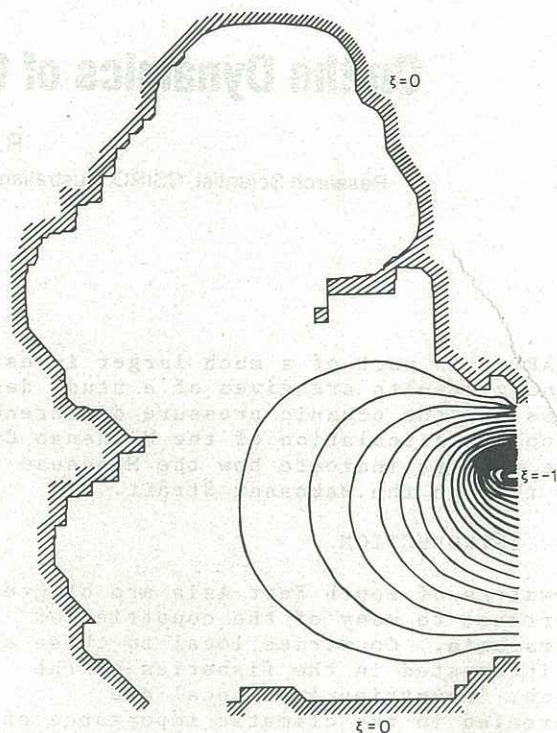


Figure 1 Contours of ξ_1 with no wind stress.

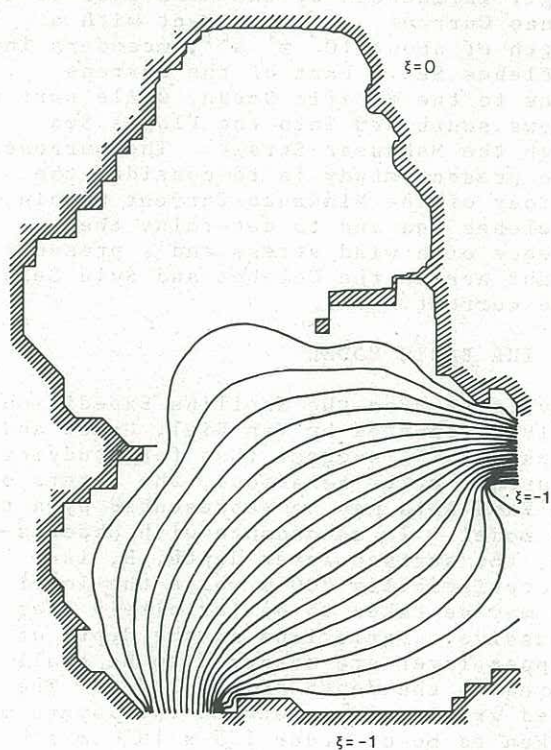


Figure 2 Contours of ξ_2 with no wind stress.

Hence assuming

$$0 \left(\left| \frac{p_s}{\rho} \right| \right) \sim 0 \left(\left| \frac{p_M}{\rho} \right| \right) \ll 10^2 \text{ m}^2 \text{ s}^{-2} \quad (8)$$

it follows that

$$\alpha_1 = 7 \times 10^7 \sqrt{\frac{p_s}{\rho}} \text{ m} \quad (9)$$

$$\alpha_2 = 2 \times 10^5 \sqrt{\frac{p_M}{\rho}} \text{ m} \quad (10)$$

It should be noted that because of the low velocity in the Sulu Sea as produced by the model, the neglect of the small flows through the Philippines and Balabac Strait may cause large quantitative errors in the mechanism proposed for the control of the Mindanao Current meander by the South China Sea. However, in accordance with the hypothesis given above it seems reasonable to assume that the predictions are qualitatively correct.

3 THE INFLUENCE OF WIND STRESS

The basic model as just described has two severe problems. Firstly, the velocity field predicted does not resemble the observed velocity field in the Sulu Sea and the north western part of the Celebes Sea. Secondly, the value of α_1 appears to be too sensitive to the pressure in the South China Sea. Both of these problems can be alleviated by the inclusion of wind stress.

When wind stress is included, (1) takes on the form

$$\nabla^2 \psi = -F ((\nabla \psi)^2 - 2\phi) \quad (11)$$

where ϕ is the potential defined by

$$\tau_x = \rho H \frac{\partial \phi}{\partial x} \quad \tau_y = \rho H \frac{\partial \phi}{\partial y} \quad (12)$$

for a potential wind stress (τ_x , τ_y).

Hughes has noted that a solution of the form (3) still applies but now (4) must be replaced by Helmholtz type equation

$$\nabla^2 \xi = 2F^2 \phi \left(\xi + \frac{1}{F} \right) \quad (13)$$

As in the case of no wind stress, the solution of (13) can be split into two variable parts $\alpha_1 \xi_1$ and $\alpha_2 \xi_2$ and a constant part $-\frac{1}{F}$. The two variables ξ_1 and ξ_2 are plotted in Figures 3 and 4.

Here $2F^2 \phi$ has been taken to be $-2.5 \times 10^{-18} (x-y) \text{ m}^{-3}$ where (0,0) is taken to occur at Manado near the southern most connection between the Pacific Ocean and Celebes Sea. This form for ϕ is typical of conditions which may occur in June. The circulation pattern is now much more acceptable although the pattern within the Sulu Sea remains substantially influenced by the small flows through its boundaries.

A similar analysis to that used earlier can be carried out to determine the way in which the pressure at the Makassar Strait

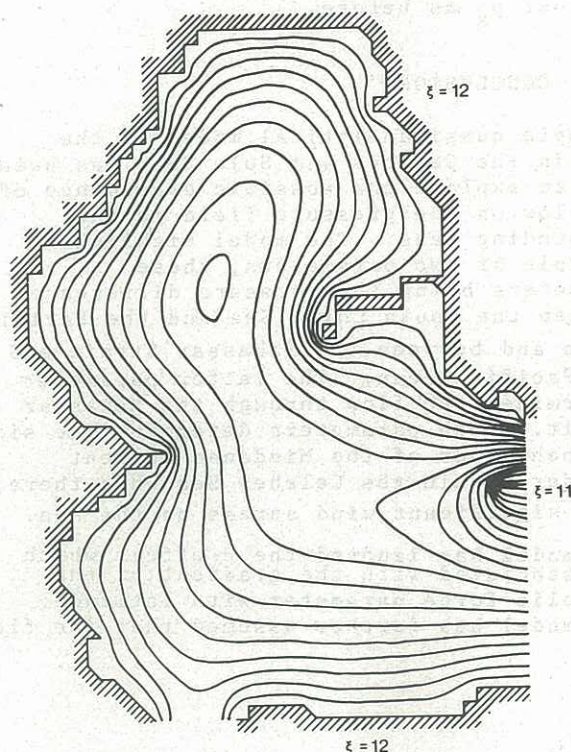


Figure 3 Contours of ξ_1 with wind stress.

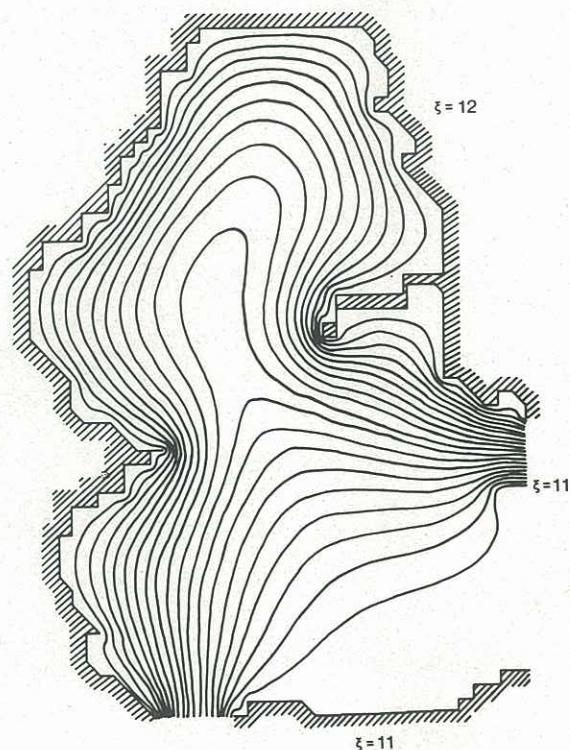


Figure 4 Contours of ξ_2 with wind stress.

and the Balabac Strait influences the circulation. The results are more acceptable. Interestingly the behaviour of α_1 is now influenced both by p_s and p_M not just p_s as before.

4 CONCLUSIONS

A simple quasi-analytical model of the flow in the Celebes and Sulu Seas has been used to explore the possible dependence of the flow on the pressure field in the surrounding seas. The model highlights the role of two parameters, these parameters being the pressure difference between the South China Sea and the Pacific Ocean and between the Makassar Strait and the Pacific Ocean. The latter parameter determines the flow through the Makassar Strait. Both parameters determine the size and behaviour of the Mindanao Current meander within the Celebes Sea when there is a significant wind stress on the sea.

The model has ignored the β -effect which is associated with the gradient of the Coriolis force parameter with latitude. The model has further assumed that the flow

is from a once initially tranquil state. Information relating to the effect of these simplifications will be presented at the Conference.

5 REFERENCES

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