THE FLORIDA STATE UNIVERSITY

COLLEGE OF ARTS AND SCIENCES

THE EFFECTS OF HALMAHERA ON THE INDONESIAN THROUGHFLOW

By

Steven Morey

A thesis submitted to the
Department of Oceanography
in partial fulfillment of the
requirements for the degree of
Masters in Science

Degree Awarded:
Fall Semester, 1997

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The pathways of, and the relative contributions of North Pacific (NP) and South Pacific (SP) water to, the Pacific to Indian Ocean throughflow are examined using the Navy Layered Ocean Model. The role of Halmahera Island in directing flow along the pathways and in determining the composition of the throughflow is also studied. The simulations use a horizontal resolution of up to ¼° between like variables, and have a vertical resolution ranging from 1.5 layer reduced gravity to 6 active layers with realistic bottom topography. All of the simulations are forced by the *Hellerman and Rosenstein* [1983] monthly wind stress climatology. The predominant throughflow pathway consists of NP water travelling through the Celebes Sea, Makassar Strait, Flores Sea, and to the Indian Ocean through the Timor, Savu, and Lombok Straits. Model results show that the island of Halmahera is responsible for preventing a flow of SP water into the Celebes Sea, and for diverting some SP water southward through the Seram and Banda Seas. The island impacts the lower thermocline and intermediate water pathways throughout the entire year, and affects the surface layer during the boreal spring through fall. To estimate the relative contributions of the NP and SP surface water to the throughflow, Lagrangian drifters are advected backwards in time from near the exit to the throughflow region to their respective sources. Tracking these buoys, we find that the presence of

Halmahera changes the throughflow composition in the surface layer from about 69% NP and 31% SP to 92% NP and 8% SP, thus resulting in a fresher throughflow. Halmahera does not change the composition of the throughflow in the undercurrent layer, which is fed by the NP, or in the lower thermocline and intermediate water layers, which are fed by water from the SP.

1. Introduction

The Indonesian throughflow provides the only interbasin exchange of water at low latitudes from the Pacific to the Indian Ocean. There has been much interest lately in determining the relative contributions to the throughflow from the saline SP and the fresher NP [e.g., *Godfrey et al.*, 1993; *Wajsowicz*, 1993; *Fine et al.*, 1994; *Gordon*, 1995; *Hautala et al.*, 1996; *Nof*, 1996], as well as interest in the pathways water takes through the Indonesian Seas [e.g., *Ffield and Gordon*, 1992; *Wajsowicz*, 1996; *Ilahude and Gordon*, 1996; *Shriver and Hurlburt*, 1997]. It is important to understand the dynamics of this region because of the role it may play in El Niño/Southern Oscillation (ENSO) development, Pacific and Indian Ocean circulation [*Verschell et al.*, 1995], and as an upper ocean return path of warm water to the North Atlantic for the global thermohaline circulation [*Gordon,* 1986; *Schmitz*, 1996; *Shriver and Hurlburt*, 1997].

Water from the Pacific Ocean enters the Indonesian seas near the region where a jet of water from the South Equatorial Current (SEC) along the northern coast of New Guinea meets the Mindanao Current (MC), as well through the South Sulu Sea from the South China Sea (Figure 1). The jet from the SEC retroflects around the Halmahera Eddy (HE) into the eastward flowing North Equatorial Countercurrent (NECC). The North Equatorial Current (NEC) bifurcates east of the Philippines, with the southern branch becoming the MC and the northern branch the Kuroshio. Part of the water

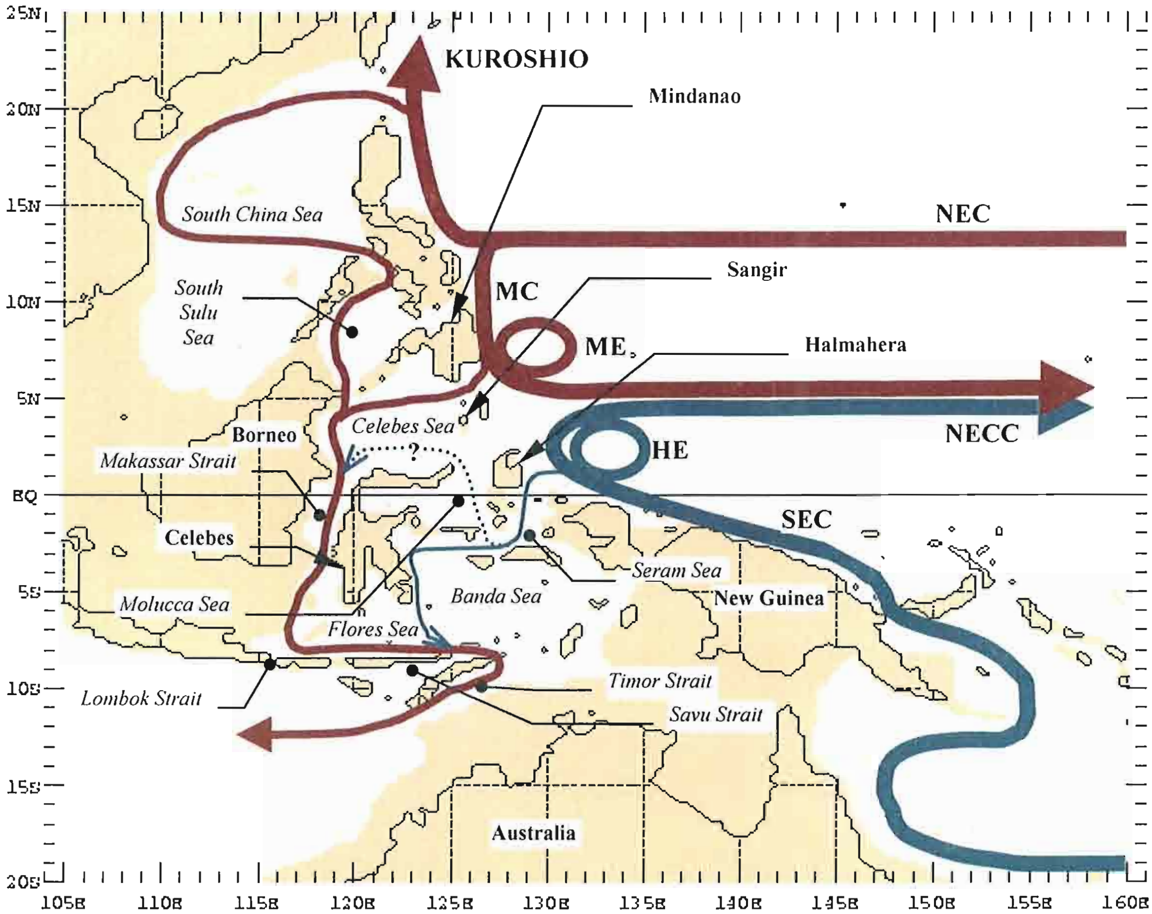


Figure 1: Schematic diagram of the geography, major currents, and pathways in the region of the Indonesian throughflow. Blue arrows represent SP water and red arrows represent NP water. A possible pathway from the SEC through the Celebes Sea is suggested by the dotted line. The model land, extending to the 200 m isobath, is shaded.

flowing southward in the MC retroflects around the Mindanao Eddy (ME) to join the NECC, while the remainder enters the Celebes Sea where some passes through to the Indian Ocean. There is some seepage of water from the SEC into the Indonesian seas near Halmahera. The majority of the Indonesian throughflow water exits to the Indian Ocean through the Timor Strait, with smaller transports through the Savu Sea and Lombok Strait.

The relative contributions to the throughflow from the NP and SP are important in determining the characteristics of the water entering the Indian Ocean. It is understood that all water in the Pacific Ocean must have at some time been in the SP because the basin is closed to the north. However, SP thermocline water can have a salinity that is 0.5 psu higher than NP thermocline water [*Gordon*, 1986]. The saline SP water is freshened by precipitation as it travels across the Pacific Ocean in the NECC before reaching the NP. The tongue of low salinity water stretching west from Indonesia through the Indian Ocean suggests that this water originates in the NP. A linear frictionless model for determining the circulation around Australia with some small islands and reefs omitted failed to show the NP as the dominant source [*Godfrey*, 1993]. *Wajsowicz* [1993] showed that the existence of Halmahera is particularly important for determining the throughflow pathways using a simple analytical model and a general circulation model. This small island, spanning about 3 degrees of latitude, is located directly on the equator at the entrance to the Indonesian seas and in the vicinity of the retroflection of the incoming currents. It is the unique location of Halmahera that is responsible for its impact on the Indonesian throughflow.

We can study the effects of Halmahera on the Indonesian throughflow by comparing the behavior of the ocean with and without the island. The ability of computer models to simulate the ocean with the presence or absence of topographical features makes them logical tools for studies such as this. We use the Navy Layered Ocean Model (NLOM) with up to six active layers and a horizontal resolution of ¼° in latitude. In Section 2, we describe the numerical model and how it is used in the experiments. The results of the experiments are discussed in Section 3. We demonstrate that Halmahera prevents SP water from flowing into the Celebes Sea, and deflects some SP water southward through the Banda Sea. We next discuss how the role of Halmahera changes seasonally as a result of seasonal changes in wind forcing of the equatorial Pacific. The island has the greatest impact on the surface layer flow when the magnitude of the throughflow is strongest during the southeast monsoon and transition periods from the boreal spring through fall. Finally, we present results from a novel experiment involving Lagrangian drifters travelling backward in time to determine where the water exiting the throughflow region originated. The results from this experiment show that Halmahera is at least partially responsible for the predominantly NP source of water to the throughflow. The conclusions are summarized in Section 4.

2. The Model

The numerical ocean model used in this study is a primitive equation layered model based on the original version by *Hurlburt and Thomson* [1980] with major modifications and enhancements [*Wallcraft*, 1991]. The vertically integrated equations for the n layer finite depth hydrodynamic model are for layers $k = 1,\ldots,n$:

$$
\begin{aligned}
&\frac{\partial \vec{V}_k}{\partial t} + \left(\nabla \cdot \vec{V}_k + \vec{V}_k \cdot \nabla\right)\vec{v}_k + \hat{\mathbf{k}} \times f\,\vec{V}_k \\
&= -\,h_k \sum_{l=1}^{n} G_{kl} \nabla\left(h_l - H_l\right) + \frac{\left(\vec{\tau}_{k-1} - \vec{\tau}_k\right)}{\rho_0} + \max(0, \omega_k)\vec{v}_{k+1} \\
&\quad - \left[\max(0,-\omega_k) + \max(0, \omega_{k-1})\right]\vec{v}_k + \max(0,-\omega_{k-1})\vec{v}_{k-1} \\
&\quad + \max(0,-C_M\omega_{k-1})(\vec{v}_{k-1} - \vec{v}_k) + \max(0, C_M\omega_k)(\vec{v}_{k+1} - \vec{v}_k) \\
&\quad + A_H h_k \nabla^2 \vec{V}_k \\
&\frac{\partial h_k}{\partial t} + \nabla \cdot \vec{V}_k = \omega_k - \omega_{k-1}
\end{aligned}
$$

where the notation is as described in the Appendix. The model uses kinematic and no slip boundary conditions. Mixing between layers is allowed in the multi-layer simulations by using a diapycnal mixing scheme based on oxygen saturation [*Shriver and Hurlburt*, 1997].

The model domain is the global ocean from 72°S to 65°N and has a horizontal resolution of 0.25° in latitude by 0.3515625° in longitude between like variables on the C grid [*Mesinger and Arakawa,* 1976]. The bottom topography is interpolated to the model grid from the 1/12° ETOP05 data set [*National Oceanic and Atmospheric Administration, 1986*] with some modifications before smoothing. The model boundary is the 200 m isobath (near the shelf break) and the maximum depth is set at 6500 m. The amplitude of the bottom topography above 6500 m is scaled by a factor of 0.65 to confine it to the lowest layer. The mean resting layer thicknesses are chosen such that layer six represents deep and abyssal water (see Table 1). The upper two layers represent the surface layer and the undercurrent layer, and layers 3-5 represent lower thermocline and intermediate water. The density for each layer is calculated from the *Levitus* [1982] oceanic climatology. In all experiments, the model is forced by *Hellerman and Rosenstein* [1983] monthly mean wind stress, which has been smoothed and interpolated to the model geometry.

The ocean model is run with and without Halmahera. To remove the island from the simulation, we replace Halmahera and the surrounding model land with a new topographic surface calculated using cubic splines. The simulation without Halmahera is an extension of the simulation that includes the island, and the model is again spun up to equilibrium after altering the topography. A linear reduced gravity model with one active layer, referred to as a 1.5 layer model, is also run with and without the island. The NLOM is run in linear mode by scaling the winds down by a factor of 1000 so that the nonlinear terms become insignificant in the equations. The model fields are then scaled up by a factor of 1000 to restore them to their proper magnitude.

Table 1: Ocean Simulation Descriptions and Parameters

Number of Layers	Includes Halmahera	A (m^2s^{-1})	Layer densities (σ_T)	Resting Layer Thicknesses	Comments
1.5	Yes	300	25.45/27.55	250/∞	Linear
1.5	No	300	25.45/27.55	250/∞	Linear
6	Yes	300	25.25/26.59/27.03 27.30/27.53/27.77	155/185/260 375/525/bottom	Nonlinear
6	No	300	25.25/26.59/27.03 27.30/27.53/27.77	155/185/260 375/525/bottom	Nonlinear

3. Results

The model used for this study simulates the global ocean since the Indonesian throughflow involves interbasin transport and is thought to be a warm surface water return route for the global thermohaline circulation [*Gordon*, 1986; *Schmitz*, 1996; *Shriver and Hurlburt*, 1997]. We concentrate, however, on the region involving the Indonesian archipelago and the nearby major currents.

3.1. The Effects of Halmahera on the Mean Flow

The leading order response to wind forcing of the Pacific Ocean, Indian Ocean and the connecting seas is Sverdrup flow (Figure 2). The annual mean Pacific to Indian Ocean wind driven transport in the linear 1.5 layer simulation is 16.4 Sv (10^6 m^3/s). This is consistent with the estimates of 14 Sv by *Piola and Gordon* [1984] based on a freshwater budget for the Pacific and Indian Oceans, 16 ± 4 Sv by *Godfrey* [1989] based on a global Sverdrup model, 18.6 ± 7 Sv by *Fieux et al.* [1994] based on geostrophic transports from August, 1989, and 15.1 Sv by *Shriver and Hurlburt* [1997] based on results of a 6-layer global ocean model. The throughflow is fed by the NEC in the NP and the SEC in the SP. The nearshore jet from the SEC that flows along the northern coast of New Guinea retroflects just east of Halmahera around the HE to join the

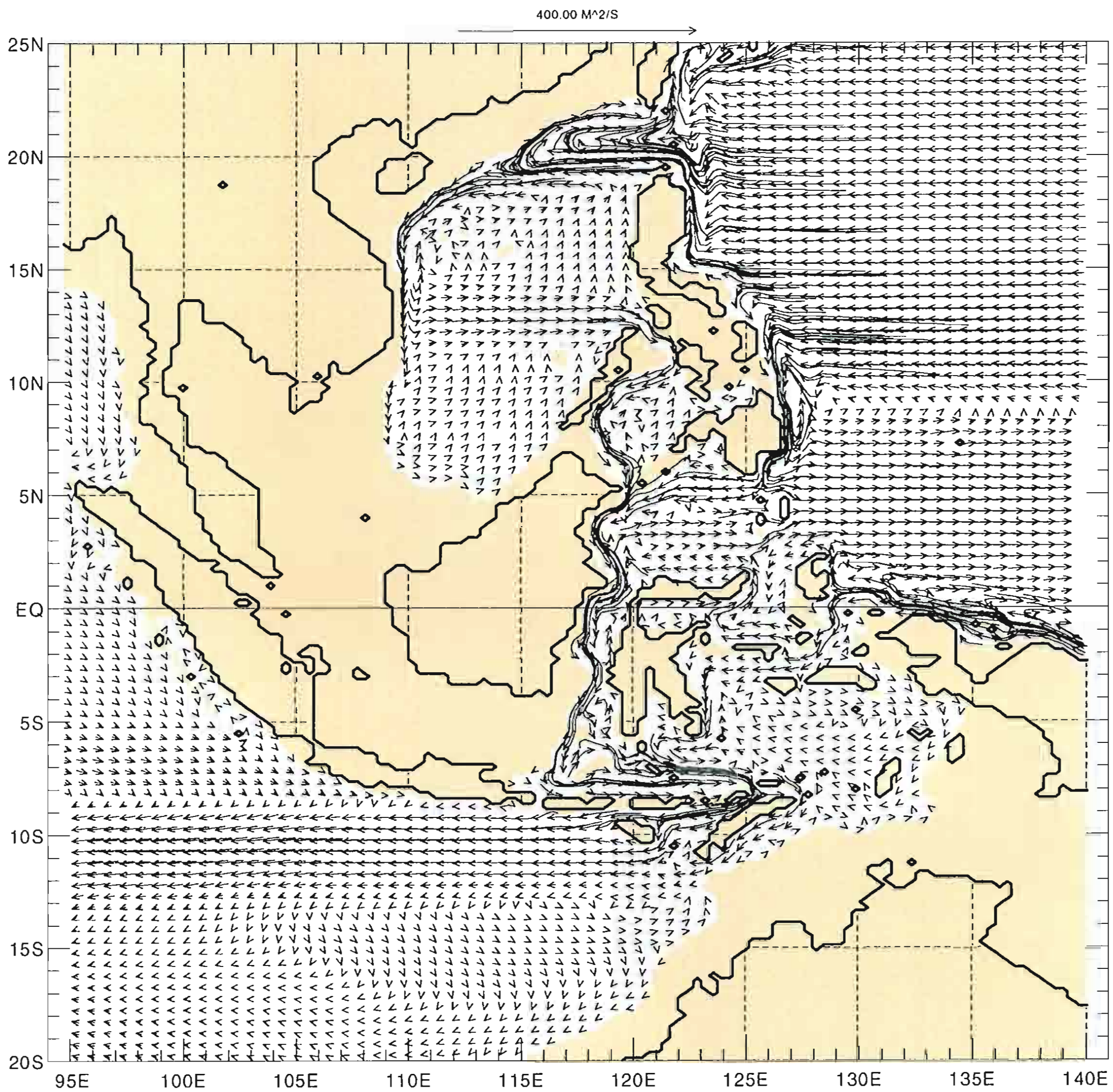


Figure 2: Mean transports from the linear 1.5 layer simulation with Halmahera.

eastward flowing NECC. Part of the MC retroflects around the ME to also join the NECC, which flows across the basin and recirculates into the NEC in the eastern Pacific. The rest of the MC enters the Celebes Sea where some turns eastward to join the NECC and some flows southward through the Makassar Strait becoming the primary throughflow pathway. Another pathway is fed by the Kuroshio, which splits north of the South China Sea, spilling into the South Sulu Sea and joining the MC in the Celebes Sea.

Other possible throughflow routes originating with the SEC are suggested by the linear model (Figure 1). The modeled mean transports indicate that not all of the water from the SEC retroflects into the NECC. Instead, the westward current bifurcates at the eastern coast of Halmahera. Part of the southern branch flows toward the Banda Sea, and the rest flows through the Molucca Sea. Some of the SP water in the Molucca Sea enters the Celebes Sea and may contribute to the flow through Makassar Strait.

The nonlinear simulation exhibits similarities with the linear simulation, but shows some important departures from the Sverdrup flow. The upper ocean (layers 1-5) Pacific to Indian Ocean mean transport is 15.8 Sv which is very close to the linear result, but the greater vertical resolution allows for the existence of significantly different pathways. The major features found in the linear model are evident in the surface layer of the nonlinear model (Figure 3a). This is expected since the currents near the ocean's surface are primarily a response to the wind forcing. Nonlinear processes are responsible for eddy generation throughout the region, however these eddies do not entirely mask the large-scale features. The NP to Indian Ocean pathways from the MC and South Sulu Sea through Makassar Strait still appear to be the predominant routes for the throughflow. At

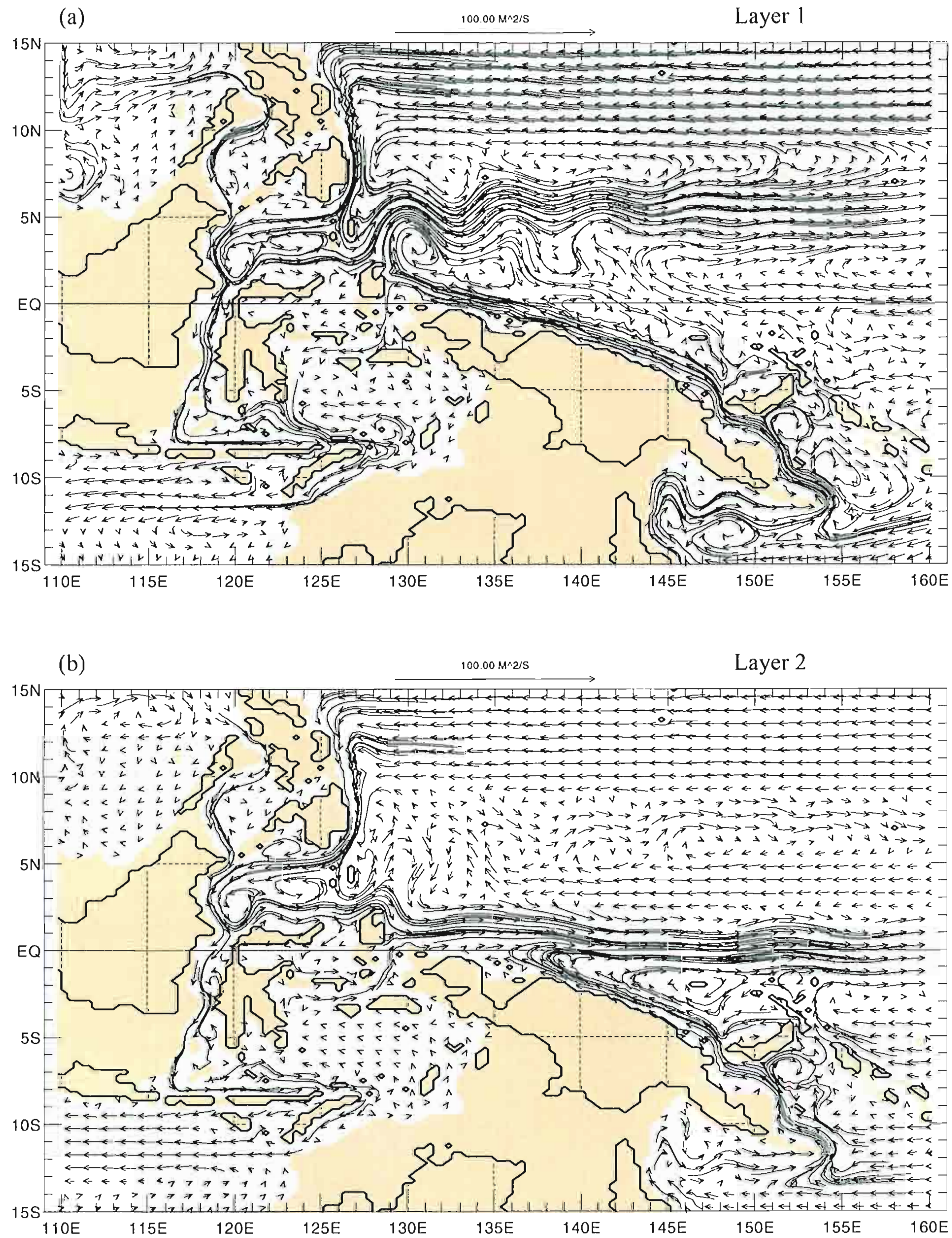


Figure 3: Mean transports from the nonlinear 6 layer simulation with Halmahera for (a) layer 1, (b) layer 2, and (c) layers 3+4+5.

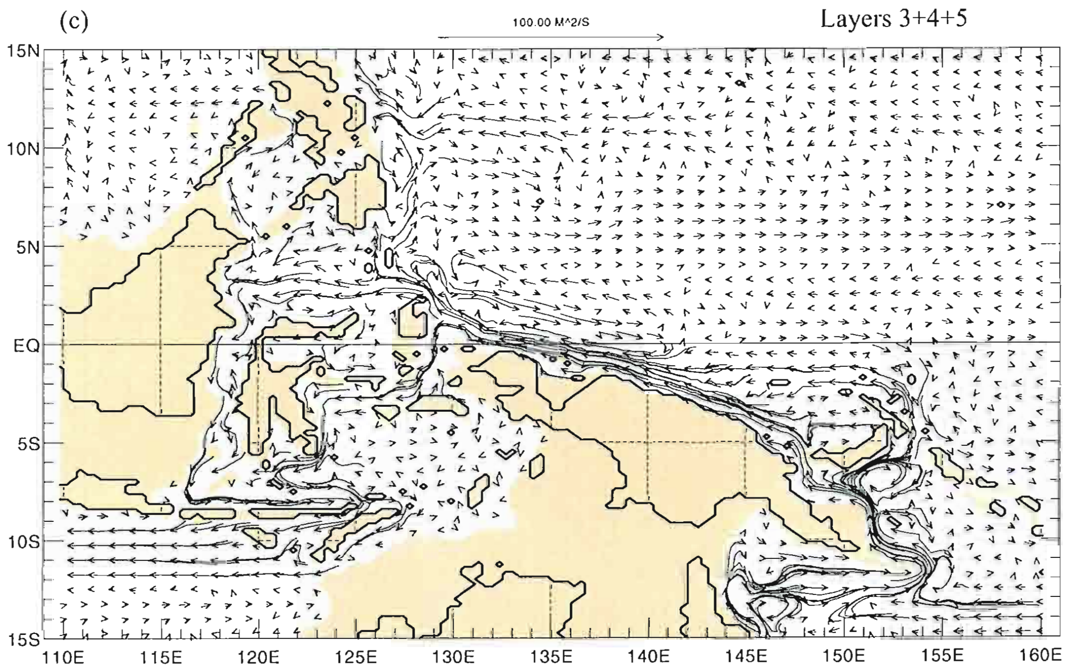


Figure 3--continued

Table 2: Mean Transports in Sverdrups across Sample Locations. Positive values indicate eastward or northward volume transport normal to the transport section. The highlighted values show the principal effects of Halmahera on the throughflow pathways. RG1.5 = 1.5 layer reduced gravity linear model. BT6 = 6 layer nonlinear model with realistic bottom topography. + H = Halmahera is present in the simulation. – H= Halmahera is not present in the simulation.

	Simulation	Total Throughflow	Mindanao to Sangir	Sangir to Celebes	Makassar Strait	Celebes to New Guinea	South Sulu Sea
Layer 1	RG1.5 + H	-16.4	-8.8	-0.4	-13.6	-2.8	-4.4
	RG1.5 - H	-16.4	-8.3	-1.5	-14.2	-2.2	-4.4
	BT6 + H	-6.5	-6.1	3.0	-5.4	-2.1	-2.4
	BT6 - H	-6.4	-3.0	-0.9	-6.0	-1.4	-2.3
Layer 2	BT6 + H	-3.6	-8.1	5.7	-3.6	1.1	-1.0
	BT6 - H	-3.6	-9.1	6.7	-3.5	0.9	-1.0
Layers 3+4+5	BT6 + H	-5.7	-0.2	-2.8	-2.2	-3.6	0.7
	BT6 - H	-5.8	1.3	-7.1	-5.2	-0.7	0.7

the entrance to the strait, the nonlinear results show that a significant amount of NP water flows toward the east through the Celebes Sea before joining the NECC. This is because in the nonlinear model, an average of 14.4 Sv flows into the Celebes Sea from the MC in the upper ocean (layers 1-5) compared to only 8.8 Sv in the linear model (Table 2). Topographical constrictions prevent all of this water from entering Makassar Strait, thereby forcing some to turn eastward. The mean transport in the MC is nearly equal in the linear and nonlinear simulations, so nonlinear processes may be responsible for allowing more of the current to recirculate in the Celebes Sea instead of around the ME. The nonlinear results show the bifurcation of the SEC at Halmahera with the northern branch joining the NECC and much of the southern branch flowing through to the Banda Sea. The small amount of SEC water entering the Molucca Sea is prevented from entering the Celebes Sea by the eastward flow of NP water.

The most evident departure from the Sverdrup pathways involves the EUC. Equatorial upwelling in the central and eastern Pacific drives the modeled EUC in layer 2 (Figure 3b). This layer contributes an annual average of 3.6 Sv of water from the NEC to the throughflow. The pathway from the MC and South Sulu Sea to the Indian Ocean follows the pathway found in layer 1. The NP water exiting the Celebes Sea does not join the NECC, however, but feeds the EUC along with all of the SEC layer 2 water. Water in the EUC then follows a circuitous path involving upwelling to the NECC surface layer in the eastern Pacific before flowing again westward in the NEC to feed the throughflow. This was found to be a dominant pathway for the Indonesian throughflow by *Shriver and Hurlburt* [1997].

Layers 3 through 5 in this model represent the lower thermocline and intermediate water (Figure 3c). Together, these layers contribute 5.7 Sv to the Pacific to Indian Ocean throughflow. In the lower thermocline, the flow along the New Guinea coast bifurcates at Halmahera and both branches pass directly through to the Indian Ocean instead of joining any eastward currents in the Pacific. The northern branch, transporting 40% of the volume, travels through the Celebes Sea and Makassar Strait. The southern branch, containing the remainder of the water, flows through the Seram and Banda Seas before exiting the throughflow region.

The model results discussed so far suggest that Halmahera may indeed play an important role in determining throughflow pathways. The SEC jet along the New Guinea coast is observed to bifurcate at the eastern edge of Halmahera in the linear and nonlinear simulations, and the mean position of the HE appears to be immediately east of the island. When Halmahera is not considered in the linear simulation, the HE is found just east of the northern tip of Celebes (Figure 4). An additional 1.1 Sv of SP water is allowed to enter the Celebes Sea and contribute to the Makassar Strait pathway. Of this transport, Halmahera deflects 0.6 Sv southward through the Seram and Banda Seas, and causes the remaining 0.5 Sv to retroflect into the NECC.

The mean layer 1 transports in the nonlinear simulation also demonstrate how Halmahera prevents SP water from entering the Celebes Sea (Figure 5a). Without the island, the cyclonic circulation of NP water in the Celebes Sea is no longer evident in the mean picture. Instead, water from the SEC augments the flow from the MC and South Sulu Sea to feed the throughflow via Makassar Strait, and the volume transport of SP

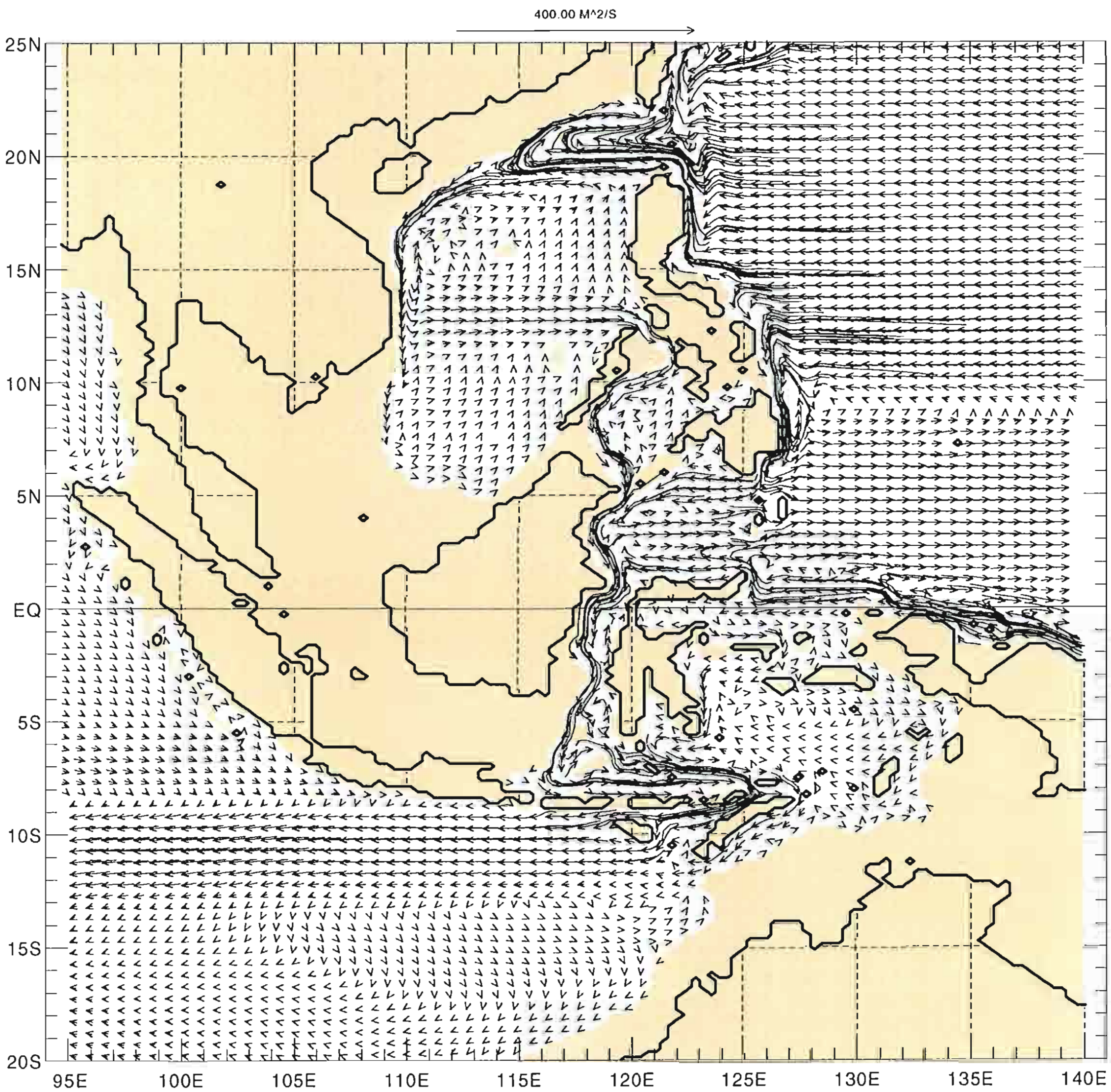


Figure 4: Mean transports from the linear 1.5 layer simulation without Halmahera.

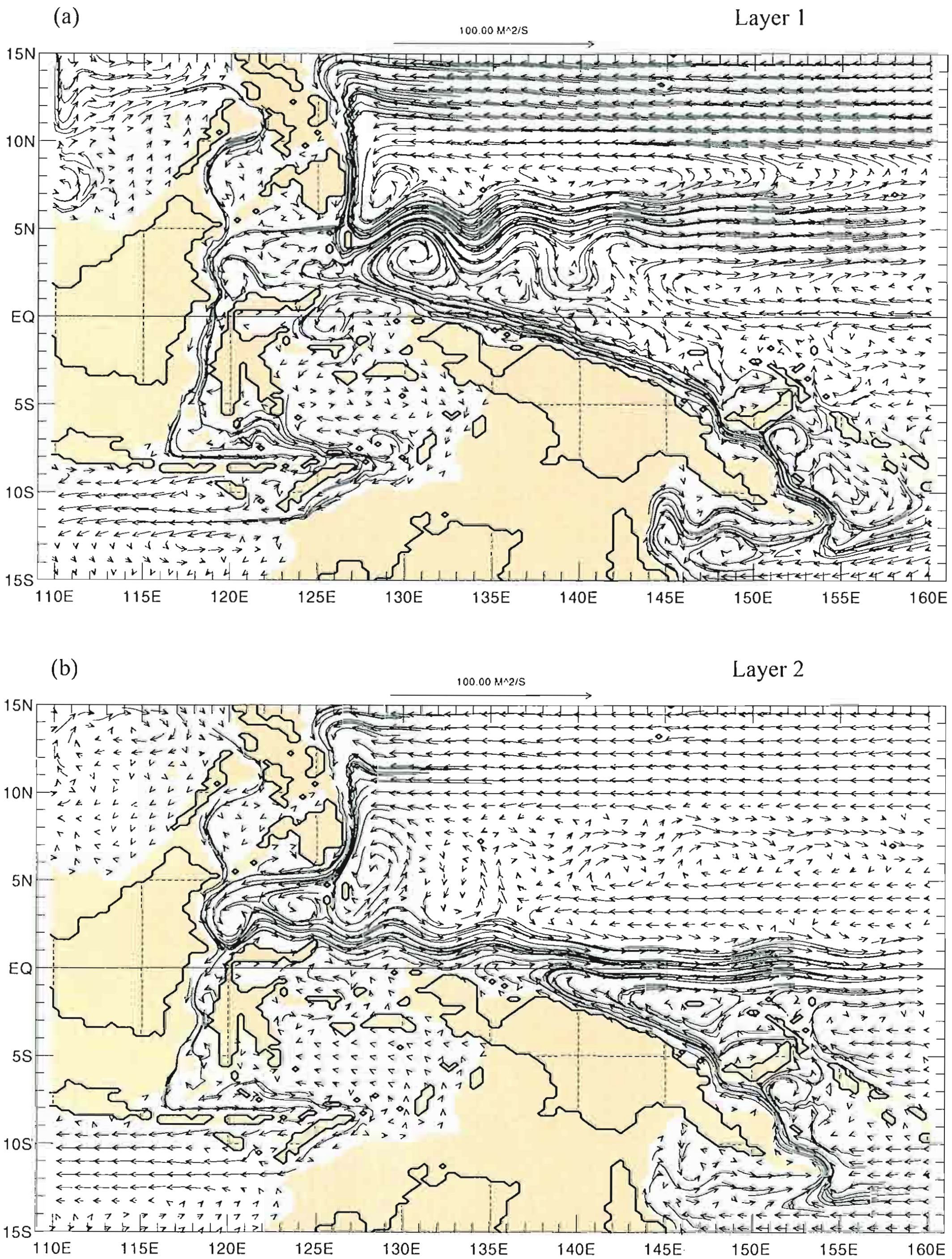


Figure 5: Mean transports from the nonlinear 6 layer simulation without Halmahera for (a) layer 1, (b) layer 2, and (c) layers 3+4+5.

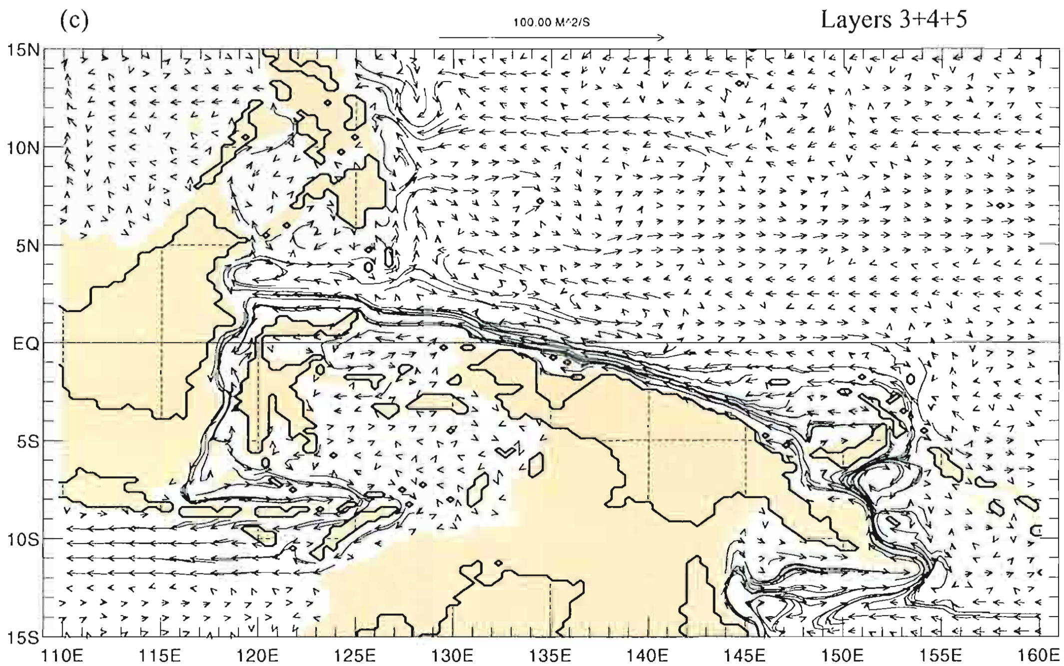


Figure 5--continued

water through the Seram and Banda Seas decreases. Unlike the results from the linear simulation, however, the mean position of the center of the HE does not change with the removal of Halmahera in the nonlinear simulation. The eddy elongates zonally without the island, but the mean position of the center remains fixed. Thus, processes other than coastline steering are responsible for determining the location of the SEC retroflection.

Halmahera has no significant effect on the mean flow in layer 2 (Figure 5b). Even though the island is situated on the equator, its meridional extent is small enough so that it does not affect the EUC. The undercurrent simply flows around the island to the north and south and rejoins at the equator to the east of the island. The simulated transport in the EUC remains fixed regardless of the island's presence or absence. An analysis of the layers below the EUC shows that Halmahera is responsible for diverting 3 Sv of lower thermocline and intermediate water through the Seram and Banda Seas away from its preferred route through the Celebes Sea and Makassar Strait (Figure 5c).

3.2. The Effects of Halmahera on the Seasonal Variability of the Local Circulation

Study of the mean circulation patterns in the Indonesian throughflow region reveals that the Halmahera is responsible for altering the pathways of the throughflow. In the surface layer, the island prevents SP water from flowing into the Celebes Sea, and diverts some of this water south along the eastern coast of Celebes. In layers 3-5, the lower thermocline and intermediate water, Halmahera forces about 3 Sv of the throughflow to travel through the Seram and Banda Seas instead of through the Celebes Sea and Makassar Strait. Currents in the Indonesian region exhibit strong seasonal variability due to the geographic location where atmospheric processes are dominated by the monsoons. It is therefore reasonable to believe that the throughflow pathways change seasonally, and that Halmahera's importance in determining these pathways may also vary throughout the year.

Time series of transports from the ocean model along the throughflow pathways in the lower thermocline show a maximum Pacific to Indian Ocean transport during the boreal winter and spring and a minimum transport during the boreal summer and fall (Figure 6). A similar semiannual signal in the throughflow below 500 m has been observed with current meter moorings in the Timor Passage [*Molcard et al.*, 1996]. Halmahera reduces the strength of the Celebes Sea → Makassar Strait pathway and increases the transport in the pathway through the Seram Sea throughout the entire year. This indicates that Halmahera's role in governing the pathways in the lower thermocline and intermediate water is simply coastal steering. The island is directly in the path of the westward current that feeds the throughflow at this depth throughout most of the year causing the current to bifurcate north of the Seram Sea. Here, the two branches can follow different routes through the Indonesian seas. Otherwise, the current would continue westward until it hit the coast of Borneo where bifurcation would also take place, however the only pathway available would be through Makassar Strait.

The effect of Halmahera on the surface currents is a more complicated issue. The transport time series along the throughflow pathways in layer 1 indicate that the island affects the pathways a great deal during the boreal spring through fall, but has less of an impact from December to February (Figure 7). From March to November the transport

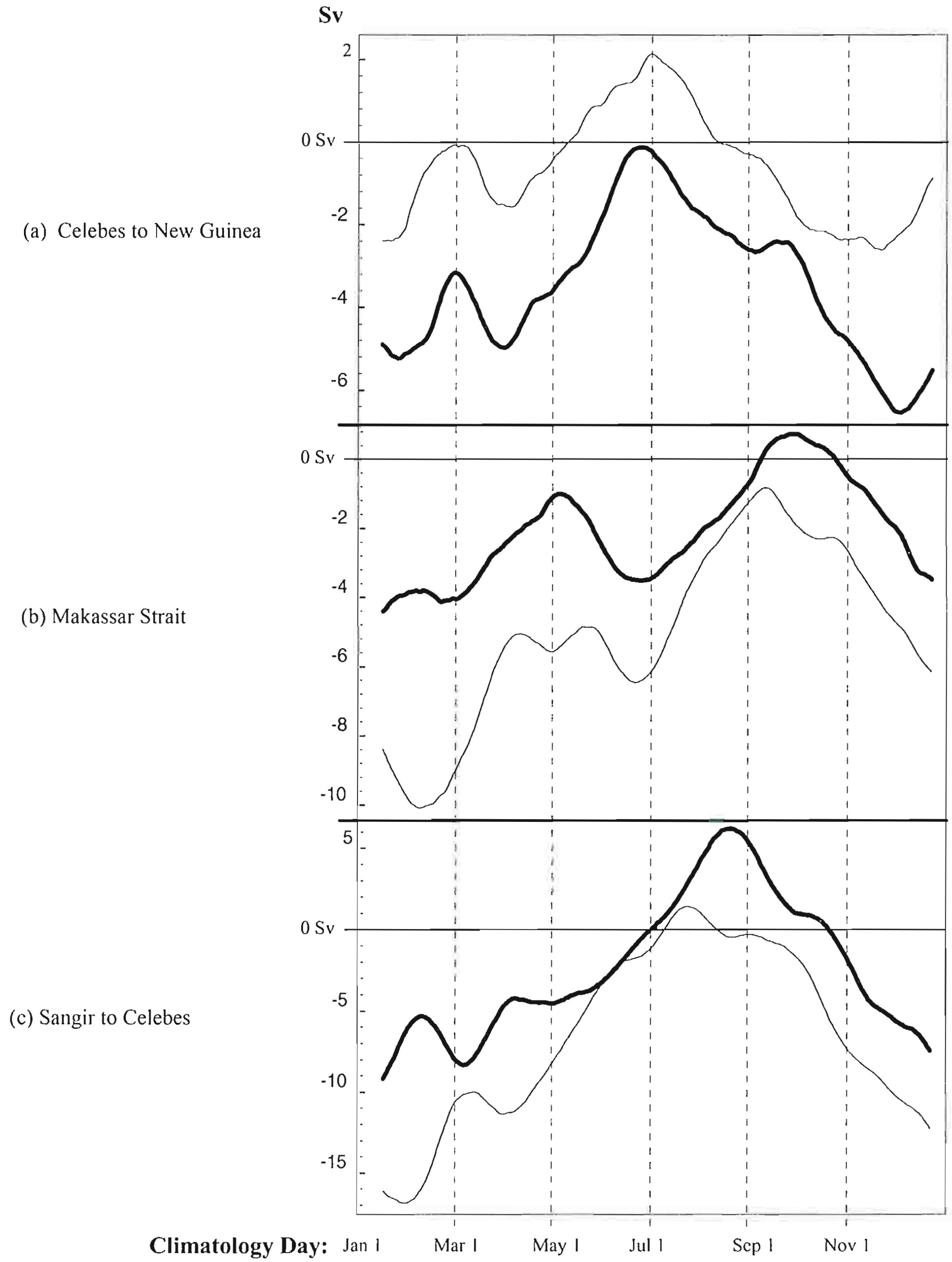


Figure 6: 5 year climatology transports for layers 3+4+5 of the nonlinear 6 layer simulations at locations (a) between Celebes and New Guinea, (b) Makassar Strait, and (c) between Sangir and Celebes. Heavy lines are the transports for the simulation with Halmahera and thin lines are the transports for the simulation without Halmahera. The transports have been filtered with a 30-day running mean.

Figure 7: 5 year climatology transports for layer 1of the nonlinear 6 layer simulations at locations (a) between Mindanao and Sangir, (b) between Sangir and Celebes, and (c) between Celebes and New Guinea. Heavy lines are the transports for the simulation with Halmahera and thin lines are the transports for the simulation without Halmahera. The transports have been filtered with a 30-day running mean.

from the MC through the Celebes Sea is greatly enhanced when Halmahera is present in the model (Figure 7a). During these months, Halmahera directs slightly more water southward between Celebes and New Guinea and prevents a strong flow of SP water through the Celebes Sea (Figures 7a-b). This allows for a larger NP contribution to the Celebes Sea → Makassar Strait throughflow pathway.

The monsoons are largely responsible for the seasonal variability of the Indonesian throughflow and its pathways. Easterly winds in the Pacific pile up surface water toward Indonesia throughout the year (Figure 8). This sets up a pressure gradient between the western Pacific and eastern Indian Ocean that drives the throughflow. During the northwest monsoon (Figure 8a), the pressure gradient is weakest. In addition, the Ekman transport in the southern hemisphere is toward the northeast opposing the Pacific to Indian Ocean throughflow in the surface layer. When the southeast monsoon develops (Figure 8c), the pressure gradient is at its maximum and a southwestward Ekman transport compliments the Pacific to Indian Ocean transport [*Fieux et al.*, 1994]. The effect of the monsoon seasons on the magnitude of the throughflow is evident in the time series of the upper layer Pacific to Indian Ocean transport (Figure 11c). This semiannual transport variability has been observed by *Molcard et al.* [1996].

Snapshots of the upper layer transports during the northwest monsoon do not show the jet of SEC water along the entire northern New Guinea coast as clearly as during the rest of the year (Figures 9a, 10a). Little SP water penetrates west of New Guinea, and we find a strong cyclonic flow of NP water in the Celebes Sea. March and April begin a period of transition between the monsoon seasons, and weak and variable

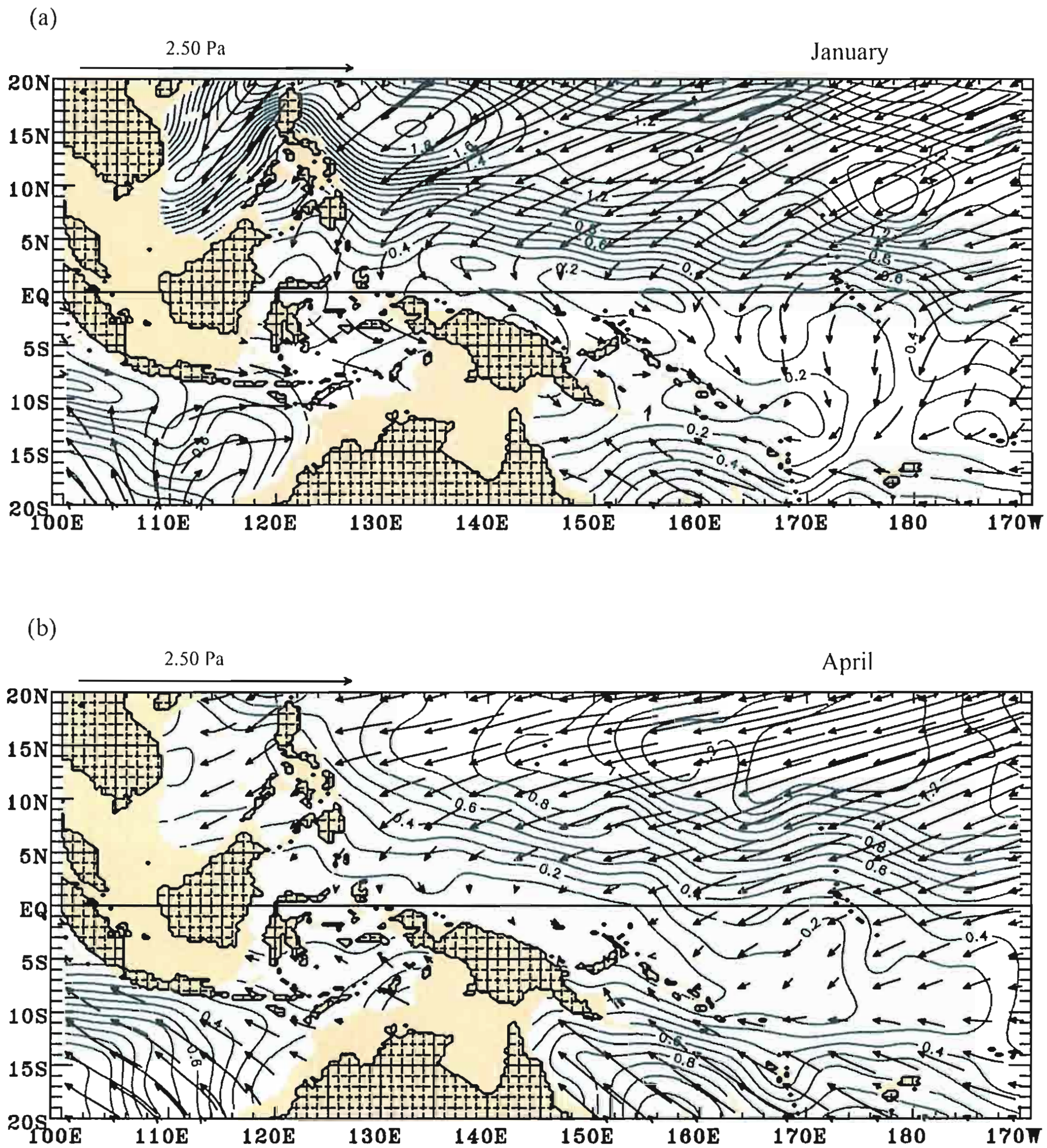
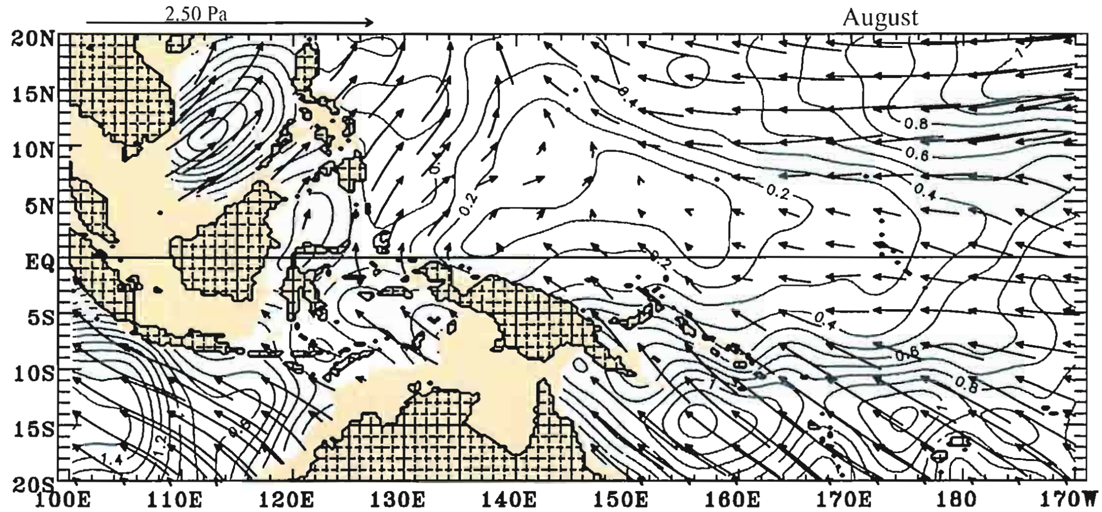


Figure 8: *Hellerman and Rosenstein* [1983] smoothed monthly wind stress and wind stress magnitude for (a) January, (b) April, (c) August, and (d) October. Contours are drawn every 0.1 Pa.

(c)



(d)

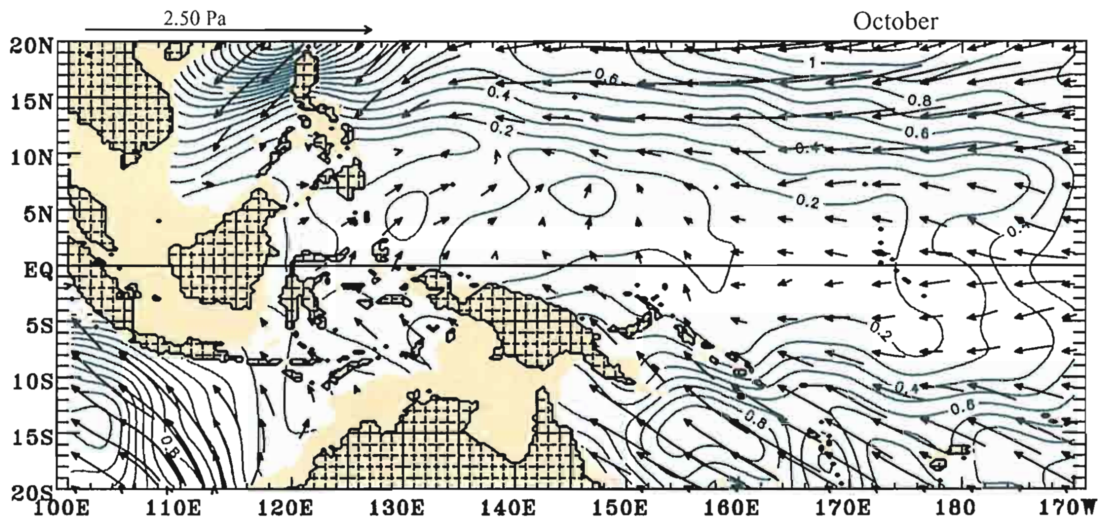


Figure 8--continued.

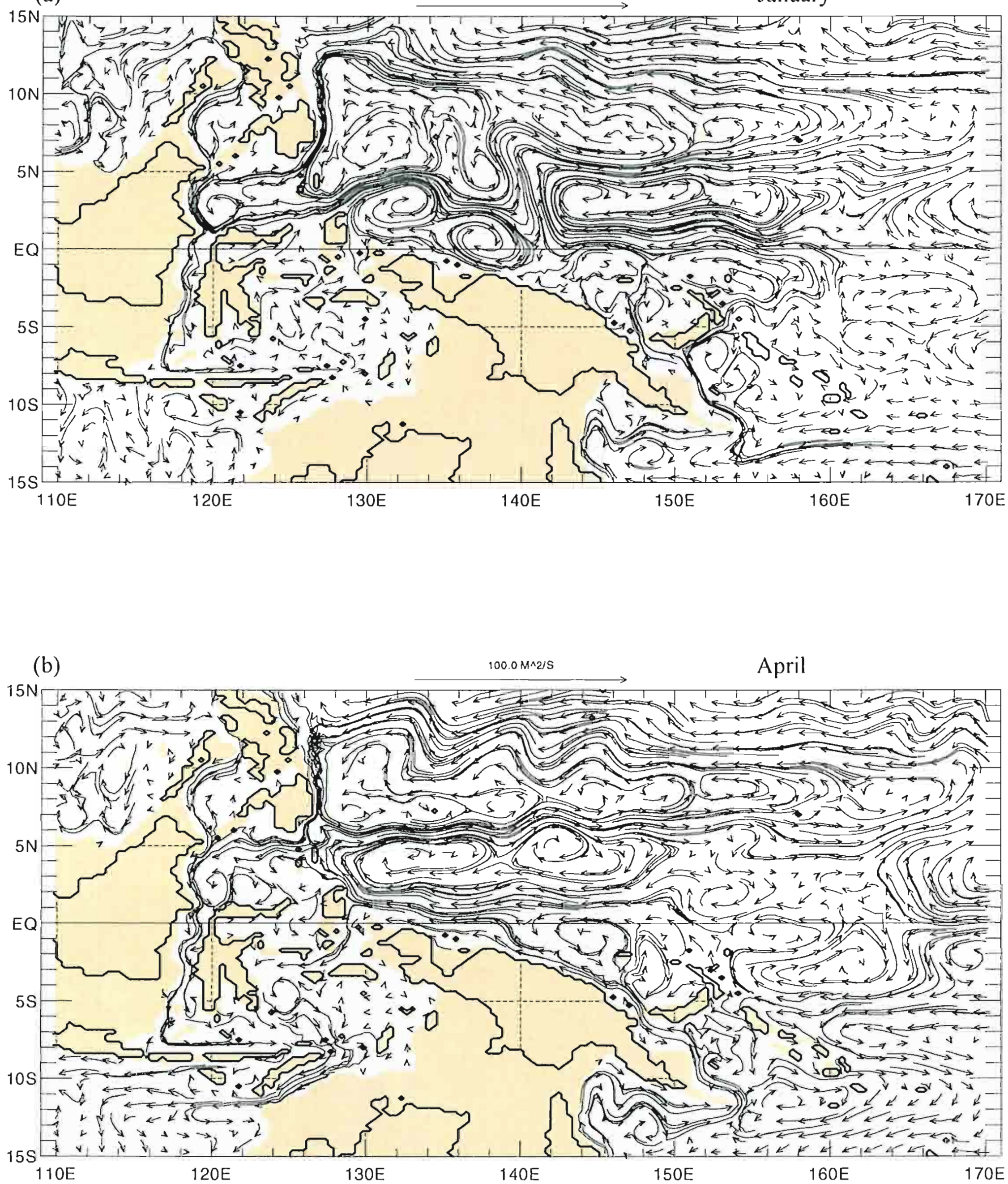
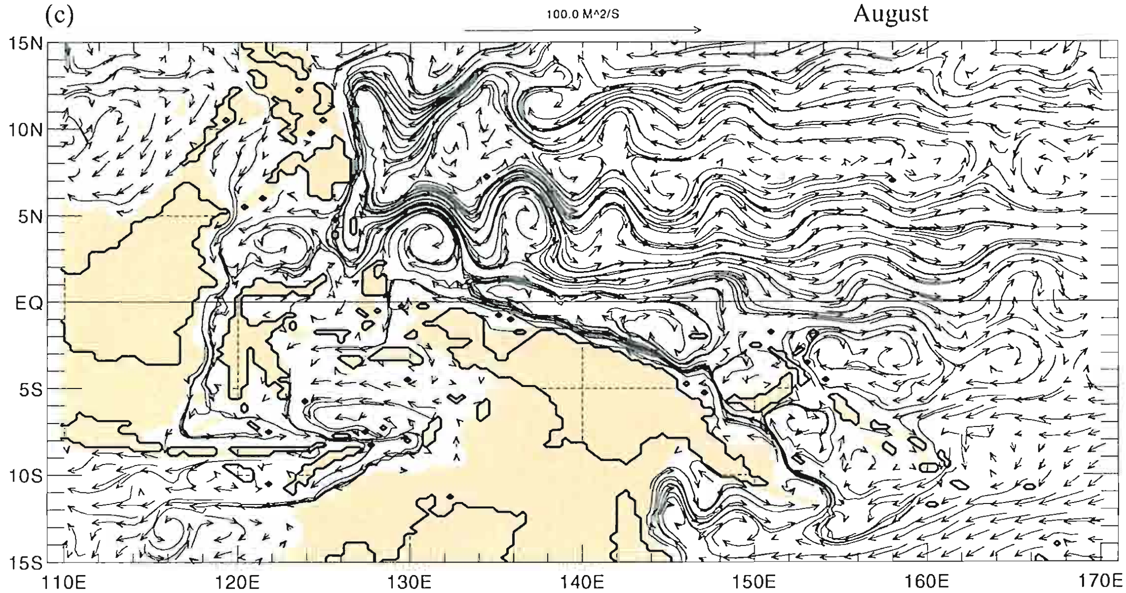


Figure 9: Layer 1 transports from the nonlinear 6 layer simulation with Halmahera from a particular day in (a) January, (b) April, (c) August, and (d) October.

(c) August



(d) October

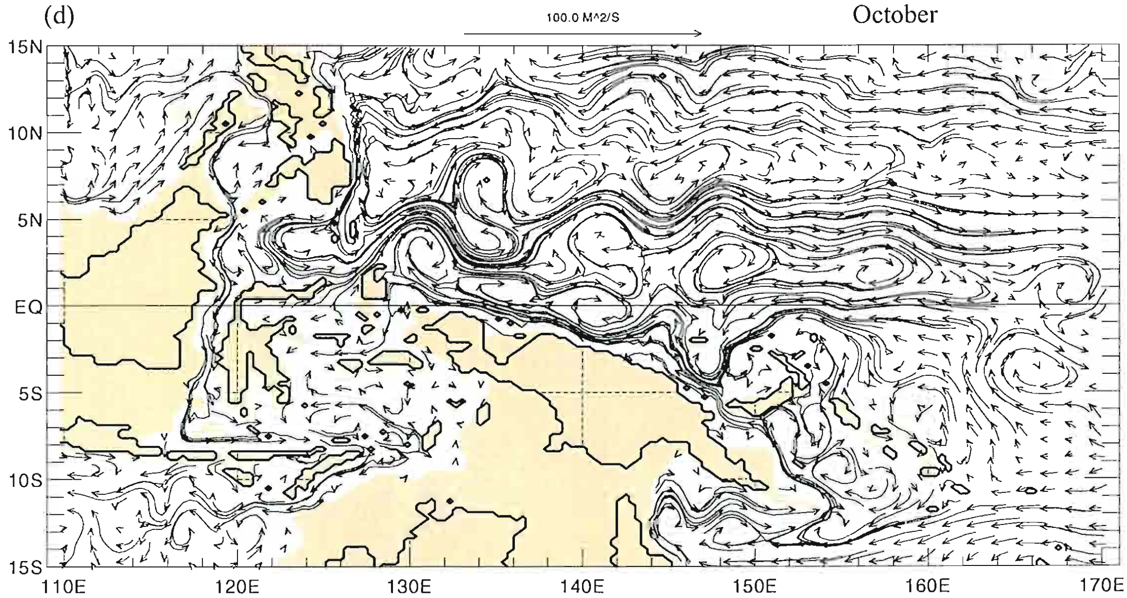
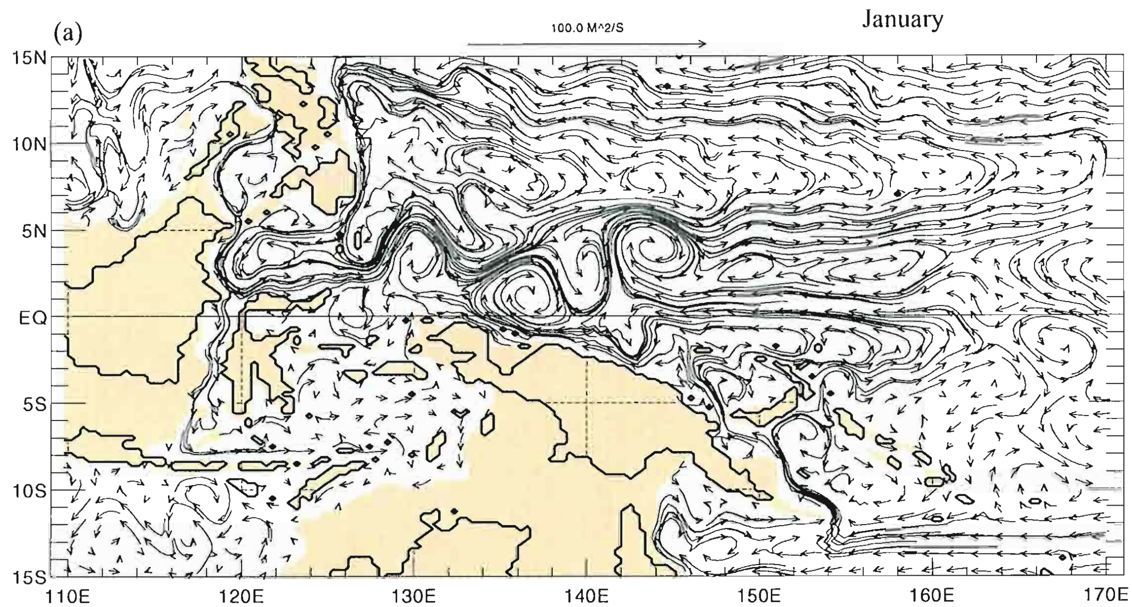


Figure 9--continued.



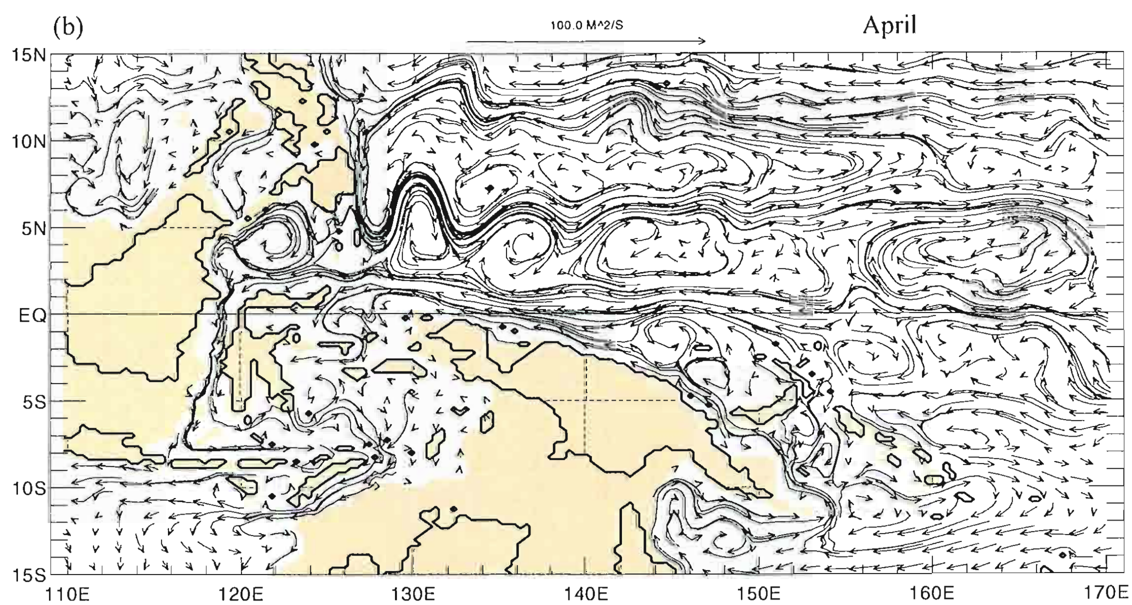
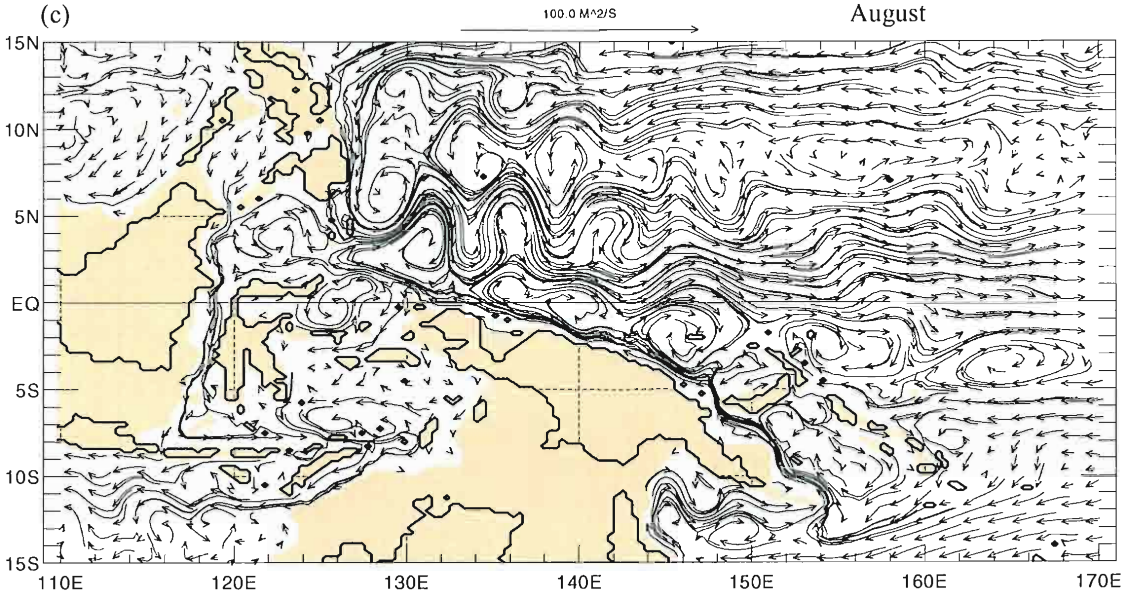


Figure 10: Layer 1 transports from the nonlinear 6 layer simulation without Halmahera from a particular day in (a) January, (b) April, (c) August, and (d) October.

(c) August



(d) October

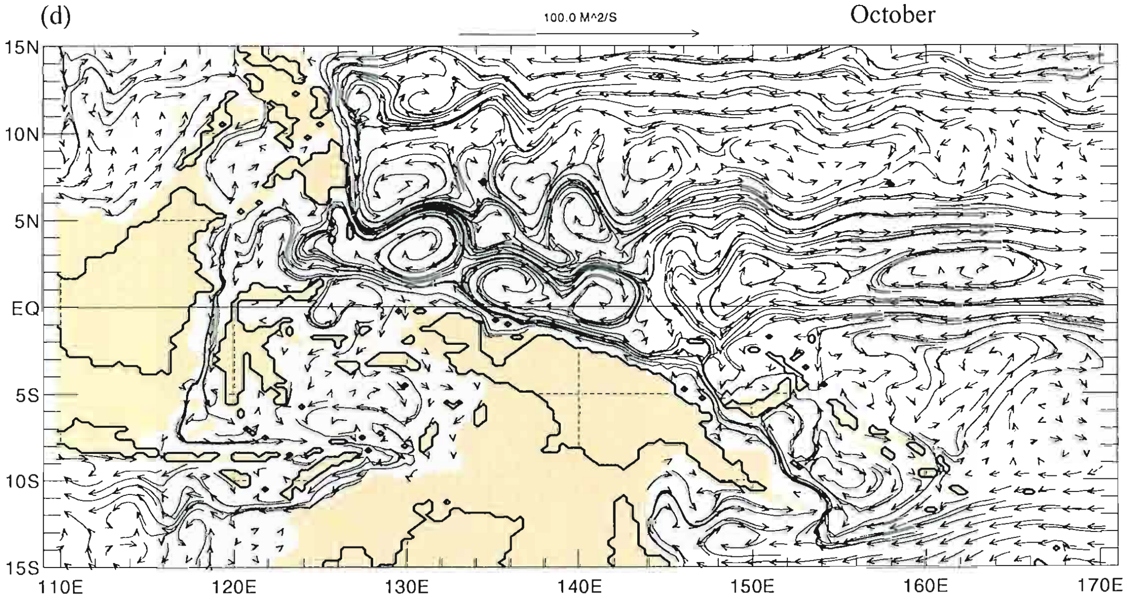


Figure 10--continued.

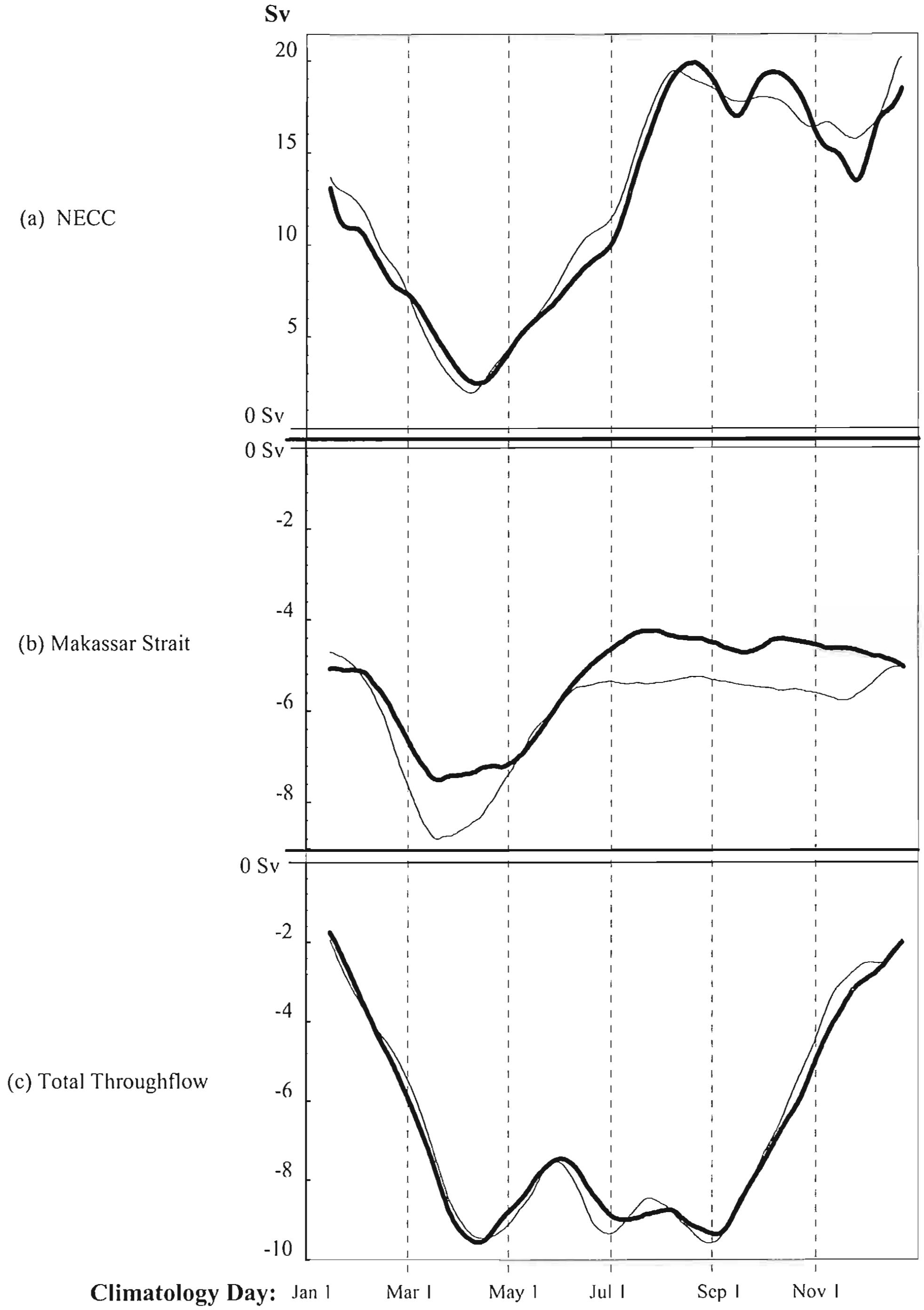


Figure 11: 5 year climatology transports for layer 1 of the nonlinear 6 layer simulations at locations (a) in the NECC, (b) in Makassar Strait, and (c) between Australia and Bali, representing the total throughflow. Heavy lines are the transports for the simulation with Halmahera and thin lines are the transports for the simulation without Halmahera. The transports have been filtered with a 30-day running mean.

winds appear throughout the Indonesian region (Figure 8b). At this time the SEC jet is broad and strong and the center of the HE moves northward to near 5° N. Halmahera begins to have a major impact on the local circulation at this time of the year. This regime continues until the development of the northwest monsoon in the boreal winter (Figures 9c-d, 10c-d).

During the boreal spring, water from the SP flows freely into the Celebes Sea with Halmahera absent, and this strong flow is only partially obstructed by the island's presence. From July through the end of the year, however, there is a much weaker westward flow of SP water to the west of the HE, and the island of Halmahera effectively prevents any from entering the Celebes Sea (Figure 7b). This is in response to the seasonal variation in transport of the NECC (Figure 11a). The strength of the NECC is dependent upon the pressure gradient between the ridge that represents the northern boundary of the SEC and the trough that represents the southern boundary of the NEC. In March and April, the pressure difference in the western tropical Pacific reaches its minimum, and there is a corresponding minimum in the NECC transport. The pressure difference increases to a maximum in September and October, with the NECC transport responding in kind [Atmosphere-Ocean Dynamics, 1982]. The increased volume transport in the NECC is fed by a stronger retroflection of the western boundary currents. Thus, there is a weaker westward flow to the west of the HE, and Halmahera prevents any intrusion of SP water to the Celebes Sea. The seasonal change in the surface layer throughflow transport, driven by the Pacific to Indian Ocean pressure gradient and monsoon winds, and the variation in strength of the NECC, driven by the cross-stream pressure gradient in the western Pacific, together determine when and how Halmahera affects the Indonesian throughflow.

3.3. The Effects of Halmahera on the Composition of the Throughflow

Oceanographers have long used Lagrangian drifters to determine the trajectories for parcels of water in the ocean [e.g., *Shaw and Rossby*, 1984; *Lukas et al.*, 1991]. This approach has also been used successfully in ocean models, advecting buoys in a simulated velocity field [e.g., *Miyama et al.,* 1995]. Information from such experiments allows oceanographers to determine where water from a certain location is going. In the study of Halmahera's impact on the Indonesian throughflow, we are interested in where water flowing through the straits to the Indian Ocean is coming from. More specifically, we are interested in how Halmahera affects the relative contributions of the NP and SP surface water to the Indonesian throughflow. We have shown that the currents around the Indonesian Archipelago are highly variable. We therefore expect that studying the streamlines will not yield much information about the actual paths fluid parcels take through the Indonesian Seas. We instead wish to follow fluid parcels exiting the Indonesian throughflow region back to their sources.

To investigate this issue, we deploy drifting buoys in the modeled ocean near the straits connecting the Indian Ocean to the Indonesian seas and advect them backwards in time in the flow field. This involves numerically solving the initial value problem

$$\frac{d\mathbf{X}}{dt} = \mathbf{u}$$
$$\mathbf{X} = \mathbf{X}_0 \quad \text{at} \quad t = t_0$$

for the time-varying position $\mathbf{X}$ of each buoy with a two-dimensional velocity $\mathbf{u}$. We use a fourth order Runge-Kutta scheme with a time step of 6 hours, starting with the last record of the velocity field and going backwards in time. The initial position of each buoy is $\mathbf{X} = \mathbf{X}_0$ at $t = t_0$, the time that it is deployed. The transport climatology for the layer 1 throughflow shows a perpetual Pacific to Indian Ocean flow (Figure 11c). Consequently, we can assume with reasonable certainty that water immediately to the north of the Lombok, Savu, and Timor Straits will pass through to the Indian Ocean. This is the location we choose to seed the drifting buoys in this experiment (Figure 12).

The sample tracks for the reverse drifters clearly show that the SEC, MC, and South Sulu Sea provide all of the inflow to the Indonesian Seas. Further, they illustrate that the dominant pathway for NP water is the Celebes Sea → Makassar Strait → Flores Sea → Indian Ocean route. When Halmahera is not considered in the simulation, SP water can contribute to the pathway followed by the NP water, or can flow through an eastern pathway following the Seram Sea → Banda Sea → Indian Ocean route. When Halmahera is present in the simulation, all of the SP contribution to the throughflow is forced to take this eastern path, and there is evidence that a small amount of NP water flowing through the Molucca Sea can contribute to this pathway as well. Even though the transport measurements indicate a SP to Celebes Sea flow during the boreal spring when the island is present, this flow is too weak and short lived for any of the water to reach Makassar Strait and contribute to the throughflow.

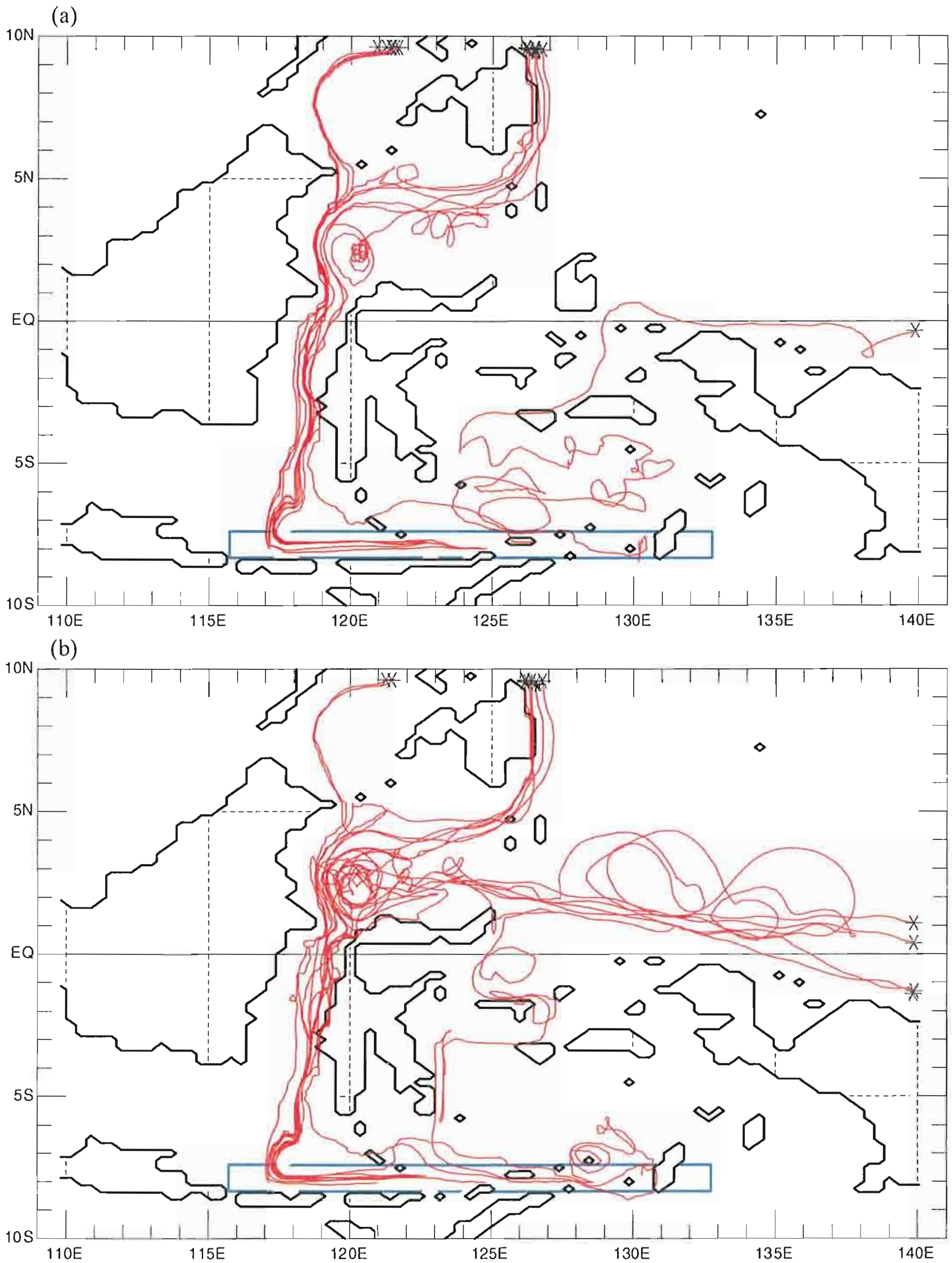


Figure 12: Sample tracks for 12 buoys in the nonlinear simulations (a) with Halmahera and (b) without Halmahera. The buoys were deployed in the surface layer near the exit of the throughflow region (inside the blue rectangle) and advected backwards in time for seven years. Asterisks denote the locations where the buoys entered the region.

We can estimate the relative contributions of the NP and SP to the throughflow using the reverse drifting buoys by tracking a large number of buoys as they travel backwards in time. The full set of Lagrangian drifters consists of 196 buoys dropped at regular intervals 24 times per year for the last three years of a seven year period, yielding a total of 14,112 buoys. Of these, about 30% are found to have entered the throughflow region during the seven-year experiment (Table 3). The rest either enter the region before the experiment, or are beached as they are advected backwards in the reversed flow field. In the simulation without Halmahera, about 69% of the buoys that enter the region during the experiment originate in the NP, and the remaining 31% are from the SP. When Halmahera is considered in the model, roughly 92% of the buoys entering the region come from the NP and only 8% originate in the SP. An estimate of the composition of the throughflow from the general circulation model used by *Wajsowicz* [1993] is 74% NP – 26% SP without Halmahera and 92% NP – 8% SP with Halmahera. This estimate discounts any contribution to the throughflow from SP water that enters the Celebes Sea before exiting to join the NEC. A nonlinear analytical model used by *Nof* [1996] predicts that 11 Sv NP water and 1 Sv SP water (± 5 Sv) will contribute to the flow through a channel cutting a tilted wall that separates two basins, corresponding to the Pacific to Indian Ocean throughflow.

Table 3: Results from the Reverse Lagrangian Drifters Experiment.

Halmahera Present or Not Present	Number of Buoys Entering the Region During the Experiment	Originating in NP		Originating in SP	
		Number of Buoys	Percent of Total	Number of Buoys	Percent of Total
Present	3812	3503	91.9%	309	8.1%
Not Present	4064	2791	68.7%	1273	31.3%

4. Summary and Conclusions

In this study we have examined the pathways for, and relative contributions of, NP and SP water flowing through the Indonesian archipelago to the Indian Ocean using the Navy Layered Ocean Model. We have also examined the role Halmahera plays in directing flow along the pathways, and in determining how much NP and SP water finds its way to the Indian Ocean through the region. The simulations are able to resolve the detailed topography of the region by using a horizontal resolution of up to ¼° between like variables. To examine the linear response of the ocean to wind forcing, we have used a 1.5 layer reduced gravity model. The nonlinear simulations have a vertical resolution of 6 active layers including realistic bottom topography in the deepest layer. All of the simulations are forced by the *Hellerman and Rosenstein* [1983] monthly wind stress climatology.

Sverdrup flow shows that the throughflow is predominantly fed by the MC and water from the Kuroshio that flows through the South Sulu Sea, both sources coming from the NEC. The throughflow pathway for NP water is through the Celebes Sea, Makassar Strait, Flores Sea, and to the Indian Ocean through the Timor, Savu, and Lombok Straits. The jet of water that flows along the northern coast of New Guinea and originates in the SEC bifurcates near the coast of Halmahera with some water from the southern branch leaking into the Banda Sea. The SEC and MC retroflect around the HE and ME, respectively. The island of Halmahera is responsible for preventing a flow of SP water into the Celebes Sea, and for diverting some SP water southward through the Seram and Banda Seas.

The nonlinear model clarifies the different pathways that exist in deeper layers. Layers 3 through 5 combined contribute an annual average of 5.7 Sv to the mean throughflow volume transport of 15.8 Sv. All of this water originates in the SP. Throughout the entire year, Halmahera is responsible for diverting about 3 Sv of this flow southward through the Seram and Banda Seas, while the remainder takes the Celebes Sea → Makassar Strait → Flores Sea → Indian Ocean route. Halmahera has little effect on layer 2, the undercurrent layer. Because of its small north-south extent, the EUC simply flows around the island and then back to the equator before continuing eastward.

Halmahera has the largest impact on the surface water throughflow pathways from March to November. During this part of the year, the throughflow transport is strongest and a jet of water from the SEC flows along the New Guinea coast toward Halmahera. In this regime, Halmahera diverts some SP water southward to follow the Seram Sea → Banda Sea → Indian Ocean route and blocks a flow of SP from entering the Celebes Sea. In March and April, the SEC retroflection into the NECC is weakest. In the absence of Halmahera, water from the SEC jet flows freely into the Celebes Sea. A small amount of SP water seeps into the Celebes Sea around the island when it is present, but the flow is too weak and short-lived for it to contribute to the western pathway. In the late boreal summer and fall, the retroflection of the western boundary currents into the NECC is stronger and Halmahera prevents any SP water from intruding into the Celebes Sea.

A set of simulated Lagrangian drifters travelling backwards in time through the model velocity field indicates the source of the throughflow water and explains the effect that Halmahera has on the composition. A large number of drifters are placed near the exit to the throughflow region at regular intervals during the last three years of a simulated seven year experiment and advected backwards in time. If we choose to estimate the relative contributions of the NP and SP by counting the number of buoys that enter the region from each hemisphere, we find that Halmahera changes the throughflow composition from about 69% NP – 31% SP to 92% NP – 8% SP. This compares favorably with previous estimates [*Wajsowicz*, 1993; *Nof*, 1996]. All water in the NP resided at some time in the SP, but it is freshened by precipitation as it journeys along the equator in the NECC before entering the NP. Thus, Halmahera's presence is a contributing factor to the observed low salinity of the water exiting the Indonesian Seas to the Indian Ocean.

APPENDIX

The following symbols are for the model equations of the Navy Layered Ocean Model used in this study.

$$\nabla = \hat{\mathbf{i}}\frac{1}{a\cos\theta}\frac{\partial}{\partial\phi} + \hat{\mathbf{j}}\frac{1}{a}\frac{\partial}{\partial\theta}$$

a = radius of the Earth (6371 km)

$\hat{\mathbf{i}}, \hat{\mathbf{j}}, \hat{\mathbf{k}}$ = unit vectors positive eastward, northward, and upward, respectively

θ, ϕ = latitude and longitude, respectively

A_H = coefficient of horizontal eddy viscosity

C_k = coefficient of interfacial friction

C_b = coefficient of bottom friction

C_M = coefficient of additional interfacial friction associated with entrainment

$D(\phi, \theta)$ = total ocean depth at rest

f = Coriolis parameter

g = acceleration due to gravity

$$G_{kl} = \begin{cases} g & \text{for } l \le k \\ g - g\left(\dfrac{\rho_l - \rho_k}{\rho_0}\right) & \text{for } l > k \end{cases}$$

h_k = kth layer thickness

h_k^+ = kth layer thickness at which entrainment starts

h_k^- = kth layer thickness at which detrainment starts

H_k = kth layer thickness at rest

$$H_n = D(\phi, \theta) - \sum_{l=1}^{n-1} H_l$$

$\vec{v}_k$ = kth layer velocity

$\vec{\mathrm{V}}_\mathrm{k} = h_k \vec{v}_k$ = kth layer transport

ρ_k = kth layer density, constant in space and time

ρ_0 = constant reference density

$\vec{\tau}_w$ = wind stress

$$\vec{\tau}_\mathrm{k} = \begin{cases} \vec{\tau}_w & \text{for k} = 0 \\ C_k \rho_0 \left| \vec{v}_k - \vec{v}_{k+1} \right| \left(\vec{v}_k - \vec{v}_{k+1} \right) & \text{for k} = 1,\ldots, \text{n - 1} \\ C_b \rho_0 \left| \vec{v}_n \right| \vec{v}_n & \text{for k} = \text{n} \end{cases}$$

$$\omega_k = \begin{cases} 0 & \text{for k} = 0, \text{n} \\ \omega_k^+ - \omega_k^- - \Omega_\kappa \hat{\omega}_k & \text{for k} = 1,\ldots, \text{n - 1} \end{cases}$$

$$\omega_k^+ = \tilde{\omega}_k \left[\frac{\max\left(0, h_k^+ - h_k\right)}{h_k^+} \right]^2$$

$$\omega_k^- = \tilde{\omega} \left[\frac{\max\left(0, h_k - h_k^-\right)}{h_k^+} \right]^2$$

$$\tilde{\omega}_k = \frac{\iint \left(\omega_k^+ - \omega_k^- \right)}{\iint \Omega_k}$$

$\tilde{\omega}_k$ = kth interface reference diapycnal mixing velocity

$\Omega_\mathrm{k}(\phi, \theta)$ = kth interface weighting factor for global diapycnal mixing designed to conserve mass within a layer in compensation for explicit diapycnal mixing due to $h_k < h_k^+$ (i.e., $\omega_k^+ - \omega_k^-$) and net transport through the lateral boundaries of layer k

REFERENCES

Ffield, A., and A. L. Gordon, Vertical mixing in the Indonesian thermocline, *J. Phys. Oceanogr., 22*, 184-195, 1992.

Fieux, M., C. Andrie, P. Delecluse, A. G. Illahude, A. Kartavtseff, F. Mantisi, R. Molcard, and J. C. Swallow, Measurements within the Pacific-Indian oceans throughflow region, *Deep Sea Res., Part 1, 41*, 1091-1130, 1994.

Fine, R. A., R. Lukas, F. B. Bingham, J. J. Warner and R. H. Gammon, The western equatorial Pacific: A water mass crossroads, *J. Geophys. Res., 99*, 25,063-25,080, 1994.

Gill, A. E., *Atmosphere-Ocean Dynamics*, p. 482-483, Academic Press, Inc., San Diego, 1982.

Godfrey, J. S., A. C. Hirst, and J. L. Wilkin, Why does the Indonesian Throughflow appear to originate from the North Pacific?, *J. Phys. Oceanogr., 23*, 1088-1098, 1993.

Gordon, A. L., Interocean exchange of thermocline water, *J. Geophys. Res., 91*, 5037-5050, 1986.

Gordon, A. L., When is "appearance" reality? Indonesian Throughflow is primarily derived from North Pacific water masses, *J. Phys. Oceanogr., 25*, 1560-1576, 1995.

Hautala, S. L., J. L. Reid, N. Bray, The distribution and mixing of Pacific water masses in the Indonesian Seas, *J. Geophys. Res., 101*, 12,375-12,389, 1996.

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

Hurlburt, H. E., J. D. Thomson, A numerical study of Loop Current intrusions and eddy-shedding, *J. Phys. Oceanogr., 10*, 1611-1651, 1980.

Ilahude, A. G., A. L. Gordon, Thermocline stratification within the Indonesian Seas, *J. Geophys. Res., 101*, 12,401-12,409, 1996.

Levitus, S., Climatological atlas of the World Ocean, *NOAA Prof. Pap. 13*, 173 pp., U.S. Govt. Print. Off., Washington, D.C., 1982.

Lukas, R., E. Firing, P. Hacker, P. L. Richardson, C. A. Collins, R. Fine, and R. Gammon, Observations of the Mindanao Current during the Western Equatorial Pacific Ocean Study. *J. Geophys. Res., 96*, 7089-7104, 1991.

Miyama, T., T. Awaji, K. Akitomo, and N. Imasato, Study of seasonal transport variations in the Indonesian Seas, *J. Geophys. Res., 100*, 20,517-20541, 1995.

Molcard, R., and M. Fieux, The Indo-Pacific throughflow in the Timor Passage, *J. Geophys Res., 101*, 12,411-12,420, 1996.

National Oceanic and Atmospheric Administration, ETOP05 digital relief of the surface of the Earth, *Data Announce. 86-MGG-07*, Nat. Geophys. Data Cent., Washington, D. C., 1986.

Nof, D., What controls the origin of the Indonesian throughflow?, *J. Geophys. Res., 101*, 12,301-12,314, 1996.

Richardson, P. L., and T. K. McKee, Surface velocity in the equatorial oceans (20°N - 20° S) calculated from historical ship drifts, *WHOI Tech. Rep. 89-9*, 50 pp., Woods Hole Oceanographic Institution, Woods Hole, MA, 1989.

Schmitz, W. J., Jr., On the world ocean circulation: volume II, the Pacific and Indian Oceans / a global update. *WHOI Tech. Rep. 96-08*, 150 pp., Woods Hole Oceanographic Institution, Woods Hole, MA, 1996.

Shaw, P. T., and T. Rossby, Towards a Lagrangian description of the Gulf Stream, *J. Phys. Oceanogr., 14*, 528-540, 1984.

Shriver, J. F., and H. E. Hurlburt, The contribution of the global thermohaline circulation to the Pacific to Indian Ocean throughflow via Indonesia, *J. Geophys. Res., 102*, 5491-5511, 1997.

Verschell, M. A., J. C. Kindle, and J. J. O'Brien, Effects of Indo-Pacific throughflow on the upper tropical Pacific and Indian Oceans, *J. Geophys. Res., 100*, 18,409-18,420, 1995.

Wajsowicz, R. C., A simple model of the Indonesian Throughflow and its composition. *J. Phys. Oceanogr., 23*, 2683-2703, 1993.

Wajsowicz, R. C., Flow of a western boundary current through multiple straits: An electrical circuit analogy for the Indonesian throughflow and archipelago. *J. Geophys. Res., 101*, 12,295-12,300, 1997.

Wallcraft, A. J., The Navy Layered Ocean Model users guide, *NOARL Rep. 35*, 21 pp., Nav. Res. Lab., Stennis Space Cent., MS, 1991.