Variations in Gyre Closure at the Water Mass Crossroads of the Western Equatorial Pacific Ocean

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ABSTRACT

Assuming the flow over the depth of interest may be described by a 2D streamfunction, \( \psi \), a general analytical method for determining the path of each streamline through a series of channels, which may be western boundary layers or straits, is presented. At each intersection, a channel operator, \( C(b) = \mathrm{mid}(\psi_a, \psi_b, \psi_c) \), is defined, where \( \psi_a, \psi_b, \psi_c \) are the values of \( \psi \) on either side of the channel, and the operator is applied to the bounding streamlines of the flow \( \psi_a \). By assigning water mass properties to each streamline entering the system, the composition of the flow in each channel is determined.

The method is applied to the western equatorial Pacific, where the equatorward western boundary currents, which close the northern and southern wind-driven tropical gyres, meet. Parameters determining whether streamlines of the cold, fresh Mindanao Current and warm, salty South Equatorial Current (SEC) turn east and enter the North Equatorial Countercurrent (NECC), or west and enter the Indonesian archipelago, are identified. Further, their contributions to flow in Makassar Strait, the Maluku passages, and the Halmahera Sea are determined as analytic functions of the values of the streamfunction on Sulawesi and Halmahera, and \( \psi(y) \), the value at the interior edge of the west Pacific boundary layer, at latitudes \( y_N, y_P \). The latitude \( y_N \) depends on the degree of nonlinearity assumed, and is defined in general terms as the northernmost of either the latitude of the northern tip of Halmahera or the northernmost latitude at which ocean interior streamlines of the NECC originate from the SEC. The latitude \( y_P \) is that of the northern tip of Irian Jaya.

In general, outside parameter ranges where the archipelago inflow is from a single source, the model gives that the fractional contributions to the inflow, and so NECC, are less sensitive to variations in the west Pacific, the larger the throughflow. Also, the larger the throughflow, the more South Pacific component is present in the archipelago inflow, and so the fresher the NECC, for given conditions in the western equatorial Pacific. Interestingly, the model’s Indonesian channels act as a dynamic filter on the inflow with that from the North (South) Pacific entering through the western (eastern) channels, which is consistent with observations.

Taking the single channel representation of the Indonesian archipelago so that the fractional contributions are a function of \( \psi = \psi(y) \) only, the Sverdrup streamfunction for the Pacific is used to represent variations in \( \psi \), on interannual to interdecadal timescales. For Florida State University (FSU) wind stresses from 1961 to 1998, there is substantial variability in \( \psi \) that implies significant composition variations on all timescales considered irrespective of the choice of throughflow magnitude. As expected, the archipelago in-flow composition is dominated by the North Pacific contribution, the more northerly the choice of \( y_P \). In contrast, wind stresses derived from European Centre for Medium-Range Weather Forecasts 10-m winds for the period 1987–95 yield a Sverdrup streamfunction that varies little over possible latitudes of \( y_N \), and importantly \( \psi \) is mainly positive over these latitudes giving a wholly SEC-fed archipelago inflow, and so a relatively fresh NECC. A further contrast is provided by wind stresses derived from SSM/I data for the period 1988–96. These yield a Sverdrup streamfunction, which varies little with time over equatorial latitudes, but takes on substantial negative values, so that the archipelago inflow is almost wholly fed by the Mindanao Current, and the NECC is relatively salty.

Insufficient salinity data exist to confirm or refute the estimated FSU-based composition variations on interannual and intradecadal timescales. However, the interdecadal signal of a tendency toward a greater SEC contribution over the last 15 years can be substantiated. Salinity profile data from the National Oceanographic Data Center show a fresher western equatorial Pacific in the region of the SEC and its retroflexion into the NECC in the epoch 1981–95 compared with the epoch 1966–80. The Pacific entrance to the Indonesian archipelago is saltier in the later epoch.

1. Introduction

The western equatorial Pacific is the meeting point of the equatorward western boundary currents, which close the northern and southern wind-driven tropical gyres. Streamlines from these currents either connect with those of the eastward North Equatorial Countercurrent (NECC) and Equatorial Undercurrent, or turn westward into the Indonesian archipelago, and so into the Indian Ocean. Fine et al. (1994) described the region as a water mass crossroads, as the Mindanao Current is typically colder and fresher than the South Equatorial Current (SEC) and New Guinea Coastal Current over
the thermocline, due to ventilation in the North Pacific subtropical gyre.

The importance of establishing the manner of gyre closure in the western equatorial Pacific lies in its impact on the stratification of the Indian Ocean, as described by Godfrey (1989) and Hirst and Godfrey (1993), and in refining our understanding of the heat and freshwater budgets of the Pacific and Indian climate system since a throughflow fed by the Mindanao Current implies a compensatory cross-equatorial mass transport in the Pacific Ocean, whereas one fed by the SEC does not require interhemispheric transport. The fractions of Mindanao Current and SEC that enter the Indonesian archipelago have been the subject of much debate; see Godfrey et al. (1993) and Wajsowicz (1993b) for example. Gordon (1995), using data from the Arus Lintas Indonesia (ARLINDO) cruises, notes that over the thermocline, the western passages of the archipelago, in particular Makassar Strait, contain North Pacific water mass whereas the eastern passages contain South Pacific water mass. As the observed southward transport through Makassar Strait is much greater than through the Maluku passages and the Halmahera Sea, the throughflow is considered to be of predominantly North Pacific water mass.

To date, studies have only investigated the throughflow’s impact on the climate in terms of mass transport in open and closed archipelago scenarios. The question of the effect of any variability in the water mass source remains unanswered, as no variability has been documented. Wajsowicz (1999), in trying to understand why the tropical gyres closed in the Parallel Ocean Climate Model (POCM) run by A. J. Semnter and colleagues at the Navy Postgraduate School, Monterey, so that the thermocline waters of the archipelago were fed by the SEC, found that wind stress variations over the tropical Pacific could imply variations in gyre closure in the western equatorial Pacific with significant variations in the water mass composition of the throughflow, and NECC, on timescales from interannual to interdecadal.

In this study, the simple streamfunction composition model of Wajsowicz (1993b) is revisited in sections 2 and 3 and extended to include the effect of nonlinear dynamics in western boundary layers and more complex geometries. Nonlinearity is incorporated as “features” of the western boundary layer, specifically overshooting and recirculation in the form of a stationary eddy. The concept results in analytical composition fractions expressed as a function of latitude $y_N$, defined as the more northerly of the northern tip of Halmahera or the northernmost latitude at which streamlines of the NECC are connected to those of the SEC. In section 3, analytic expressions for the composition in each of the major entrance channels of the archipelago are derived to enable a more thorough comparison with data, as they become available.

The importance of $y_N$ is revealed in section 4 when the Sverdrup streamfunction is used in conjunction with the simple composition model. First, the Sverdrup streamfunction is calculated from Florida State University (FSU) data for 1961–98. These streamlines undergo considerable latitudinal excursions with time over the equatorial waveguide in the western Pacific. However, the amplitude of the excursions diminishes considerably poleward of the waveguide. Hence, the more northerly $y_N$, the less $\psi(y_N)$ varies with time, and so the less the composition fraction varies. Repeating the calculations using European Centre for Medium-Range Weather Forecasts (ECMWF) 10-m winds for 1987–95 and Special Sensor Microwave/Imager (SSM/I) surface winds for 1988–96 gives gyre closures, and hence compositions, at opposite extremes of the range, namely throughflow wholly fed by the SEC and Mindanao Current respectively for typical values of $y_N$.

Evidence of variability in gyre closure in the western equatorial Pacific is sought in the salinity data archives of the National Oceanographic Data Center in section 5. There is insufficient data to qualitatively assess the interannual and intradecadal variability, but the prediction of a more salty archipelago and fresher western equatorial Pacific since the early 1980s by the simple model forced by FSU data is supported. A summary of results and discussion is provided in section 6.

2. Simple gyre closure and composition model

Salient features of the western equatorial Pacific Ocean, Indonesian archipelago, and eastern equatorial Pacific Ocean are shown in Fig. 1. It is supposed that the flow field integrated over the depth of interest can be represented by a 2D streamfunction $\psi$, such that $u = -\partial \psi / \partial y$, $v = \partial \psi / \partial x$. Assuming, without loss of generality, $\psi = 0$ on the Americas and Asian continent, then the anticlockwise northern tropical gyre formed by the westward North Equatorial Current (NEC), the Mindanao Current, an equatorward western boundary current, and the eastward North Equatorial Countercurrent is composed of streamlines with negative values of $\psi$. The value of $\psi$ on the Australian continent, $\psi_{\text{A}}$, is typically negative corresponding to a southward Indonesian throughflow. Hence, the clockwise southern tropical gyre formed by the westward and equatorward SEC and eastward South Equatorial Countercurrent (SECC) is composed of streamlines with positive values of $\psi$ flanked on the western edge of the SEC by streamlines with negative values. The boundary between the northern and southern tropical gyres is the streamline upon which $\psi = 0$, which joins the zero streamline along the coast of the Americas. In the ensuing analysis, the 200-m isobath is taken as the boundary of the various islands, and so Irian Jaya–Papua New Guinea (PNG) is assumed part of the Australian continent, and Java, Kalimantan, and the Philippines assumed part of the Asian continent; this is reasonable as there is little energy at time periods longer than annual to force significant flow through their adjacent straits. The islands of Halmahera...
Fig. 1. Schematic of the western equatorial Pacific Ocean including the Indonesian archipelago and eastern equatorial Pacific Ocean, showing the major landmasses and surface currents. Ocean depths shallower than 200 m are shaded light gray. Assuming the flow integrated over a certain depth can be described by a 2D streamfunction $\psi$, then $\psi$ is assumed to take the values 0 on the American and Asian continents shaded black, and $\psi_A < 0$ on the Australian continent shaded dark gray. In the models developed herein, the islands within the archipelago, shaded mid gray, are assumed either distinct or part of the adjacent continents. For example, on Halmahera and Sulawesi, $\psi = \psi_H$ and $\psi_S$, respectively, which are assumed either equal or different from $\psi_A$.

and Sulawesi upon which $\psi$ takes the values $\psi_H$, $\psi_S$ respectively, are assumed distinct.

Following Wajsowicz (1993b), it is supposed that $\psi$ is a known function $\psi_F$ along the interior edge of the Pacific western boundary layer. The streamlines entering the western boundary layer of the northern tropical gyre are assigned the appellation North Pacific (NP), assuming the water mass that they encompass has characteristics of that region. Similarly, those entering the western boundary layer of the southern tropical gyre are denoted South Pacific (SP). The task is then to determine which streamlines exit the western boundary layer to form the countercurrents, which continue westward into the archipelago and form the throughflow. By $y_1$, the Mindanao Current is 12 Sv of which 10 Sv may potentially form the throughflow, specifically the streamlines from 0 to $-10$ Sv next to the coast. However by $y_2$, the Mindanao Current is reduced to only 5 Sv with 7 Sv having exited the western boundary layer to form the NECC. These 5 Sv consist of streamlines, all of which may form the throughflow. By $y_3$, the Mindanao Current has completely exited the western boundary layer to form the NECC; none makes up the throughflow. Hence, the value of $\psi_F$ at the southern tip of the Philippines determines which streamlines of the Mindanao Current exit the western boundary layer to form the NECC, and which enter the Celebes Sea. Some streamlines will just enter the sea and exit farther south to join the NECC. Hence, the determining latitude for the fraction of the Mindanao Current entering the archipelago is the northern tip of the Australian continent, $y_N$. The streamlines of the Mindanao Current that make up the throughflow are those with values from 0 to
of the boundaries; so once again only 5 Sv of the 2
on the bounding landmasses of the strait under the
can be represented by a single channel. In section 3,
to the Asian continent, whereas the SP water mass
has low absolute value streamlines and flows adjacent
to the northernmost tip of the Australian continent.

In a mixed composition throughflow, the NP water mass
archipelago with SP waters to the east of the NP waters.

SEC crosses the equator and enters the northern tropical
by the Mindanao Current. An equivalent amount of the
port implied when a fraction of the throughflow is fed
as showing senarios for fixed continents with different
y
2
12 Sv on the boundaries,
5 to 0 Sv. These results can
be generalized by noting that, if \( \psi_c \), \( \psi_n \) are the values
on the boundaries of the strait, then streamlines of the
throughflow with values between mid(0, \( \psi_c \), \( \psi_n \)) and
mid(0, \( \psi_c \), \( \psi_n \)) pass through the strait.

b. Nonlinear western boundary layer dynamics

In Godfrey (1989) and Wajsowicz (1993b), as above, it
was assumed that relative vorticity is destroyed at the
latitude of creation within the western boundary layer,
so there is no recirculation gyre nor overshooting of
boundary current at the tip of a landmass. Godfrey et
al. (1993), however, noted that this implied a predomi-
antly SEC-fed throughflow in the climatological
mean, taking \( \theta_r \) as that given by the Sverdrup stream-
function derived from Hellerman and Rosenstein (1983)
wind stresses. They noted that higher order dynamics,
for example viscous effects or barotropic instability,
were required to make the SEC retroreflect into the NECC
rather than proceed westwards into the archipelago. In
the uppermost panel, \( \psi \) varies linearly in \( x \) over the boundary
layer corresponding to the case considered in section
2a; the throughflow is fed predominantly by the SEC.
The second panel shows the effect of weak nonlinearity;
the schematic SEC and Mindanao Current overshoot
their adjacent landmasses and the weak Halmahera and
Mindanao Eddies further perturb the streamlines. The
throughflow composition factor, NP:SP, is increased
from 1:9 to 3:7.

The third panel of Fig. 3 shows the effect of strong
nonlinearity with the boundary currents overshooting
their respective landmasses such that they overlap lati-
dudinally, but there is no eddy. The fractional composi-
tion is shifted further in favor of the North Pacific.
The resulting fraction depends on the assumed zonal
staggering of the currents, or associated landmass. The
observed staggering of the Philippines to the west of
Irian Jaya±PNG produces a composition with a greater
fraction from the North Pacific. The effect of including
the Mindano and Halmahera eddies as well is shown in
the bottom panel of Fig. 3. The perturbation to the
streamlines is sufficient to enhance the North Pacific
contribution in the case of the observed staggering, but
the effect is reversed for the oppositely staggered land-
masse. Results for the two types of staggering have
been shown to emphasize the importance in modeling
studies of simulating well the location and size of the
eddies.

In the examples shown in Fig. 3, the NP:SP ratio
depends on the value of \( \psi_r \) at the latitude \( y_N \), whose
definition has been generalized to the northernmost
Fig. 2. Schematics of the streamfunction describing flow within western boundary layers and straits. In (a), (b), and (c) the streamfunction $\psi$ is specified as zero on the Asian continent and $\psi_F(y)$ at the interior edge of the western boundary layer. The throughflow is assumed to be 10 Sv southward so that $\psi$ on the Australian continent is $-10$ Sv and streamlines with values between 0 and $-10$ Sv may form the throughflow. The streamfunction within the western boundary layer is determined according to the rule that relative vorticity is destroyed at the latitude of creation so that $\psi$ increases/decreases monotonically with $x$ in the boundary layer. The Asian western boundary layer adjacent to the Philippines is shown in (a) with the Mindanao Current entering from the top. Assuming $\psi_F(y) < 0$, then its magnitude at latitude $y$ is $\psi_F(y)$ and streamlines with values from 0 to mid($0$, $\psi_F(y)$, $-10$ Sv) may continue southward to make up the throughflow. Hence at $y_1$, the Mindanao Current is 12 Sv and streamlines with values from 0 to $-10$ Sv may make up the throughflow, but by $y_2$, 7 Sv of the Mindanao Current has exited the western boundary layer into the NECC, and only 5 Sv is available to make up the throughflow. If $\psi_F > 0$ as at $y_3$, then all of the Mindanao Current exits into the NECC, and none enters the archipelago. The Australian western boundary layer is shown in (b) with the SEC entering from the bottom. Assuming $\psi_F(y) > -10$ Sv, then its magnitude at latitude $y$ is $\psi_F(y) + 10$ Sv, and streamlines with values from $-10$ Sv to mid($0$, $\psi_F(y)$, $-10$ Sv) may continue northward to make up the throughflow. Hence at $y_1$, the magnitude of the SEC is 13 Sv with streamlines from 0 to $-10$ Sv flowing northward potentially to make up the throughflow, but by $y_2$, 8 Sv of the SEC has exited the boundary layer, 3 Sv into the SECC and 5 Sv into the NECC, so that only 5 Sv remains to make up the throughflow. If $\psi_F(y) < -10$ Sv, as at $y_3$, then all of the SEC enters the countercurrents and none enters the archipelago. The combined boundary layers with a single channel archipelago is shown in (c); the meridional extent of the Australian continent represented by a thin rectangle corresponds to latitudes $y_1$, $y_2$, and $y_3$ in (a) and (b) in the panels from left to right respectively. Four types of water mass are identified by shading: In order of increasing darkness they are NP that circulates within the northern tropical gyre, NP that flows through the archipelago, SP that flows through the archipelago or enters the northern tropical gyre, and SP that circulates within the southern tropical gyre. Throughflow streamlines in straits with the same total transports, but different bounding values of $\psi$ are identified in (d).

(southernmost) of either the northern tip of Irian Jaya–PNG or the northernmost (southernmost) latitude at which a streamline from the ocean interior connects with one from the SEC (Mindanao Current) for NW–SE staggering (NE–SW staggering). In the linear case, $y_N$ is the northern tip of Irian Jaya, but in the strongly nonlinear case with NW–SE (NE–SW) staggering, $y_N$ is the northern (southern) extent of the Mindanao (Halmahera) eddy. In section 4, the effective $y_N$ is taken as $2^\circ$ of latitude north of Halmahera, based on observed historical ship-drift currents, current meter measurement, and buoy tracks during the Western Equatorial Pacific Ocean Climate Studies (WEPOCS), as described in Lukas et al. (1991).
COMBINED ASIAN & AUSTRALIAN WESTERN BOUNDARY LAYERS: MINDANAO & SOUTH EQUATORIAL CURRENTS

(d)

Fig. 2. (Continued)
c. Two mechanisms to change the throughflow composition

Changes in $y_N$ provide a second mechanism for changing the throughflow composition; the first, shown in Fig. 2c, was changes in $\psi_F$. The two mechanisms, which will be discussed further in section 5 in the context of observed changes in salinity, are summarized in Fig. 4. In Fig. 4a, $y_N$ is the same in both upper and lower panels, but the streamfunction at the interior edge of the western boundary layer, $\psi_F$, is more negative at a given latitude in the lower panel. This results in a fresher throughflow with the northern extent of SP water mass in the NECC unchanged. In Fig. 4b, $y_N$ is the same in both upper and lower panels, but the SEC retroreflects farther north in the lower panel. This results in a fresher throughflow with an increase in the northern extent of SP water mass in the NECC.

It should be emphasized that Figs. 4a, b are schematics designed to illustrate concepts and that in practice a change in $\psi_F$ may necessarily result in a change in $y_N$ and throughflow magnitude. However, it should be noted that a change in wind stress over a region that does not affect $\psi_F$ over possible latitudes of $y_N$, or $y_N$ itself, could produce a change in throughflow magnitude. Also, a change in wind stress over a region that does not affect the throughflow magnitude or $\psi_F$ over the latitudes of possible $y_N$ could change the strength of the SEC, and so $y_N$.

3. Fractional distribution in single- and multiple-channel models

In the previous section, the throughflow composition was determined for a single-channel representation of the archipelago. In reality, there are three major entrances to the archipelago. In two, flow enters the Celebes Sea from the Pacific, and then passes to either the west or east of Sulawesi, that is, through Makassar Strait or the Maluku passages. The third entrance is via the Halmahera Sea. Below, four geometric configurations are considered to illustrate the role of each island in determining the throughflow composition. An understanding of this is important as coarse-resolution climate GCMs cannot resolve all of the islands and straits in the archipelago, and compromises must be made. Also, for comparison with observations, as in section 5, and in designing monitoring programs, it is useful to have a model of the composition in each strait.

The four configurations considered are shown in Fig. 5 along with an example streamfunction field; the net NP:SP composition in each strait is given in the top left-hand corner of each plot. In order to determine the North Pacific and South Pacific fractions that make up the archipelago inflow and NECC, the fate of the streamlines, whose values span those of the throughflow, needs to be calculated at each junction of currents shown in Fig. 5. It is useful to nondimensionalize the streamfunction $\psi$ on its value on the Australian continent, $\psi_A$, whose absolute value is the magnitude of the throughflow. Therefore the relevant streamlines have nondimensional values between 0 and 1. Hereafter $\psi$ denotes the nondimensional streamfunction, and $\phi^\psi$ will be used to denote the dimensional form.

a. Single channel

For the case of a single channel, for example as shown in Fig. 5a, North Pacific streamlines in the Mindanao Current with values between 0 and $\psi_N$ approach the entrance to the channel at latitude $y_N$, where $\psi_N = \psi_F(y_N)$. A streamline enters the channel if its value lies between 0 and 1. Therefore, defining the operator $M$ on a variable $\psi_n$ by

$$M(\psi_n) = \text{mid}(0, \psi_n, 1) = a,$$

then the relevant streamlines of the Mindanao Current that approach the entrance to the channel have values $M(\psi_n)$, that is, 0 to $N$, and those of the SEC have values $N$ to 1. Therefore, the fractional contributions of NP and SP water mass to the archipelago inflow are, respectively,

$$F_{NP} = N, \quad F_{SP} = 1 - N, \quad (3.1)$$

as found in dimensional form in section 2. In Fig. 5a, $\psi_N = 0.4$, therefore the fractional composition ratio $F_{NP}:F_{SP}$ is 40:60. In writing (3.1), it is implicitly assumed that $\psi_F < 0$, and that $\psi_F$ is monotonically decreasing between a high in the vicinity of Papua New Guinea and a low in the vicinity of the Philippines. The latter condition can be relaxed to include local extrema with the same result.

The nondimensional relationship (3.1) is plotted in Fig. 6a. The flow is composed wholly of water from
Fig. 4. Two different ways of producing a fresher throughflow. In (a), $\psi_N$, the streamfunction at the interior edge of the western boundary layer changes so that at the determining latitude $y_N$, $\psi_N = \psi_N(y_N)$ is more negative in the lower picture. In (b), $\psi_N$ is unchanged, but the SEC is assumed to retroreflect farther northward in the lower picture; that is, $y_N$ is farther north. The shading of water masses is as in Fig. 2c. Although the throughflow is fresher in the lower picture of both (a) and (b), the mechanisms are different and can be distinguished by noting that the NECC is also saltier in the lower panel of (b) at a higher latitude.

Unfortunately, there are insufficient observations to mark out a time spiral on Fig. 6b. It could be argued that the whole parameter space depicted in Fig. 6 is not realized in practice, as changes in $\psi_N^*$ and $\psi_N^*$ are correlated. However, on timescales for which the island rule, Wajsowicz (1993a), is valid, changes in $\psi_N^*$ could result from changes in the wind stress in the midlatitudes of the South Pacific as well as the equatorial region, whereas those in $\psi_N^*$ are due solely to changes over the equatorial latitudes. In section 4, results assuming variations in $\psi_N^*$ are given by Sverdrup streamfunction variations are discussed for a range of possible throughflow magnitudes.

b. Dual channel: Including Sulawesi

It is straightforward to include Sulawesi in the above model, as it is sheltered from the Pacific interior flow by the Halmahera–Papua New Guinea–Australia landmass (see Fig. 5b). The streamlines of each water mass entering the archipelago, that is, in the western boundary current next to Kalimantan between the latitudes of the northern tips of Halmahera and Sulawesi, is as in the single channel model, namely $[0, N]$ for NP and $[N, 1]$ for SP. It is then a question of determining the direction of the streamlines at the intersection of currents at the latitude of the northern tip of Sulawesi (see Fig. 5b). Define the operator $S_\psi$ on $a$ by
Fig. 5. Schematics of the four types of geometry considered in the analytical composition model. A single-channel representation; for example, only Makassar Strait is resolved, the Halmahera Sea and Maluku passages are not, is depicted in (a). A double channel sheltered from the Pacific, for example, the straits either side of Sulawesi are resolved but the Halmahera Sea is not, is depicted in (b). A double channel exposed to the Pacific, for example, the straits either side of Sulawesi are resolved but the Halmahera Sea is not, is depicted in (c). Finally, a model with all three entrances to the archipelago resolved is shown in (d). An example streamfunction, as given by the simple model, is contoured with the western boundary layer scale exaggerated. Streamlines, which have values spanned by the throughflow, are denoted by dash–dot lines. Otherwise positive contours are denoted by solid lines, negative by dashed, and the zero contour by a dotted line. The value of the streamfunction on Sulawesi in (b) and (d), and Sulawesi–Halmahera in (c), is 0.3 that on Australia–PNG, that is, the throughflow. Additionally, in (d), the value of the streamfunction on Halmahera is 0.7 that on Australia–PNG. The ratio of North Pacific to South Pacific composition is 40:60 in (a), (b), and (d), and 30:70 in (c) for the net throughflow. In (a) the mix is 40:60 in Makassar Strait, the only pathway. In (b), (c), and (d) the fraction of the throughflow in Makassar Strait is wholly NP. In (c) and (d) the fraction of the throughflow in the Halmahera Sea is wholly SP. In (b) the mix in the Maluku passages is 10:60. In (d) the mix in the Maluku passages is 10:30.

\[
S_b(a) = \text{mid}(a, b, S),
\]

where \( S = M(\psi_b) \) and \( \psi_b \) is the value of \( \psi \) on Sulawesi; \( a, b \) are the outcomes of the operator \( M \) on any variables \( \psi_a, \psi_b \). Then, the streamlines of NP, SP water mass entering Makassar Strait, which make up the throughflow, are obtained by applying the \( S_0 \) operator to \([0, N]\) and \([N, 1]\) (cf. Fig. 2d). Hence, denoting the fractions of NP, SP water mass in the throughflow in Makassar Strait by \( W_{\text{NP}}, W_{\text{SP}} \) respectively, this yields

\[
W_{\text{NP}} = S_0(N), \quad W_{\text{SP}} = S - S_0(N).
\]

The fractions through the Maluku passages, \( E_{\text{NP}}, E_{\text{SP}} \) are just the remainders. Hence

\[
E_{\text{NP}} = S_1(N) - S, \quad E_{\text{SP}} = 1 - S_1(N),
\]

where the identity

\[
S_0(a) + S_1(a) - S = a,
\]

where \( a \) is the outcome of the operation \( M \) on any variable \( \psi_b \), has been used. Expressions (3.3) and (3.4) could be obtained directly by applying the \( S_0 \) operator to \([0, N]\) and \([N, 1]\), and remembering that \( S_1(0) = S \). Adding (3.3) and (3.4) gives (3.1); that is, as expected, the net throughflow composition is the same as in the single channel model. Sulawesi, sheltered from the Pacific, acts simply as a zonal divider on the incoming streamlines.

The fractional contributions, as given by (3.3) and (3.4), are contoured by lines in Figs. 7a,b respectively. If \( \psi_b \geq 1 \), then all of the throughflow passes through Makassar Strait; none passes through the Maluku passages, which is denoted by cross-hatching in Fig. 7b. If \( \psi_b < 0 \), then all of the throughflow is carried by the Maluku passages, hence the cross-hatched region in Fig. 7a. If a strait carries all of the throughflow, then the fractional composition in the strait is just (3.1) and the regions in Figs. 7a,b correspond directly to Fig. 6a. It
is noteworthy that the transport through Makassar Strait is wholly from the Mindanao Current not only for $\psi_N \geq 1$, $\psi_S \geq 1$, but also for $\psi_N \geq 0$ and $\psi_S > 0$. It is wholly from the SEC for $\psi_N < 0$ and $\psi_S > 0$. In the Maluku passages, the transport is wholly from the Mindanao Current if $\psi_N \geq 1$ for all $\psi_S < 1$. It is wholly from the SEC not only for $\psi_N < 0$, but also for $\psi_N \leq \psi_S < 1$. Therefore, the two pathways may behave differentially, and observation of pure North Pacific water in Makassar Strait does not necessarily imply a net Pacific inflow solely from the Mindanao Current nor conditions in the western equatorial Pacific such that $\psi_N \geq 1$.

Also shown in Fig. 7, using shaded contours, is the composition as a fraction of the throughflow that passes through the particular strait instead of the total throughflow. In Fig. 5b, $\psi_N = 0.4$ and $\psi_S = 0.3$, therefore substituting in (3.3), $W_{NP}, W_{SP}$ is 30:0, and in (3.4), $E_{NP}, E_{SP}$ is 10:60. As shown in Fig. 7a, the flow through Makassar Strait is wholly NP, and small perturbations to $\psi_N$ and $\psi_S$ will not affect the source. In contrast, from Fig. 7b, the flow in the Maluku passages is dominated by the SP source, and the composition is sensitive to small perturbations in $\psi_N, \psi_S$.

The above expressions make no attempt to quantify the composition of any recirculation around Sulawesi. If $\psi_N^* > \psi_S^*$, then there is southward transport $\psi_N^* - \psi_S^*$ in excess of the throughflow through Makassar, which enters the western boundary layer of Sulawesi and is carried northward to reenter Makassar Strait. The composition of this water mass is indeterminate and will depend local conditions, namely, local surface fluxes and mixing.

c. Dual channel: Including Halmahera

The single-channel model also can be readily extended to include Halmahera as a distinct island, as de-
scribed in Wajsowicz (1993b) (see Fig. 5c). The two channels could be Makassar Strait and the Halmahera Sea, or the Maluku passages and the Halmahera Sea. Therefore the terminology used will be the western passage and the Halmahera Sea. Unlike incorporating Sulawesi, in this example the NP, SP contributions to the throughflow may be different, as Halmahera is directly exposed to the Pacific interior flow, and so a new latitude \( y_p \) enters the calculation. For the case of relative vorticity destroyed at the latitude of creation in the western boundary layer, \( y_p \) is the northern tip of Halmahera (previously described as the tip of the Australian continent) and \( y_s \) is the northern tip of Irian Jaya.

The SP throughflow streamlines of the SEC with values between \( P = M(\psi_p) \) and 1 approach the Halmahera Sea. Those with values between 1 and \( H_i(P) \) enter the sea, hence \( E_{SP} \) is the same as in (3.4) but with \( H \) replaced by \( S \) and \( P \) replacing \( N \), where \( \psi_s \) is the value of \( \psi \) on Halmahera and the operators \( H_0, H_1 \) are defined by replacing \( S \) with \( H \) in (3.5). Streamlines with values between \( H_i(P) \) and 0 are replaced by those with values from \( H \), which is derived by considering the fate of the NP water mass, which contributes to the throughflow if both Sulawesi and Halmahera are distinct islands, as shown in Fig. 5c. The total North and South Pacific contributions to the throughflow are as in Fig. 5c. For Makassar Strait, the North and South Pacific contributions, \( W_{SP} \), \( W'_{SP} \) are obtained by applying the \( S_0 \) operator to (3.8), yielding

\[
W_{SP} = H_0[H_4(N) - P)].
\]

(3.6)

The NP contribution through the western passage, \( W_{SP} \), is the same as in (3.3) but with \( H \) replaced by \( S \). The NP water mass, which contributes to the throughflow via the Halmahera Sea, is given by

\[
E_{NP} = H_1[H_1(N - H_0(N))].
\]

(3.7)

which is derived by considering the fate of the NP streamlines with values from \( H_0(N) \) to \( N \) as they turn southward [cf. (3.6)].

Summarizing and noting identities such as

\[ H_1[\ldots H_1[\ldots] = H, \]

the fractional contributions through the western passage are

\[
W_{NP} = H_0(N), \quad W_{SP} = H - H_0[\max(N, P)]
\]

(3.8)

and through the Halmahera Sea they are

\[
E_{NP} = H_1[\min(N, P)] - H, \quad E_{SP} = 1 - H_1(P).
\]

(3.9)

Under the assumption \( \psi_s > \psi_p \), (3.8) reduces to the equivalent of (3.3), and (3.9) reduces to the equivalent of (3.4) but with \( P \) replacing \( N \). Therefore the fractional contributions through the western strait are independent of \( P \); and those through the Halmahera Sea are independent of \( N \). Plotting (3.8) and (3.9) would yield Fig. 7 with the \( x \) axis defined as \( \psi_p \) in both (a) and (b) and the \( y \) axis defined as \( \psi_s \) in (b). Figure 7a would describe the western passage, and Fig. 7b the Halmahera Sea.

In Fig. 5c, \( \psi_N = 0.4, \psi_P = 0, \psi_H = 0.3 \) (= \( \psi_s \)). Substituting in (3.8) gives \( W_{SP} = 30:0 \) and in (3.9) gives \( E_{SP} = 0:70 \). Therefore, the throughflow is saltier than in the previous examples, and the two channels each carry a pure source. Looking at the regime maps, Fig. 6, small perturbations to \( \psi_s, \psi_p, \psi_H \) will not alter the pure source flows.

d. Triple channel: Including Halmahera and Sulawesi

The next step is to combine the previous models and determine expressions for the fractional contribution to the throughflow if both Sulawesi and Halmahera are distinct islands, as shown in Fig. 5d. The total North and South Pacific contributions to the archipelago inflow are as in Fig. 5c. For Makassar Strait, the North and South Pacific contributions, \( W'_{SP} \), \( W''_{SP} \) are obtained by applying the \( S_0 \) operator to (3.8), yielding

\[
W'_{SP} = S_0[H_0(N)],
\]

\[
W''_{SP} = \min(S, H) - S_0[H_0[\max(N, P)]].
\]

(3.10)

For the Maluku passages, the contributions \( C_{NP}, C_{SP} \) are just the quantities in (3.8) minus those in (3.10), namely,

\[
C_{NP} = S_1[H_0(N)] - S,
\]

\[
C_{SP} = \max(S, H) - S_1[H_0[\max(N, P)]].
\]

(3.11)

where the identity (3.5) has been applied.

For the Halmahera Sea, the contributions are as in (3.9); namely,

\[
E_{NP} = H_1[\min(N, P)] - H,
\]

\[
E_{SP} = 1 - H_1(P).
\]

(3.12)

The fractional contributions (3.10)–(3.12) are plotted in Fig. 8 as functions of \( \psi_s \) (= \( \psi_p \)) and \( \psi_s \) for \( \psi_H = 0.6 \), which should be compared with Fig. 7. In Makassar Strait, Fig. 8a, the throughflow component is wholly NP in the parameter range \( \psi_s \), \( \psi_s \geq \psi_p \), which contrasts with the converse case in Fig. 7a. It is wholly SP for \( \psi_s \geq 0 \), as in Fig. 7a. In the Maluku passages, Fig. 8b, there is no throughflow streamline for \( \psi_s \leq \psi_H \), which contrasts with the condition \( \psi_s \geq 1 \) in Fig. 7b. It is wholly NP for \( \psi_H \geq \psi_s \), \( \psi_s \leq \psi_H \) in contrast with the condition \( \psi_s \geq 1 \) in Fig. 7b. It is wholly SP for \( \psi_H \geq \psi_s \), \( \psi_s \leq \psi_H \) in Fig. 7b.

The fractional contribution in the Halmahera Sea is independent of \( \psi_s \), and is given by that on the ordinate through \( \psi_s \) in Fig. 7b with the \( y \) axis redefined as \( \psi_s \); see Fig. 8c.

Returning to Fig. 5d, where \( \psi_N = 0.4, \psi_P = 0, \psi_H = 0.7 \), and \( \psi_s = 0.3 \). Substituting in (3.10) gives \( W'_{SP}, W''_{SP} \) as 30:0 and in (3.11) gives \( C_{NP}, C_{SP} \) as 10:30. Small perturbations to the specified \( \psi \) values will not change the purely NP composition in Makassar Strait, but will affect the fractions of the mixed flow in the
Fig. 8. The fractional composition for the triple-channel model, given by (3.10)–(3.12), is plotted in (a) for Makassar Strait and (b) for the Maluku passages, as a function of $\psi_S$ and $\psi_H$ for $\psi_P = 0.6$, assuming $\psi_S < \psi_N$. It is plotted in (c) for the Halmahera Sea as a function of $\psi_S$ and $\psi_P$ for $\psi_H = 0.6$, assuming $\psi_S < \psi_N$. NP contours are solid lines and SP contours are dot-dash lines. The contour interval is 0.1. Cross-hatching denotes a region where there is no throughflow streamline in the strait. These line contours overlay a shaded contour map of the NP:SP ratio for the throughflow within the channel (vs the total throughflow as in the line contours). The scale for the shading is given on the rhs.

Fig. 9. As in Fig. 8 except the fractions are plotted as a function of $\psi_S$ and $\psi_H$ for $\psi_N = 0.6$ in (a) and (b), and $\psi_S = 0.6$ in (c), assuming $\psi_S \leq \psi_N$.

Maluku passages. Substituting in (3.12) gives $E_{NP} = E_{SP}$ as 0:30; so the flow is wholly SP and remains so for small perturbations to the specified $\psi$ values.

For completeness, the fractional contributions (3.10)–(3.12) are plotted in Fig. 9 as functions of $\psi_P$ and $\psi_S$ for $\psi_H = 0.6$ ($\geq \psi_S$). There is no throughflow streamline in Makassar Strait if either $\psi_S \leq 0$ or $\psi_H \leq 0$; see Fig. 9a. The NP contribution is independent of $\psi_S$ for $\psi_S \leq \psi_H$, $\psi_H \leq \psi_N$, and independent of $\psi_H$ for $\psi_H \geq \psi_S$, $\psi_S \leq \psi_N$. It is of wholly NP origin if either $\psi_H$ or $\psi_N$ is less than $\psi_S$. In the region $\psi_S$, $\psi_N \geq \psi_S$ of Fig. 9a, the amount of NP transport in Makassar Strait remains fixed at $\psi_N$ and the additional flow is made up of SP streamlines from the SEC. From Fig. 9, for $\psi_H \geq \psi_P \geq 1$ the throughflow is wholly confined to Makassar Strait, and the NP:SP ratio is $N : (1 - N)$, the single-channel result.

Throughflow streamlines are only found in the Maluku passages if $\psi_H \geq \psi_P$ and $\psi_S \leq 1$. It is wholly contained in the Maluku passages if $\psi_H \geq 1$, $\psi_S \leq 0$ and the NP:SP ratio is $N : (1 - N)$. In general, it is wholly NP if $\psi_H \geq \psi_S$, $0 \geq \psi_H \leq \psi_S$, and wholly SP if $\psi_H \geq \psi_N$, $\psi_S \geq \psi_S \geq 1$, corresponding to conditions in which the SEC has wholly retroflected into the countercurrent or entered the Halmahera Sea before reaching the northern tip of Halmahera and conditions in which the Mindanao Current has wholly exited into the NECC or entered Makassar Strait, respectively.

The throughflow enters the archipelago only through the Halmahera Sea if $\psi_H \leq 0$, and none enters if $\psi_H \geq 1$. The fractional contribution is independent of $\psi_N$, and the values displayed in Fig. 9c are given by the abscissa through $y = \psi_H$ in Fig. 7b with $\psi_S$ reinterpreted as $\psi_H$. 
e. Fitting ARLINDO observations

The simple triple-channel model is in broad agreement with the findings of the ARLINDO cruises described in Gordon (1995), and can be used to provide dynamical constraints on the circulation. Makassar Strait is described as the pathway for the fraction of the throughflow from the Mindanao Current, whereas the SEC contribution enters via the Halmahera Sea. In the Maluku Sea, Gordon (1995) found the stratification similar to the easternmost edge of the Mindanao Current. Choosing $\psi_h = 0.8$, based on the knowledge that the value of the streamfunction on Halmahera is similar to that on the Australian continent due to frictional rubbing, if $\psi_h \geq 0.8$, then 80% of the throughflow is from the North Pacific. If $\psi_h \geq 0.8$, then all of it passes through Makassar Strait; otherwise it is divided between Makassar Strait and the Maluku passages with the easternmost streamlines passing through the Maluku passages. From Wajsowicz’s (1993a) multiple island rule $\psi_h \approx 0.72 + 0.28 \times \psi_h = 0.94$, and so typically $\psi_h \geq \psi_h$, unless Makassar Strait exerts considerable frictional drag on Sulawesi. The ARLINDO observations indicate that $\psi_h < \psi_h$ and, further, they require $\psi_h \approx 0.8$ so that the remaining 20% from the South Pacific enters via the Halmahera Sea (see Fig. 8). From Wajsowicz’s (1999) Fig. 5a of the Sverdrup streamfunction calculated from Hellerman and Rosenstein (1983) climatological wind stresses, if $y_N = 4^\circ$N and $y_P = 0^\circ$, then $\psi_N = -15$ Sv and $\psi_P = 1$ Sv. Hence, the above arguments are valid for throughflow magnitudes up to $-\psi_N/0.8 = 18$ Sv.

4. Variability in composition implied by wind stress variations

The models described in sections 2 and 3 were quite general in terms of requiring only the existence of a streamfunction to describe the horizontal flow. In this section, the type of flow and the timescales for which the solutions are valid will be restricted by choosing the streamfunction to be that given by the Sverdrup balance; namely,

$$\beta \psi^* = \frac{1}{\rho_0} \text{curl}\tau \cdot k,$$

where $\beta$ is the planetary vorticity gradient, $\tau$ is the wind stress, $\rho_0$ is a representative density, and $k$ is the unit vector in the $z$ direction. The Sverdrup balance is valid for flows governed by linear dynamics on timescales for which variations in the wind stress occur more slowly than the Rossby adjustment timescale for the basin in question. For the equatorial Pacific, the timescale is $O(2\text{ yr})$. Results from three different wind stress datasets are presented, as significant differences were found.

a. Florida State University wind stresses

The value of the Sverdrup streamfunction at the interior edge of the Pacific western boundary layer is contoured as a function of latitude and time. The wind stress data is gridded on a $2^\circ \times 2^\circ$ grid, so latitudinal excursions of the contours of this order of magnitude are needed to be sure any signal is real. Interpreting the streamfunction as a measure of pressure, then the highs and lows over the equatorial band are consistent with El Niño/La Niña events, as is the varying strength and location of the NECC given by the gradient in streamfunction around $4^\circ$N. There is still considerable variability in the 3-yr running mean signal. At 5 and 10 yr, the northward shift of streamlines with values from 0 to $-15$ Sv with time dominates the signal. The region where $\psi^* \geq 0$ is shaded dark gray in Fig. 10 as, if this region penetrates northwards of latitude $y_N$, the throughflow is composed of wholly SP streamlines. The region

Fig. 10. The Sverdrup streamfunction at the interior edge of the Pacific western boundary layer, calculated from the FSU wind stress data, is contoured as a function of latitude and time. Results are displayed in the top panel downward for the streamfunction subject to running means of 12 months, and 3, 5, and 10 yr. Positive contours are denoted by solid lines, negative by dashed lines, and the zero contour by a dotted line. Possible choices of $y_N$, namely, the latitudes of the northern tip of Halmahera and $2^\circ$ to the north, representative of nonlinear effects, are delineated, as well as $y_N$, the latitude of the northern tip of Irian Jaya. If $\psi^*$ at $y_N$ is positive, then the net inflow is wholly South Pacific. The region of positive $\psi^*$ is shaded dark gray. To illustrate the condition for wholly North Pacific net inflow, that is, $\psi^* < 0$ at $y_N$, the region $\psi^* = -10$ Sv is chosen and the region $\psi^* < -10$ Sv is shaded light gray.
where \( \psi^*_p \leq -10 \text{ Sv} \). 10 Sv being chosen as representative of the throughflow magnitude, is shaded light gray as, if this region penetrates south of \( y_N \), the throughflow is composed of wholly NP streamlines.

Using the streamfunctions of Fig. 10 with the model of section 3a yields net Pacific inflow compositions displayed in Fig. 11, where \( y_N \) is taken as the northern tip of Halmahera; that is, the western boundary currents are assumed sufficiently linear not to overshoot the land tips. The value of the throughflow is assumed unknown, so the fractional composition is contoured as a function of throughflow magnitude. It is immediately striking that averaging the composition over the whole time period in each of the panels gives a different net composition for the period. This nonlinearity in time was noted by Wajsowicz (1993b). At all timescales shown, there are frequent periods when the \( \psi^* = \psi^*_p \) contour lies above the Halmahera latitude, hence accounting for the episodes of a pure SP source found in Fig. 11. In contrast, the periods when the \( \psi^* = \psi^*_p \) contour lies below the Halmahera latitude decrease with lengthening timescale, accounting for the fewer episodes of pure NP source in Fig. 11. As expected from Fig. 6, as the throughflow magnitude increases, the composition becomes more dominated by the SP source.

A guide to the effect of nonlinearity in the western boundary layers, or modification due to unresolved timescales, is shown in Fig. 12, where \( y_N \) is taken as 2° north of the northern tip of Halmahera. Interestingly, at 1 and 3 yr, the fractional composition pulses for the range of throughflow magnitudes. The net inflow from the Pacific is dominated by the NP source for 3–5 yr, then for a year or two, the SP source dominates; see the top two panels of Fig. 12. At 5 and 10 yr, if the throughflow is about 10 Sv, then the net inflow from the Pacific is wholly from the NP source until the mid 1980s, whereafter, the SP source has an increasing contribution.
b. ECMWF wind stresses

These data are those used to force the POCM run by A. J. Semtner and colleagues. They are derived from the twice daily analyses for the 10-m winds from ECMWF. The Sverdrup streamfunction on the interior edge of the western boundary layer of the Pacific is shown in Fig. 13a. As the time series is limited, only 1- and 3-yr running means are considered. Comparing with Fig. 10 over the same time period, the trends in the $\psi^k = 0$ and $\psi^* = -10$ Sv (representative of the throughflow magnitude) contours are similar, but the ECMWF contours are shifted at least a degree of latitude northward. The impact of this on the fractional composition is shown in Fig. 13b, for $y_N$ being the latitude of the northern tip of Halmahera and 2$^\circ$ of latitude northward. For the linear case, $y = 2.25^\circ$N in Fig. 13b, the net inflow from the Pacific is wholly from the SP source. For the nonlinear case, $y = 4.25^\circ$N in Fig. 13b, there is a significant intrusion from the NP source in the early 1990s, but only if the throughflow is small $\leq 5$ Sv. The difference in streamfunction patterns for ECMWF and FSU data was noted by Wajsowicz (1999), and thought to be the cause of POCM’s throughflow being wholly from an SP source.

c. SSM/I wind stresses

A further wind dataset available to the author is that derived from SSM/I data by R. Atlas and colleagues at NASA/Goddard Space Flight Center, Greenbelt, Maryland. The wind speeds obtained from the passive microwave sensors are given directions from the ECMWF analyses. The data were provided on a 0.5$^\circ$ x 0.5$^\circ$ grid averaged over 5-day periods. Wind stresses were calculated according to the formula

$$\tau = \rho_o C_d |u| u,$$

where $C_d = 0.8 \times 10^{-3}$ for $|u| \leq 6.7$ m s$^{-1}$ and $2.6 \times 10^{-3}$ otherwise [cf. Hellerman and Rosenstein (1983)], and $\rho_o = 1.2$ kg m$^{-3}$. The resulting Sverdrup streamfunction and fractional compositions are shown in Fig. 14.

The streamfunction pattern is somewhat different from those using FSU and ECMWF data. The northern, then southern, excursion of the relevant contours is noted, but the subsequent northward movement is not present, (see Fig. 14a). The contours are shifted a couple of degrees southward of the FSU ones, so the net inflow is wholly from the NP source in the nonlinear case for the range of throughflow magnitudes (see Fig. 14b for
\(y_N = 4.25^\circ\text{N}\). The linear case, \(y_N = 2.25^\circ\text{N}\) in Fig. 14b, is the same for small throughflow values. A contrast in fractional composition between the late 1980s and early 1990s is only found for larger values of throughflow magnitude. The results are similar whether the data are used on a 0.5° grid or averaged onto a 2° grid.

5. Evidence of decadal-scale variability in the Pacific inflow

Unfortunately, there are few observations of currents and salinity in the far western equatorial Pacific, so whether the composition is wholly from an NP source with pulsing intrusions from the SP source or whether the fractional composition is reasonably constant on intradecadal timescales cannot be ascertained. However, there is evidence that the axis of the retroflexion of the SEC shifts latitudinally with time and that there has been a shift to a more salty inflow in recent times, and this is examined below.

### a. Salinity variations along 137°E

The retroflexion of the SEC into the NECC in the western equatorial Pacific is signified by a distinct salinity front, Fig. 15, between about 100 and 300 m; there is some seasonal variability in the location of the front. These data are from the World Ocean Data Set 1994, Levitus et al. (1994). Japanese oceanographers took measurements along 137°E twice a year from the late 1960s, which have been archived at NODC. The salinity observations from NODC’s World Ocean Database 1998, Boyer et al. (1998a, b), and Levitus et al. (1998), within 0.5° of longitude of 137°N, and which had a good
The interannual variability in salinity integrated between 100 and 300 m, and averaged over the depth, along 137°E is shown in (a). The data is binned from WODB-98 profile collection. The corresponding anomaly relative to the monthly climatology is shown in (b). The total number of observations making up the result shown in (a) is given in (c); about six observations make up each profile. An indication of seasonal bias in observations is given in (d), where the excess number in the Northern Hemisphere summer or winter expressed as a percentage of the total number of observations is contoured.

The quantity plotted is

\[ S^\text{100-300}_k(x, y) = \frac{1}{D(x, y)} \sum_{k-1}^{k+1} S_k(x, y) \cdot d_k(x, y) \]

where \( S_k \) is the salinity at the standard level \( k \), \( d_k \) is the sum of the half depths from standard level \( k \) to standard levels \( k-1, k+1 \), and \( D \) is the total depth over which observations are summed. The values of \( k \) correspond to depth values between 100 and 300 m. The anomaly from the monthly mean is shown in Fig. 16b. The anomaly is relative to the monthly mean, as there is considerable seasonal bias in the observations (see Figs. 16c,d). It is difficult to pick out the detailed fluctuations suggested by the streamfunction patterns of section 4, but it appears that salty water was found farther north in the period 1965–80 than in 1980–95, which suggests that the SEC retroflection extended farther north in the former time period. This is indicative of the second mechanism for throughflow composition variation discussed in section 2c and illustrated in Fig. 4b. Further, the second mechanism occurs because the first mechanism occurred, as seen in the Sverdrup streamfunction in the bottom panel of Fig. 10. In the Sverdrup streamfunction plot, bottom panel of Fig. 10, the zero streamline lies to the south of the northern tip of Halmahera and the \(-15 \text{ Sv}\) streamline is found around 4°N in the earlier epoch, and the potential throughflow streamlines of the SEC turn eastward to join these streamlines implies a stronger SEC and fresher throughflow in the earlier epoch. However, a stronger SEC suggests a more northerly retroflection in the earlier epoch, which would also give a fresher throughflow and a saltier NECC at higher latitudes; see Fig. 4b, the latter being as observed in Fig. 16.

b. Salinity variations in the Indonesian archipelago

All of the salinity profile data in NODC’s World Ocean Database 1998 were examined. The sparsity over the Indonesian region was severe; in many places, only one profile existed for the last century. In Fig. 17a, the difference in \( S^\text{1000}_k \) between the epochs 1966–80 and 1981–95 is plotted. The increased freshness with time in the western equatorial Pacific is evident. Freshness as far east as 170°W has been reported in
The difference in salinity, integrated between 100 and 300 m and averaged over the depth, between the epoch 1966–80 and the epoch 1981–95 for the Indo–Pacific region is displayed in (a). The values are determined from the WODC-98 profile data. There is seasonal bias in the data, and the equivalent display using WOA-94 monthly climatology in place of the actual profile values is displayed in (b). The difference in monthly anomalies between the two epochs is displayed in (c), that is, equivalent to (a) with the seasonal bias removed.

Figure 17a shows an increase in saltiness with time in the entrance to the Celebes Sea, Maluku passages, Halmahera Sea, and Makassar Strait, which agrees with the prediction from the simple single-channel model. However, the Seram and Banda Seas, and the southern Celebes Sea, appear fresher. The anomalies found are comparable with seasonal variations, so Fig. 17a is replotted in Fig. 17b with the profile data replaced by monthly climatology to give an indication of seasonal bias. Within the archipelago, the bias is in favor of the earlier epoch being fresher by up to 0.05 ppt. Figure 17c shows the salinity difference between the epochs adjusted for seasonal bias. The conclusions are the same except for the Halmahera Sea, which is now fresher in the later epoch. The triple-channel model is needed to explain these data. It is relatively easy to find a regime in which the conditions $\psi_0$ decreases with time, $\psi_0 < 1$, the fractional composition in Makassar Strait and the Maluku passages become more salty, and the Halmahera Sea apparently freshens are met such that the net inflow composition becomes more salty with time. As a demonstration, consider the quantitative example: initially $\psi_0 = 1.0$, $\psi_p = 0.0$, $\psi_s = 0.6$, $\psi_H = 0.8$ and finally $\psi_0 = 0.5$, $\psi_p = 0.0$, $\psi_s = 0.7$, $\psi_H = 0.9$. Then from (3.8) and (3.9), the net NP:SP ratio changes from 80:20 to 50:50. From (3.10)–(3.12), the initial ratios in the individual channels are 60:0 (Makassar), 20:0 (Maluku), and 0:20 (Halmahera). The final ratios are 50:20 (Makassar), 0:20 (Maluku), and 0:10 (Halmahera). If one believes that the observed increased saltiness in Makassar Strait is due not to SP water mass flowing through but to a change in the saltiness of the Mindanao Current, then this can be achieved by requiring $\psi_0 > \psi_p$ in the final state. The amount of SP water mass flowing through the Halmahera Sea is reduced with the remainder flowing through the Maluku passages. It is argued that the Halmahera Sea will appear fresher since, if its throughflow is sufficiently reduced, its salinity is no longer determined by a branch of the SEC flushing through but by local effects. That $\psi_H$ approaches unity with time is consistent with the bottom panel of Fig. 10, which shows a reduced shear in $\psi_H$ over the latitudes over which Halmahera is exposed to its effect.

Detecting a correlated signal in the Indian Ocean is difficult and leads one to question whether there is an XCTD analysis of the 1990s versus historical data by Sprintall et al. (1998, personal communication).
(b) Equivalent Monthly Climatology
100m-300m Depth-Integrated Salinity

(c) WODB-98 Profile Data Seasonally Adjusted
100m-300m Depth-Integrated Salinity

Fig. 17. (Continued)
relationship between variability in the source of the net Pacific inflow and composition of the outflow into the Indian Ocean. From Fig. 17c, there is a suggestion that the region near the Australian shelf has freshened, whereas to the northwest where the throughflow penetrates is saltier.

6. Summary and discussion

A simple, diagnostic, 2D streamfunction model was developed in sections 2 and 3 to provide quantitative estimates of the water mass type of the throughflow in each of the three major input channels of the Indonesian archipelago, namely Makassar Strait, the Maluku passages, and the Halmahera Sea. It is an extension of the model described in Wajsowicz (1993b). It includes both Halmahera and Sulawesi as distinct islands and a parameterization of nonlinear effects. Also, the fractional composition equations are derived using “channel operators,” which bring out the general formulation of the problem, so enabling the technique to be applied to different geometries with more islands and channels.

The model is diagnostic in the sense that the value of the streamfunction on each island as a fraction of that on the Australian continent must be given, and the value of the streamfunction on the interior edge of the Pacific western boundary layer at latitudes $y_N$, $y_P$ must be specified. For the western equatorial Pacific, $y_N$ is the northernmost of the latitudes of the northern tip of Halmahera and of the SEC retroreflection into the NECC. The latitude $y_P$ is that of the northern tip of Irian Jaya. Schematics in Fig. 3 are used to illustrate the effect of nonlinearity in the Pacific western boundary layer on $y_N$, in particular the role of the Halmahera and Mindanao eddies, and the significance of zonal staggering of the landmasses. Although the eddies have been described previously [see, e.g., Lukas et al. (1991); Masumoto and Yamagata (1991)] their role as described herein had not been surmised.

Regime maps were plotted for four different archipelago geometries, which represent choices modelers may make when restricted by grid size from resolving all of the straits within the archipelago. The channel system acts as a filter on the water mass types. North Pacific water mass associated with low absolute value streamlines passes through the western passages, whereas South Pacific water mass associated with high absolute value streamlines passes through the eastern passages, which is in agreement with the observations reported in Gordon (1995). The model explains why a pure SP signal is very unlikely to be observed in Makassar Strait, as this would require the southern extent of the northern tropical gyre (outside the western boundary layer) not to extend equatorward of the northern extent of the Mindanao eddy. Similarly, a pure NP signal is unlikely ever to be observed in the Halmahera Sea, as this would require the southern extent of the northern tropical gyre to extend well south of the equator. As more data in the region become available, the simple model could be used to give dynamical bounds on the circulation, given the fractional composition in each channel, and vice versa. When transport and composition information are both available, then agreement or not with the model will yield further information about the general circulation, for example, the importance of an upwelling/downwelling region in invalidating the 2D streamfunction construct.

As well as the concise nondimensional expressions, the dimensional form of the single-channel model was considered to emphasize properties, such as the stronger the throughflow, (i) the greater typically the South Pacific fraction for a given value of the forcing streamfunction at $y_N$, and (ii) the less sensitive the composition fraction to variations in the forcing streamfunction at $y_N$. It is noteworthy that the dimensional forms are slightly misleading, as they suggest more degrees of freedom than exist. However, even with the nondimensional forms, it is unclear from the data available whether all of the parameter space described in the plots of section 3 is achieved in reality.

Possible long-term variations in Pacific inflow composition were explored in section 4 using the model in its simplest form, as a single channel. The Sverdrup streamfunction was used to determine the variability in the forcing streamfunction at $y_N$, the only parameter in the model. For FSU wind stress data spanning 1961 to 1998, it was found that the streamlines over the range of possible $y_N$ (from the northern tip of Halmahera to the southern tip of the Philippines) make considerable latitudinal excursions with time even when a 10-yr running mean was applied. In terms of predicted composition, the model was sensitive to the choice of $y_N$. If $y_N$ was taken as the northern tip of Halmahera, then the composition was predominantly South Pacific on all timescales irrespective of throughflow magnitude. However, if $y_N$ was taken 2° farther north, then the composition was predominantly North Pacific, and, if the throughflow magnitude were assumed about 10 Sv or less, then it would be wholly North Pacific for most of the time. Despite these discrepancies, both choices of $y_N$ showed a trend toward an increasing South Pacific component to the inflow over the length of the time series.

This predicted trend suggested examination of historical salinity records. In section 5, it was found that there are latitudinal variations in the northern extent of the retroreflection of the SEC, as identified in the salinity data along 137°E. For the FSU time period from 1961 to present, these data suggested that the SEC and its retroreflection were found farther northward in the epoch 1966–80 than in the epoch 1981–95, which was consistent with the Sverdrup streamfunction tendency. Further examination of the salinity profiles over the western equatorial Pacific and Indonesian archipelago showed that the western equatorial Pacific had freshened between the epochs and regions of the archipelago have
become saltier in agreement with the simple model. The triple-channel model was used to show how, although the overall tendency may be for a more salty net inflow, the different channels may respond differently, which implies caution is required in making any statements about variability in the net composition based on observations in a single strait, for example, Makassar Strait. A concern, particularly for modelers, is that upon repeating the calculations with wind stresses derived from ECMWF 10-m winds for 1987–95 and from SSM/I data for 1988–96, the results were completely different. The Sverdrup streamfunction for ECMWF wind stresses gave a positive streamfunction over most of the range of $\gamma$, and thus a wholly SEC-fed inflow, whereas the SSM/I data gave large negative values and thus a wholly Mindanao Current–fed inflow. As described in Wajsowicz (1999), the ECMWF result likely accounts for the Parallel Climate Ocean Model and the Los Alamos Parallel Ocean Program model having inflows dominated by the SEC.

Whether there is any long term variability in the salinity of the Pacific inflow into the Indonesian archipelago due to shifts in the Pacific basinwide wind stress patterns, and thus variations in the fractions from the Mindanao Current and SEC, is unknown. Evidence in the form of an analytical model, wind stress, and salinity data has been presented, which suggests that there could have been. If contrary evidence is found, then it will be useful to examine which assumptions were incorrect. For example, a weaker Indonesian throughflow and stronger nonlinearity in the Pacific western boundary currents than considered could move the system into a regime of wholly North Pacific inflow for all time in the FSU-forced model. The validity of the Sverdrup streamfunction over the latitudes of the NECC has been questioned by many (e.g., Meyers 1980). In practice, the arguments presented herein do not require the Sverdrup streamfunction to be valid, they require only the existence of a 2D streamfunction to represent the flow, whose latitudinal variability mimics that of the Sverdrup streamfunction with time. Wyrski (1974) described considerable variability in the equatorial currents from 1950 to 1970, based on sea-level records, so the variability in Fig. 10 is very plausible.

Tying in possible decadal shifts in throughflow, and thus the NECC, composition fractions with the observed decadal-scale thermal anomalies in the North Pacific subtropical gyre (see e.g. Deser et al. 1996), or changes in the background stratification of the equatorial Pacific (see, e.g., Graham 1994) is difficult and needs further investigation using coupled GCMs. A reduced export of North Pacific thermocline water into the Indian Ocean would result in a reduced cross-equatorial transport of South Pacific water. If the shift is of large enough amplitude and persists long enough, then the North Pacific would be increasingly isolated from the rest of the world’s oceans and residence times would increase.

Whether any variability in the water mass composition of the Pacific inflow translates into variability in the outflow composition into the Indian Ocean will depend on the residence times of the water masses in the Indonesian seas. The longer they reside, the more likely they are to undergo modification due to local effects such as precipitation and mixing. In a single-channel model, any variability in the Pacific inflow composition will immediately impact the Indian Ocean. In practice, the Indonesian seas may well mask much of the variability in composition. If the latter is true, then the design of the archipelago in climate GCMs needs careful consideration.

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