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SHORT CONTRIBUTION

How the ratio of meridional flux of fresh-water to flux of heat fixes the latitude where low salinity intermediate water sinks

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ABSTRACT

Prescription of the meridional fluxes of fresh-water and heat fixes lower limits on the magnitude of meridional volume fluxes, the direction and relative depths at which they occur, and the latitude at which low salinity intermediate water converges and sinks. It also reveals that the main transport occurs in two separate meridional cells with opposing sense of rotation, and determines the latitude of the boundary between them.

1. The Southern Hemisphere oceans

The strong zonal circulation of the Antarctic Circumpolar Current maintains an S,T relation which is largely similar in each of the southern oceans. Fig. 1 shows the S,T relation for several *Discovery* stations at different latitudes (all near 115°E longitude). As a first approximation we will assume that the S,T relations are independent of longitude, and that the latitudinal dependence of the S,T relation shown in Fig. 1 is typical of the entire southern hemisphere.

Oceanic meridional fluxes of fresh-water, F, in units of 10^6 m^3 s^{-1} (from Baumgartner and Reichel, 1975) and of heat, H, in units of 10^{13} W (from Hastenrath, 1980) summed over different parallels of latitude are given in Table 1. The corresponding average excess of salinity, dS, and of temperature, dT, required for all southward moving oceanic water volumes over the average salinity and temperature of those volumes moving northward is also tabulated assuming a standard amplitude of water volume exchange of 30×10^6 m^3 s^{-1}. If the actual amplitude of the volume exchange is M, then the appropriate values for dS and dT may be obtained by multiplying the tabulated values by $30/M$.

The slope dT/dS (which we will call the "principal flux slope") and the length $\sqrt{dS^2 + dT^2}$, indicated to the right of the S,T curve in each panel of Fig. 1, was obtained by assigning each *Discovery* station a nominal latitude, at intervals of 5 degrees of latitude, and using the corresponding numbers in Table 1. The line segments (or "principal flux vectors") can be translated without rotation. The numeral at each end (positive is northward) gives the direction of the volume flux and its amount in units of 10^6 m^3 s^{-1}. By translation and change of length the principal flux vectors can be moved so that both ends lie on the S,T curve or one end does and the other lies on a feasible mixture of two parts of the S,T curve. If the fit is so adjusted that maximum length can be achieved, then we have found the minimum possible oceanic volume exchange which can affect both prescribed meridional fluxes of fresh-water and heat at that latitude. This idea has been exploited by Stommel (1980) to test proposed meridional fluxes for individual southern hemisphere oceans for consistency. It is unlikely

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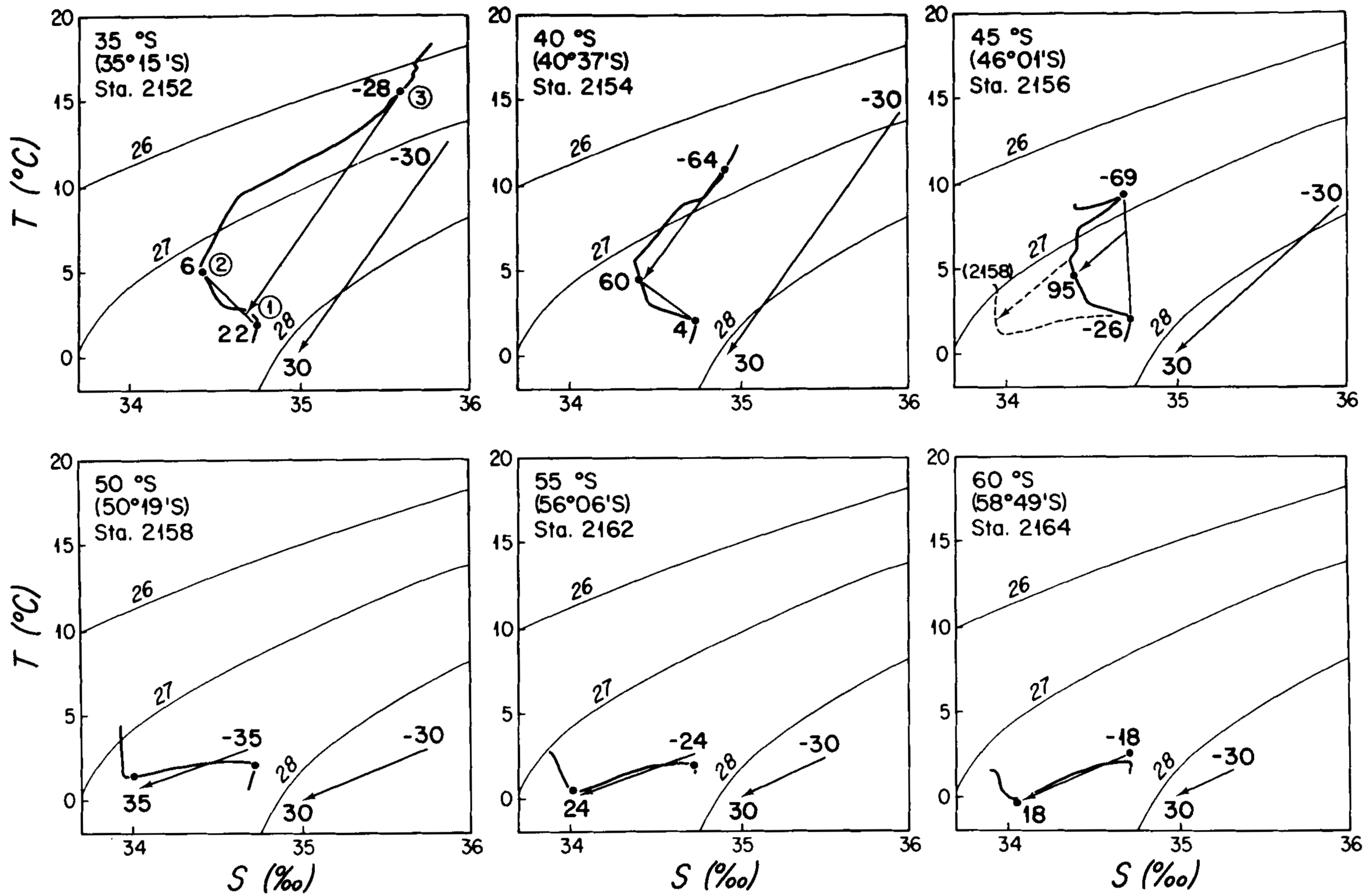

Fig. 1. S, T curves for selected *Discovery* stations near 115° E, nominal (and actual) latitudes are both indicated above the station number. The line segment to the right of each curve is the computed principal flux vector for standard volume flux of 30 ($\times 10^6$ m^3 s^{-1}), and other numerals at ends of lines are volume fluxes in same units calculated graphically by laws of mixtures (northward is positive). Some curves of constant sigma-*t* are also shown. Station 2158 is shown dashed on plot for station 2156 to show length of isopycnal flux vector (see text).

Table 1. *Southern ocean meridional fluxes, principal flux slopes, nearest Discovery stations, and mean sigma-t slopes*

Lat. °S	F 10^6 m^3 s^{-1}	H 10^{13} W	dS ‰	dT °C	dT/dS °C/‰	Nearest Station No.	Mean T °C	Sigma-t slope °C/‰
35	0.781	−161	0.91	12.8	14.0	2152	10	3.6
40	0.897	−182	1.04	14.4	14.0	2154	6	5.5
45	0.834	−111	0.97	8.8	9.1	2156	4	7.0
50	0.636	−40	0.74	3.2	4.3	2158	2	9.3
55	0.432	−30	0.50	2.4	4.7	2162	1	13.8
60	0.269	−20	0.31	1.6	5.1	2164	1	13.8

that the lower limits so computed can actually be realized: first, the volume exchanges are unlikely to be confined to the extreme temperatures at the ends of the longest possible principal flux vector; second there are likely to be other constraints (e.g. geostrophy) that may demand a higher lower limit. If the exchange process can operate near the lower limit, it may be spoken of as "the most efficient" configuration of exchange of water-masses.

Inspection of Fig 1 shows that there is a general decrease in the principal flux slope and length from 35° S to 60° S. Near 35° S and 60° S the S,T curves have long straight portions which are convenient places, with appropriate slopes, for locating optimally fitted principal flux vectors, a fact which can hardly be coincidental.

Curves of constant surface density (sigma-t) are drawn on the S,T planes in Fig. 1. Their slopes vary over the S,T plane. Near 35° S the principal flux vector has a slope greater than that of the sigma-t curve in the vicinity of the mean temperature and salinity of the S,T curve. This means that on the average the warm salty water of the most efficient southward volume flow must overlie its denser northward counterpart. At 60° S, however, the principal flux vector has a slope less than that of the sigma-t curve in the vicinity of the average salinity and temperature of the S,T curve, and consequently the most efficient southward volume flow of warm salty water must, on the average, underlie its less dense northward flowing counterpart. At an intermediate latitude near 47° S, as shown in Fig. 2 where the two slopes are displayed as functions of latitude, the principal flux vector implies isopycnal exchanges (or mixing) as the most efficient. Since this is also a latitude where the north–south change of S,T relation is most marked, we might assume that the true zonal average S,T relation at this latitude is really very broad in the range of sigma-t from 26·75 to 27·50, due to meandering of the front, in which case isopycnal mixing could be quite efficient. In this way we locate the latitude where Antarctic Intermediate Water sinks below the surface on its northward course, and find that this is also a region where isentropic (isopycnal) exchanges or mixing may be expected to account for the local meridional flux of fresh-water and heat, without invoking explicitly any dynamical constraints such

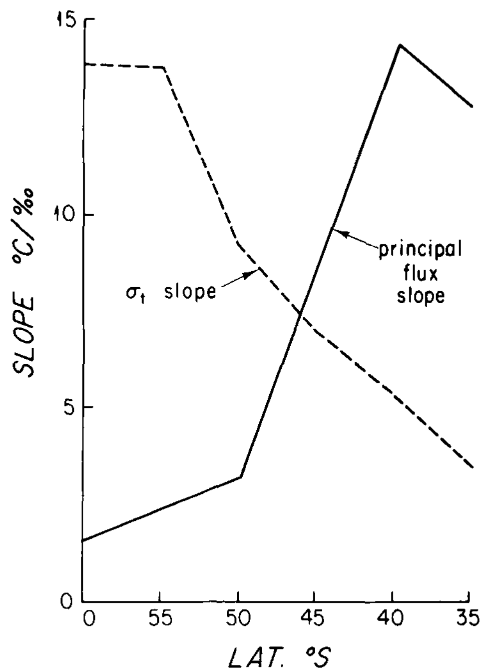

Fig. 2. Latitudinal dependence of principal flux slope and slope of sigma-t curve near avarage temperature and salinity of each station.

as Ekman pumping due to wind-stress. In contrast to many ideas about oceanic circulation which depend upon a surface boundary condition on momentum flux, the ideas developed here depend upon surface boundary conditions on fresh-water and heat flux (the meridional fluxes are equivalent to them, by integration of conservation equations).

The S,T curves in the southern ocean are, of course, only approximately independent of longitude, and from one ocean to another. It will, in the future, be helpful to prepare careful census determinations of the amount of each water type (a bivariate distribution of S and T) on certain fixed parallels of latitude. A brief discussion of these differences, and of the possible differences of the meteorologically determined oceanic fluxes of heat and fresh-water, is given in Stommel (1980).

2. Calculation of magnitude of the minimum volume fluxes in the Southern Hemisphere

Graphical solutions for the minimum volume fluxes at each nominal latitude are indicated in Fig. 1. On the right the principal flux vector is shown for standard volume flux 30×10^6 m^3 s^{-1}. The numerals at the ends of the vector indicate amount and direction of flow of the volume flux. This vector, translated, and with length adjusted, is also shown on the S,T curve. Where both ends cannot be placed upon the curve, one end is placed on the curve (point 3) and the other on a feasible mixture of low salinity water at sigma-t of 27·25 and of deep water at sigma-t 27·80 (points 2 and 1 respectively). The numerals fixed at points 1, 2, and 3 are the volume fluxes determined by laws of mixture and are summarized in Table 2. These fluxes need not necessarily be associated with steady currents; the rather large values at 40°–45° S may really be associated with strong isentropic mixing at these latitudes as mentioned above. Elsewhere the magnitudes seem to fall within the range of conventional wisdom. It is striking how continuous the northward stream of low salinity (type 2) water is. At the latitude where it sinks beneath the surface the sense of the main meridional cell reverses.

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Table 2. *Minimal volume fluxes by constructions in Fig. 1 (units 10^6 m^{3}s^{-1})*

Type	Sigma-t	60° S	55° S	50° S	45° S	40° S	35° S
3	~26.70				−69*	−64*	−28
2	27.25	18	24	35	95*	60*	6
1	27.80	−18	−24	−35	−26	4	22

* These large volume fluxes may be associated with isopycnal fluxes due to eddies on the front (see text).

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КАК ОТНОШЕНИЕ МЕРИДИОНАЛЬНОГО ПОТОКА ПРЕСНОЙ ВОДЫ К ПОТОКУ ТЕПЛА ФИКСИРУЕТ ШИРОТУ, НА КОТОРОИ ОПУСКАЮТСЯ ПРОМЕЖУТОЧНЫЕ ВОДЫ НИЗКОЙ СОЛЕНОСТИ

Задание меридиональных потоков пресной воды и тепла фиксирует нижние пределы на величины меридиональных потоков объема, направление и относительную глубину, на которой они встречаются, и широту, на которой промежуточные воды низкой солености сходятся и опускаются вниз. Оно также показывает, что основной перенос происходит в двух отдельных меридиональных ячейках с противоположными знаками вращения и определяет широту границы раздела между ними.