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A numerical simulation of the general circulation in the world ocean

Part 2. Meridional and interoceanic heat transports*

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Abstract: The meridional and interoceanic heat transports are estimated with an ocean circulation model. The annual average of the simulated meridional heat transport in the world ocean is smaller in the southern hemisphere than estimates based on observations. Its annual variation is mostly accounted for by the annual cycle of the Ekman heat transport. At low latitudes the annual range of the latter is larger than that of the total meridional heat trasnport, indicating that some processes upset the Ekman heat transport. Between about 40°S and 20°S in the South Atlantic Ocean, the heat transport is southward, which disagrees with results by other studies. The Atlantic Ocean is the only one heat importer, and the Pacific Ocean is largest exporter. Importance of the Indian Ocean for its size is emphsized.

1. Introduction

A previous paper (ARAKAWA and TAKANO, 1993, hereafter referred to as AT) described simulated temperature and velocity fields in a world ocean. The present paper will describe the meridional and interoceanic heat transports.

The relative role of the atmosphere and the oceans in the meridional heat transport has been discussed since the last century. Although the atmosphere was considered more important than the oceans for several tens of years, the role of the oceans has been emphasized in recent years. In particular, recent satellite and radiosonde observations show that the oceans transport much more heat than was previously believed.

Not a few studies based on observations were carried out on the heat transport in the Indian, Pacific, Atlantic and world oceans, and the roles of the atmosphere and the oceans in the global meridional heat transport. However, our understanding is still poor. The results are compatible with each other in some qualitative aspects: for example, in the ocean heat transport the vertical circulation (meridional overturning) is of essential importance except in the Antarctic Ocean where the horizontal diffusion is not negligible, the role of the horizontal circulation is very small, and the surface Ekman drift current has a significant effect on its annual variation. However, not all the results are quantitatively compatible, so that the role of the oceans in the global meridional heat transport is still controversial. In some studies with satellite observations (VONDER HAAR and OORT, 1973; OORT and VONDER HAAR, 1976; CARISSIOMO *et al.*, 1985), it is much more important at low and middle latitudes than the role of the atmosphere, but almost negligible in a study with atmospheric circulation model (COVEY, 1988; ROOTH, 1989).

The model used here is outlined in AT. We are concerned with four cases tabulated in Table 1, where d is a constant parameterizing the surface heat flux, k the coefficient of vertical diffusion for momentum and heat, and A the coefficient of horizontal diffusion for heat. The coefficient of horizontal diffusion for momentum is $10^5 m^2/s$ in any case.

Table 1. Values of *d*, *k* and *A* in Cases 1 to 4.

Case	$d(W/m^2K)$	$k(10^{-4}m^2/s)$	$A(10^3m^2/s)$
1	30	1.0	2.5
2	30	1.0	1.0
3	60	1.0	1.0
4	60	0.3	1.0

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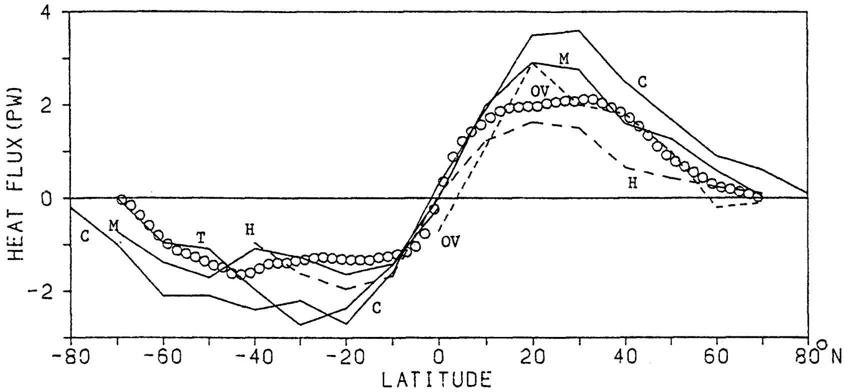

Fig. 1. Annual average of the northward heat transport (PW). Circles: Case 4, C: CARISSIMO *et al.* (1985), H: HSIUNG (1985), M: MASUDA (1988), OV: OORT and VONDER HAAR (1976), T: TRENBERTH (1979).

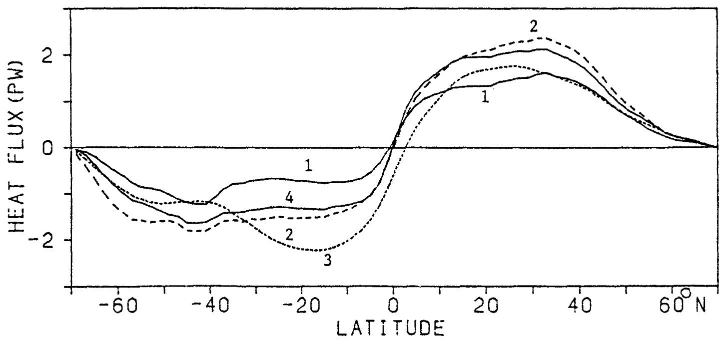

Fig. 2. Simulated annual average of the northward heat transport (PW) in Cases 1 to 4.

2. Heat transport in the world ocean

2.1. Annual average

Figure 1 shows the simulated annual heat transport in Case 4 with heat transports estimated with observations. Althouth the simulated magnitude may be smaller in the southern hemisphere, the latitudes of the maximum and minimum transports agree with those by observations.

Figure 2 shows results in Cases 1 to 4. The heat transport is small in Case 1, but, as a whole, there is no large difference between the four cases. The latitudes of the maximum and minimum transports in Case 3 agree well with those by HSIUNG (1985) using surface energy fluxes; the maximum northward transport at 25°N and the maximum southward transport at 15°S. Using hydrographic data and climatological wind data, BENNETT (1978) gets a northward transport between 1.1PW and 2.2PW at 30°S, which is quite different from other results based on observations such as illustrated in Fig.1. The meridional heat transport in the southern hemisphere is still a subject of controversy.

The meridional heat transport is achieved by three processes. The meridional circulation transports heat poleward by bringing warm upper layer waters poleward and cold lower layer waters equatorward. The horizontal circulation does it by bringing warm western boundary waters poleward and cold waters equatorward in the central and eastern regions. The diffusion transports heat from warm equatorial regions to cold polar regions. Compared with the contribution from the meridional circulation, the contributions from the horizontal circulation and diffusion are negligible at low latitudes. South of 35°S to 40°S, there are no long coastlines extending in the meridional direction, which is not favorable for the development of the meridional circulation. Therefore,

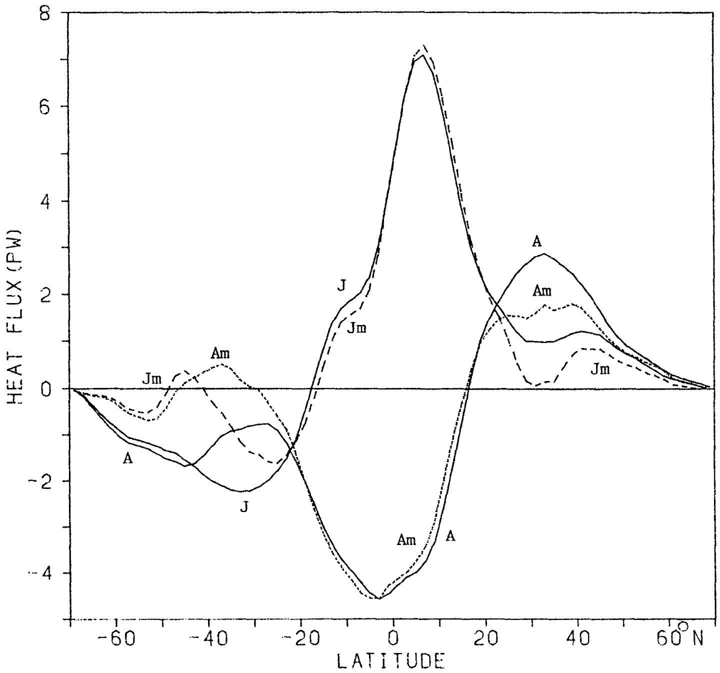

Fig. 3. Northward heat transport (PW) in January (J) and August (A) in Case 4. Heat transports by the meridional circulation in January and August are denoted by Jm and Am.

the heat transport by the meridional circulation is small and even northward at some latitudes. The horizontal circulation and diffusion are relatively important there in making the heat transport southward.

2. 2. Annual cycle

Figure 3 shows the total northward heat transport in January and August in Case 4 with the heat transport by the meridional circulation only. The latter is almost equal to the total heat transport at low latitudes but different from it at middle latitudes in both hemispheres, and the difference is more prominent in the southern hemisphere, reflecting small contribution of the meridional circulation, as mentioned above.

The annual range (difference between the maximum and minimum northward heat transport) of the heat transport across a low latitude arc is very large, mostly due to the annual cycle of the heat transport by the meridional circulation. The horizontal circulation and diffusion contribute almost nothing to it.

At middle and high latitudes, heat is transported northward in the northern hemisphere and southward in the southern hemisphere. The annual variation of the heat transport depends on that by the meridional circulation. Because the annual range of the latter is small at high latitudes, the annual variation of the heat transport is also small. The heat transport by the horizontal circulation and diffusion does not vary so much with time. The meridional circulation plays an important role in the meridional heat transport almost everywhere and throughout the year.

2. 3. Comparison of simulated and observed annual cycles

The simulated annual range in the northern hemisphere is compared in Table 2 with results by OORT and VONDER HAAR (1976) and CARISSIMO *et al.*, referred to as OVH and COV, respectively.

Both are not in agreement; OHV and COV are much larger except COV at 10°N. In OVH and COV, the meridional heat transport is southward in summer at high latitudes, but the annual average is northward in association with

Table 2. Comparison of simulated and observed annual ranges of the heat transport (PW)

	0°	10°	20°	30°	40°	50°N
OVH	11.8	10.9	5.7	4.6	5.3	4.5
COV	7.3	6.4	5.4	5.1	5.2	4.3
Case 1	5.1	6.4	1.9	1.3	0.87	0.15
Case 2	5.6	6.7	2.6	1.6	1.1	0.30
Case 3	5.4	6.7	2.5	2.0	1.8	0.67
Case 4	5.7	6.7	2.5	1.6	1.1	0.17

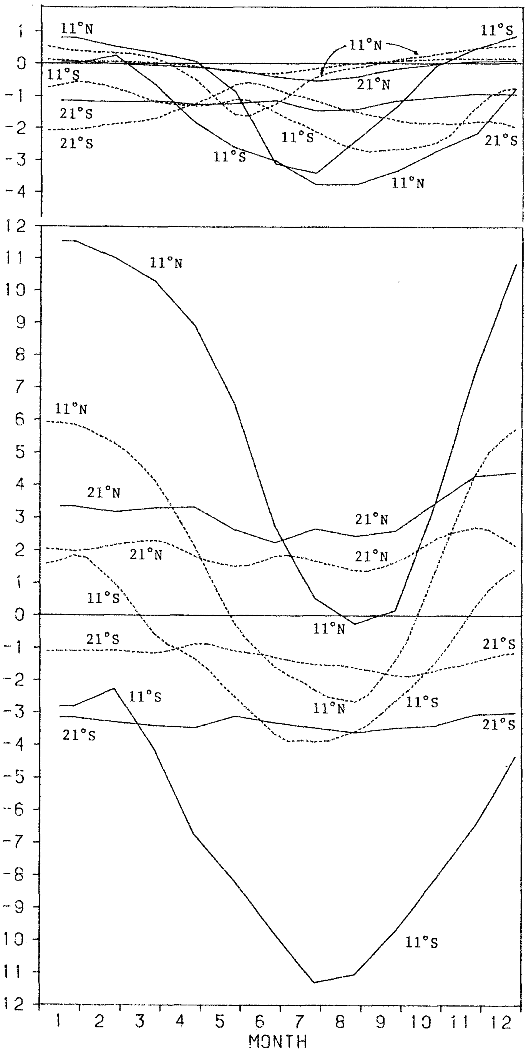

Fig. 4. Northward Ekman heat transport (broken lines) and total heat transport (solid lines) at 21°S, 11°S, 11°N and 21°N in Case 4. Upper panel for the Indian Ocean and lower panel for the global ocean. Units: PW.

its large annual amplitude. In Cases 1 to 4, however, it is northward at middle and high latitudes throughout the year.

2. 4. Comparison with the Ekman heat transport

The heat transport by the meridional circulation varies to a great extent from month to month. Because there is almost no annual variation in the temperature and the baroclinic component of velocity in deep layers, the simulated large annual variation of the meridional heat transport is brought about by its variation in surface layers. The large variation in surface layers is presumably in the heat transport by the Ekman drift current. The heat transport by the Ekman drift current is called "Ekman heat transport", which is defined here by the product $\mp$ (specific heat) × (eastward component of surface wind stress) × (mean water temperature in the Ekman layer)/(Coriolis parameter). The upper sign refers to the northern hemisphere and the lower sign to the southern hemisphere.

First, the total Ekman heat transport across a latitude arc is calculated by using the specified wind stress and simulated SST which can be considered to be the mean temperature in the Ekman layer. Second, the same wind stress data are used with observed monthly SST compiled by WASHINGTON and THIEL (1970). Both agree very well with each other throughout the year, confirming the model is successful in simulating the surface temperature, as far as the Ekman heat transport across a latitude arc is concerned.

Next, the simulated annual cycle of the total meridional heat transport is compared with that of the Ekman heat transport. Figure 4 shows examples in Case 4. As is readily understood, the absolute value of the Ekman heat transport has no meaning but its change with time and space. Both are surprisingly consistent with each other. At low and middle latitudes, the annual range of the Ekman heat transport is larger than that of the total meridional heat transport. This indicates the Ekman heat transport is offset to some extent by other porcesses, one of which is probably related to western boundary currents.

At most latitudes, the phase of the total meridional and Ekman heat transports in the Pacific and Atlantic Oceans agree well with those in the global ocean, but the magnitude of the heat transport in the Atlantic Ocean is smaller than that in the Pacific Ocean. In the northern hemisphere Indian Ocean, the phases of the total meridional and Ekman heat transports are a little ahead of those in the other two oceans, probably due to the small size of the northern hemisphere Indian Ocean basin, which makes it respond quickly to the change in external forcing.

The month-to-month variation of the total meridional heat transport at low latitudes is governed by the heat transport by the Ekman drift current. Among the three oceans, the Ekman heat transport is largest in the Pacific Ocean primarily because of its largest zonal extent.

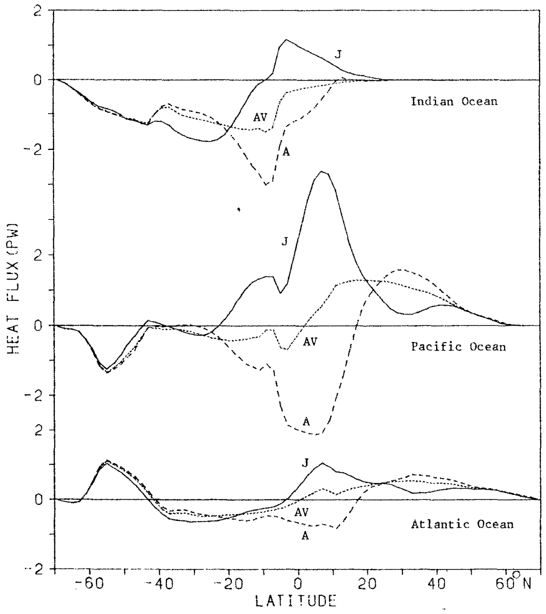

Fig. 5. Northward heat transport (PW) in the three oceans in Case 3. solid line (J): January, broken line (A): August, dotted line (AV): annual average.

3. Heat transport in the individual ocean

The variation of the annual average of the meridional heat transport with latitude in Case 4 is shown in Fig.5 with the transports in January and August in the Indian, Pacific and Atlantic Oceans.

The annual variation is large at low and middle latitudes in the Pacific Ocean and small in the Atlantic Ocean, particularly in the southern hemisphere. Because of the effect of the monsoon, it is larger in the Indian Ocean except south of 42°S.

Previous studies show (BRYAN, 1982, 1983; BUNKER, 1976; BENNETT, 1978; BRYAN and LEWIS, 1979; HASTENRATH, 1980; FU, 1981; MEEHL *et al.*, 1982; MILLER *et al.*, 1983; RUSSEL *et al.*, 1985; MILLER and RUSSELL, 1989) that the heat is transported northward in the South Atlantic Ocean. In Fig.5, it is so south of 40°S, but southward between 20°S and 40°S. Instead, it is northward in the South Pacific Ocean. However, the heat transport in the world ocean is southward, which results from a large southward transport in the South Indian Ocean.

WUNSCH *et al.* (1983) show the heat transports at 28°S and 43°S in the Pacific Ocean are indistinguishable from zero, which is close to our result in Case 3 (Fig.5) and the other three cases.

LAMB (1981) suggests from surface heat flux data that the heat transport in the Atlantic Ocean is northward with the possible exception of November-December. By use of hydrographic data, ROEMMICH (1980) obtains 1.2PW at 24°N, 0.8PW at 36°N and almost zero at 48°N in the Atlantic Ocean. WUNSCH (1980) obtains 1.2PW at 24°N-25°N and 0.75PW at 36°N. HASTENRATH(1982) obtains 1.1PW at 25°N. HALL and BRYDEN (1982) obtain 1.2PW at 25°N, while the present study gives, at 24°N, 0.48PW, 0.66PW, 0.49PW and 0.67PW in Cases 1 to 4, respectively; at 36°N, 0.57PW, 0.79PW, 0.52PW and 0.75PW in Cases 1 to 4; at 48°N, 0.43PW, 0.52PW, 0.39PW and 0.49PW in Cases 1 to 4. Simulated transports in the Atlantic Ocean are smaller than those values based on observations.

Table 3. Partition(%) of the interhemispheric heat transport in the three oceans in Cases 1 to 4.

	Case 1	Case 2	Case 3	Case 4
		Northward (Jan. 5)		
Indian Ocean	24.8	23.1	28.8	22.8
Pacific Ocean	59.7	63.2	62.2	61.5
Atlantic Ocean	15.5	13.6	8.9	15.7
		Southward (Aug. 5)		
Indian Ocean	30.6	31.7	25.7	31.4
Pacific Ocean	64.7	59.8	61.9	58.8
Atlantic Ocean	4.7	8.5	12.4	9.8

Table 4. Interoceanic heat exchange (TW). +: outgoing, −: incoming.

Case	Indian Ocean	Pacific Ocean	Atlantic Ocean
1	2	53	−55
2	2	115	−117
3	78	26	−103
4	64	111	−195

Importance of the Indian Ocean is shown in Table 3 in terms of the interhemispheric heat transport (transport across the equator). Transports in Jan.5 and Aug.5 are tabulated as representatives of northern hemisphere winter and summer transports.

The zonal extent of the equator of the Indian Ocean is 21% of the total length of the equatorial oceanic sector. It is 21% in the Atlantic Ocean and 58% in the Pacific Ocean.

The results are not significantly different from each other in Cases 1 to 4. In any case, the Atlantic Ocean contribution is small for its zonal extent, that of the Indian Ocean is very large, and that of the Pacific Ocean is fairly large for its zonal extent.

North of 25° N where the Indian Ocean does not exist any more, the annual cycle in the northern hemisphere world ocean is primarily governed by that in the Pacific Ocean.

Table 4 gives the annual averages of heat exchanged between the three oceans through the Drake Passage, Indonesian Straits, south of Australia and south of Africa. Althouth the result varies to a great extent in the Indian and Pacific Oceans, the Atlantic Ocean is essentially different from the other oceans; it is only one ocean that should import heat. Except in Case 3 the Pacific Ocean is the largest exporter.

4. Remarks

By using the simulated temperature and velocity fields, the meridional heat transport in the global ocean, the Indian, Pacific and Atlantic Oceans are calculated and compared with results of previous studies. Although reliable data are few for the present, the simulated results are mostly consistent with previous results based on observations.

However, the present study is not successful in simulating the equatorward heat transport in the South Atlantic Ocean between about 20° S and 40° S.

The surface heat flux consists of the solar radiation, long wave radiation, sensible and latent heat fluxes. To calculate these components for the surface boundary condition, reliable data are necessary on evaporation, cloudiness, long wave radiation from clouds and water vapor, which are not yet available. Hence, a simple formulation is used by assuming the surface heat flux is proportional to the difference between the predicted surface temperature and a prescribed reference atmospheric temperature, as is described in AT. The above results in Cases 1 to 4 show the heat transport is fairly variable with the magnitude of the constant of proportionality which is assumed, for simplicity, to be a constant in space and time. Better results will be obtained with better specification of the surface heat flux.

Salinity and sea ice ignored here may have some effect on the meridional heat transport through the meridional circulation driven by dense water formation at high latitudes.

Although four cases are set up with different values of the coefficients of diffusion and the constant of proportionality, we are not able to specify which case is most suitable in the light of observations, and only have a feeling about how the result is sensitive to them.

Nevertheless, the above results are encouraging. They are helpful in understanding processes of the meridional heat transport in the global ocean, the individual ocean and its annual variation. The role of the Ekman heat transport and features peculiar to each ocean are made clear to a certain degree.

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世界じゅうの海水の大循環の数値シミュレーション

第2部　南北方向および大洋間の熱輸送

新川千歳世・高野健三

要旨：第1部「水温と流速分布」に引きつづいてインド洋・太平洋・大西洋が南北方向に運ぶ熱量およびこれら3大洋の間で交換される熱量について述べる。3大洋が緯度線を横切って運ぶ熱量の和（世界じゅうの海が運ぶ熱量）は観測にもとずいたこれまでの結果とだいたい一致するが，南半球では小さすぎるようである。南大西洋のほぼ20°と40°の間では熱は南向きに運ばれており，観測結果と一致しない。年変化は，エクマン吹送流による熱輸送（エクマン熱輸送）の年変化によって生ずるが，低・中緯度では，その年較差はエクマン熱輸送の年較差よりも小さい。つまり，エクマン熱輸送を打ち消す何らかの過程が，（たぶん西側境界層内で）働いている。インド洋は小さいけれども年変化は大西洋よりも大きい。太平洋とインド洋は熱を輸出し，大西洋は熱を輸入する。