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Title FACTORS INFLUENCING THE SALINITY DIFFERENCE BETWEEN THE NORTH ATLANTIC AND NORTH PACIFIC OCEANS

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The possible causes underlying the salinity difference between the N. Atlantic and N. Pacific oceans are examined. The major salt element, Cl, is considered representative of salinity, based on the law of relative proportions. Physical means by which Cl and/or water are added to or withdrawn from the ocean basins--evaporation, precipitation, runoff, drifting ice, atmospheric transport and currents--are evaluated quantitatively after collating the most recent data available. Atlantic data allow some verification of totals by simultaneous Cl-water budgeting, while Pacific equatorial data are too sparse for effective use of this method.

Findings are inconclusive as to the true cause(s) for the salinity difference, but relative magnitudes of the contributing factors are established and illustrate the dominance of current influence.

FACTORS INFLUENCING THE SALINITY DIFFERENCE BETWEEN THE NORTH ATLANTIC AND NORTH PACIFIC OCEANS

by

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

FACTORS INFLUENCING THE SALINITY DIFFERENCE BETWEEN THE NORTH ATLANTIC AND NORTH PACIFIC OCEANS

I. INTRODUCTION

The difference in the salinities of the Atlantic and the Pacific has given rise to much speculation and several theories. The problem would be resolved if by establishing an exact water/salt budget for the two oceans one were able to show a steady state increase in Atlantic vs. Pacific salinity.

Unfortunately, this is not within the realm of present feasibility, as simple arithmetic shows. From the time of the Challenger expedition, no measurable salinity change has taken place as indicated by the findings of Montgomery (1958). If the limit of accuracy of measurements is accepted as being of the order of .02‰, and if we count the time interval as 80 years, the steady state annual change, if any exists, would have to be less than .02/80, or .00025‰.

As shown later in this paper, there is a discrepancy between evaporation and precipitation which in and of itself causes an increase in N. Atlantic salinity of about .003‰ per year. Assuming 10% accuracy on the (E-P) data, we thus have one single item in the annual water/salinity budget with an accuracy of .0003‰. Obviously, a steady state change less than .00025‰ can neither be proven nor disproven through any such budget.

In this paper the steady state is assumed to connote constant salinity, and this is the basis upon which an attempt is made to set up budgets of water and salt for the N. Atlantic and N. Pacific oceans. In the process, light is thrown on the relative magnitudes of the factors that keep the budgets individually in balance and, as a consequence, maintain the difference between the salinities in the two oceans.

When more exact methods are devised to measure the parameters, it may at some future date be possible to solve the problem of how the difference in salinities came into being. In the meantime, a fuller understanding of the factors involved may help pave the way to eventual solution.

II. DEFINITIONS AND METHOD

Definition of the geographic limits of the N. Atlantic and the N. Pacific as hereinafter referred to is made largely in accordance with Wüst's guide in Die Grenzen der Ozeane (1939). For the sake of simplicity, the European Mediterranean is excluded, however, as the net flow through the Strait of Gibralter is known with some accuracy. Allowance for the influence of the Mediterranean and Black Sea areas can therefore be made at Gibraltar without going further toward its source.

The N. Atlantic includes, then, the Baltic, North Sea, Labrador Sea and American Mediterranean, and it is bordered to the south by the equator. Figure 1 shows the limits.

The N. Pacific includes the Bering, Okhotsk, Japan, E. China and S. China Seas, and it also borders on the equator to the south, as shown in Figure 2.

Evaluation of the factors influencing the salinities of the two oceans, N. Atlantic and N. Pacific, is attempted by treating each area as a separate entity. The salinities are assumed to be affected only by

1. Precipitation and Evaporation
2. Runoff from Land
3. Wind-borne Salt

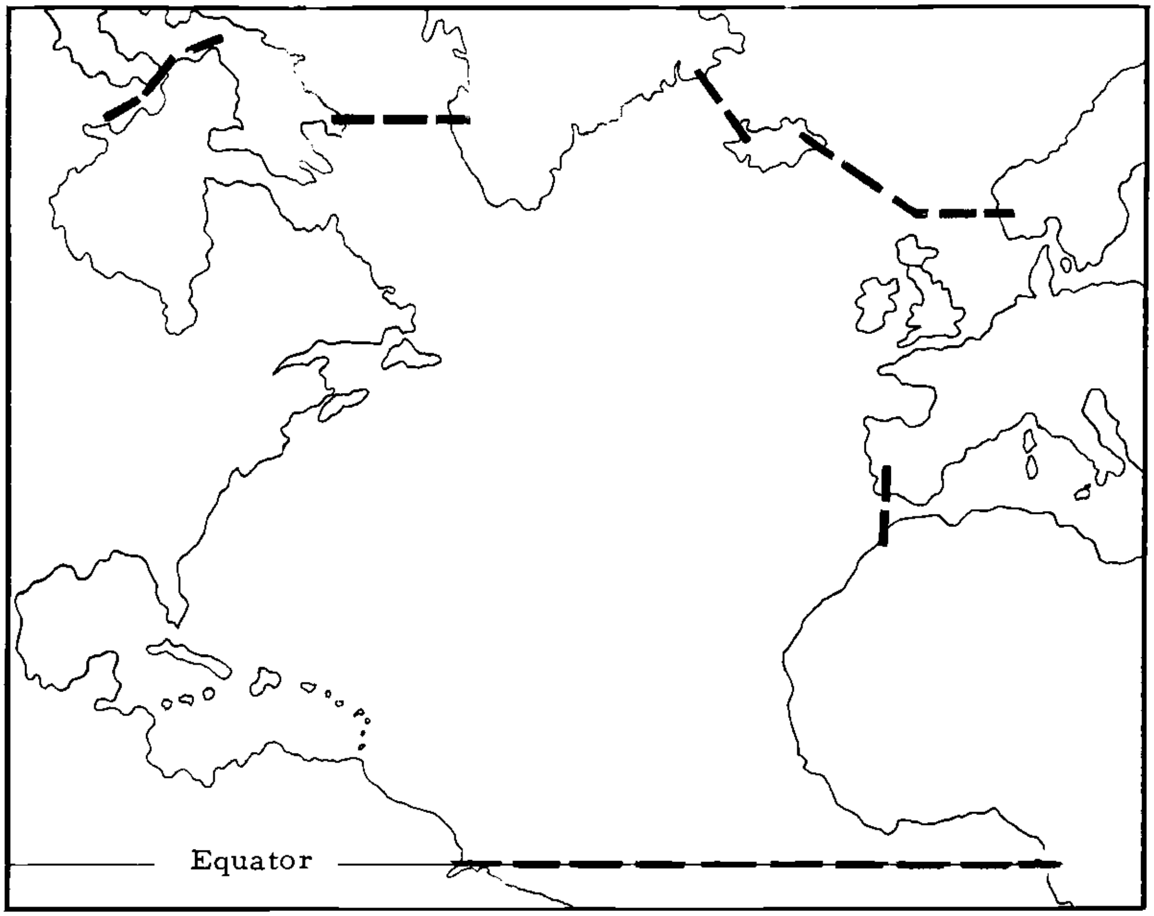

Figure 1. Defined geographic limits of N. Atlantic.

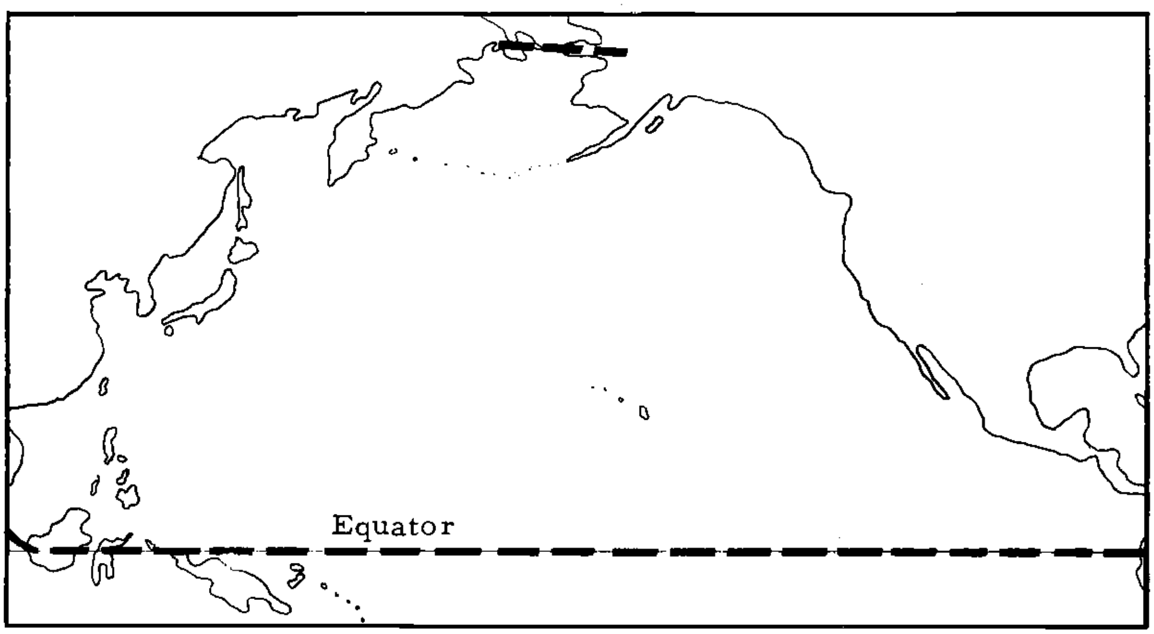

Figure 2. Defined geographic limits of N. Pacific.

4. Wind-driven Ice

5. Currents.

A survey of available literature on the first four of these factors yields quantitative values and establishes the relative magnitudes of the items without regard for any preconceived budgetary balance. Based on the data thus derived, the question of Cl contributions from currents is explored. This is done by setting forth facts about surface currents which are now known, plus assumptions which are generally accepted. Facts and assumptions are then contrasted with the requirements which impose themselves in the process of balancing for each ocean a water inflow-outflow budget, as well as one of salt content.

From Cochrane's figures (1958) the average temperature of the N. Pacific is found to be 2.4° C and the salinity 34.59‰. From the Fuglister Atlas (1957-1958) average salinity of the N. Atlantic was found by taking discrete averages of the cross sections covered by the chains of stations and in turn computing an overall average. The N. Atlantic's average temperature and salinity thus found are 5.1° C and 35.15‰. On these averages subsequent calculations and conclusions are based.

Rather than working with salinity as normally defined, i.e., comprising all of the major and minor constituents, it is practical to consider only Cl. Withdrawals due to biological activity and to spontaneous precipitation are thereby avoided. Using 55.25% as the ratio of Cl to total salinity, the Cl fractions are found to be 19.42‰ and 19.11‰ respectively for the N. Atlantic and the N. Pacific.

The water volumes in question comprise all of the water within the geographic limits as defined, the amounts being considered to be 148×10^6 km^3 for the N. Atlantic and 292×10^6 km^3 for the N. Pacific. At a density of 1.028 the mass equivalents are 1.52×10^{17} tons and 3.00×10^{17} tons. The corresponding amounts of Cl content are shown in Table 1.

TABLE 1. N. ATLANTIC AND N. PACIFIC TOTAL WATER AND Cl CONTENTS.

	Water (tons)	Cl (‰)	Total Cl (tons)
N. Atlantic	1.52×10^{17}	19.42	$2,950 \times 10^{12}$
N. Pacific	3.00×10^{17}	19.11	$5,730 \times 10^{12}$

It is obvious, of course, that water volumes are determined with less accuracy than are the density and the salinities. Computed results will throughout be held to the number of significant figures reasonably justified.

Instead of denoting ocean current flow rates in millions of m^3 per second, use will be made of the "Sverdrup unit." This terminology was proposed by Dunbar (1962). $1\ Sv = 10^6 m^3/sec$.

III. NON-CURRENT FACTORS

Evaporation and Precipitation

Values for evaporation and precipitation of the two ocean areas have been established by Jacobs (1951), who submits the figures listed in Table 2.

TABLE 2. EXCESS OF EVAPORATION OVER PRECIPITATION IN THE N. ATLANTIC AND N. PACIFIC.

	Total annual (E-P) m^3
N. Atlantic	13.7×10^{12}
N. Pacific	11.5×10^{12}

In accordance with the geographic limits as defined, the value for the Arctic Mediterranean is not included with the N. Atlantic.

Jacobs' data are derived by taking relative values of precipitation distribution from Scott (1933) and Meinardus (1934) and adjusting these by a factor for each ocean to bring the absolute values into agreement with Wüst's mean latitudinal values (1936). The latter are considered reliable because they are based on an analysis of surface salinity as a function of (E-P) and not like earlier results taken from scattered observations from island and shore stations. The figures in Table 2 shall, therefore, be used here in subsequent calculations.

For purposes of comparison with Jacobs' data, Budyko and Zubenok shall be mentioned. Budyko (1958) places the evaporation for the total world ocean at 1130 mm annually and the total river runoff equivalent to a water layer of 100 mm. He then finds by deduction the precipitation figure of 1030 mm, a value somewhat higher than Jacobs' at 812 mm.

Zubenok (1956), using much the same source material, has set up a water balance for the Arctic, Atlantic, Indian and Pacific oceans shown in Table 3.

TABLE 3. WATER BALANCE OF THE OCEANS IN AMOUNTS PER YEAR (FROM ZUBENOK).

Ocean	Variation in Surface Level				Exchange
	P (mm)	E (mm)	Runoff (mm)	Exchange (mm)	(x 10^{12} m^3)
Arctic	240	120	230	350 (out)	4. 94
Atlantic	780	1040	200	60 (in)	4. 94
Indian	1010	1380	70	300 (in)	22. 02
Pacific	1210	1140	60	130 (out)	21. 45

It is readily seen that in this balance, the water leaving the Arctic Ocean neatly equals that entering the Atlantic, while the excess from the Pacific is taken up by the shortage in the Indian Ocean.

Runoff From Land

The contribution by runoff to the Cl budgets depends on the quantity of annual discharge of water into the basins observed, as well as on the composition of its load of dissolved solids.

In 1936, McEwen calculated the annual world-wide runoff to be 9,000 cubic miles, or 38,000 km^3. He used estimated oceanic precipitation and evaporation of 244, respectively 272 ppm of ocean volume as a basis and found runoff as the (E-P) difference. In 1957, Dietrich using precipitation and evaporation data from more recent source material gave world-wide runoff as 27,000 km^3. Livingstone (1964) of the U. S. Geological Survey has published detailed figures based on direct flow measurements from rivers throughout the world. His annual total of 32,500 km^3 is about mid-between those of McEwen and Dietrich, and it probably represents the best available figure at this time. It shall be used here.

In Table 4 the average annual discharge into the N. Atlantic is listed. Grouping into regions is done in order to utilize known average compositions of dissolved loads for N. America, Africa and Europe. The size of the Amazon discharge prompted separate treatment, and the Orinoco is included with it, as they are similar in composition.

TABLE 4. DISCHARGE INTO NORTH ATLANTIC OCEAN. (ADAPTED FROM LIVINGSTONE AND BAUER).

Region	Source	Runoff	
		$\times 10^3$ ft^3 per sec.	$\times 10^9$ m^3 per yr.
A	Nelson R., Keewatin Terr.	239	214
	Other Hudson Bay	592	528
	Labrador, Newfoundland	206	184
	St. Lawrence River	500	447
	U. S. Atlantic Slope	545	487
	Mississippi	620	554
	Western Gulf of Mexico	55	49
	Central America	332	297
B	Orinoco River	600	536
	Amazon River	3, 600	3, 220
C	Niger River	326	291
	Other African West Coast	75	67
D	Rhine, Elbe Rivers	100	89
	Other Western Europe	700	626
E	Greenland		525

The chemistry of rain as source material of runoff varies greatly depending on the history of the air mass from which it falls.

Moreover, water of heavy rain falling on a river basin has less opportunity for concentration by evaporation and is less concentrated to start with than is the case for water of light showers. In subsequent steps of the cycle, water percolating through the soil will attack mineral constituents physically and chemically, leaching out the soluble fractions at varying rates. As the final discharge chemistry is a function of these two variables, rain composition and the leaching process, it is obvious that the most important factor affecting the temporal variability within a given river basin is the relative contributions of ground water and surface runoff. The discharge rate of the heavily charged ground water flow is somewhat stable while the more dilute surface runoff fluctuates readily with precipitation.

Concentration of dissolved load thus bears a complex but roughly inverse relationship to discharge, the net effect being highest in arid lands. It is interesting to note, however, that the relative proportions of the constituents remain reasonably constant when a large region is observed, as seen from Table 5. This is true even for a single river such as the Amazon, so long as its drainage basin is large enough to represent in the mean composition of its rocks the mean composition of the Earth's surface rocks.

TABLE 5. MAJOR CONSTITUENTS IN PERCENTAGES OF TOTAL DISSOLVED LOADS. (ADAPTED FROM LIVINGSTONE).

Region	HCO_3	SO_4	Cl	NO_3	Ca	Mg	Na	K	Fe	SiO_2
World Avg.	48.7	9.4	6.5	.8	12.5	3.4	5.3	1.9	.6	10.9
Africa	35.6	11.1	10.0	.6	10.3	3.1	9.1	-	1.0	19.2
N. America	47.8	14.0	5.6	.7	14.7	3.5	6.3	1.0	.1	6.3
Asia	55.7	5.9	6.1	.5	13.0	3.9	6.6		-	8.3
Amazon	41.6	1.9	6.0	-	12.5	1.1	3.7	4.2	4.4	24.6

Something analogous to the oceanic law of relative proportions is in evidence here, although the proportions of course are materially different. The purpose of this discussion is to establish the sufficiency of using the discharge by region into the N. Atlantic, in turn multiplying the discharge figures by the average dissolved load for the region.

Discharge into the N. Pacific is listed in Table 6. It should be noted that detailed data are on hand from Japan, while the Asiatic mainland is poorly known, hydrologically. As the total discharge is modest, it is unlikely, though, that serious error is introduced. The East Indies have been assumed to undergo the same chemical denudation as tropical Asia, i. e., 83 metric tons per mi^2 annually. Their share of runoff has accordingly been determined proportionately to area. The data from Tables 4 and 6 are summarized in Table 7.

TABLE 6. DISCHARGE INTO NORTH PACIFIC OCEAN. (ADAPTED FROM LIVINGSTONE).

Region	Source	Runoff	
		x 10^3 ft^3 per sec.	x 10^9 m^3 per yr.
F	Japan and Korea	225	201
G	Mainland Asia	2, 250	2, 010
	East Indies	153	136
H	Central America	165	147
	N. American Pacific Slope	799	715
	Yukon and South Alaska	394	352

TABLE 7. ANNUAL TOTAL DISSOLVED LOADS DISCHARGED INTO N. ATLANTIC AND N. PACIFIC, BY REGION.

Region	Runoff x 10^9 m^3	Mean ppm of Cl	Total Cl x 10^9 tons	Mean ppm diss sol	Total load x 10^9 tons
A	2, 760	8. 0	. 0221	142	. 392
B	3, 756	2. 5	. 0093	56	. 210
C	358	12. 1	. 0043	121	. 043
D	715	6. 9	. 0049	182	. 130
E	525	3. 0	. 0016	15	. 008
Total	8, 114		. 0422		. 775
F	201	7. 4	. 0015	111	. 022
G	2, 146	8. 7	. 0187	142	. 305
H	1, 214	8. 0	. 0097	142	. 172
Total	3, 561		. 0299		. 499

As for the Greenland region, Bauer (1954) has estimated the glacial runoff and ice contributions from the Greenland coasts. His results are listed in Table 8. Allowing for some melting in the Norwegian Sea where a small branch of the North Atlantic Current introduces some heat, 235 km^3 of glacial ice will be assumed to enter the N. Atlantic, producing 210 km^3 of water. As the liquid discharge is estimated to be 315 km^3 a total of 525 km^3 accrues.

TABLE 8. GLACIAL DISCHARGE FROM THE GREENLAND INLANDSIS.

Region	Discharge in km^3/year	
	Ice	Liquid Runoff
North Greenland	10	
West Coast	90	
Melville Bay	20	
East Coast	120	
Total	240	315

The comparative purity of this discharge is obvious. The glacial ice bergs contain essentially the chemicals inherent in the snow from which they were compacted. The runoff from the Ice Cap has not been subject to the percolation and leaching processes normal at lower latitudes but has traveled the short distance to the sea without much opportunity for enrichment by solution of terrestrial elements. The selected average values of 3 ppm of Cl and 15 ppm of total dissolved solids render the Greenland contributions very minor ones, yet they are probably overstated, if anything.

Wind-Borne Salt

It is well known that salt is carried in crystal form by the sea wind, although the interaction of the factors regulating the pick-up process is as yet poorly understood. Williams (1962) states that each m^3 of sea air carries from .07 mg to .5 mg of Cl. Woodcock (1957) quotes a measured salt fall of 3.8 lbs per acre per year over the U. S.

Wind-borne Cl is certainly related to the (E-P) but will be treated here as a separate item. Determination of its magnitude may be done by utilizing some of the data with which Conway (1942) supports his theory covering diffusion of Cl into the soil and surface waters. The mathematical relationship between distance from sea and total Cl concentration C in surface water has been approximated by Conway as--

$$C = c_1 + c_2$$

where $c_1 = 5.7\, e^{-.059x}$ is the concentration of Cl in ppm in surface water resulting from primary Cl deposition at a distance x miles from the sea, while $c_2 = .55\, e^{-.0039x}$ is the concentration of Cl in ppm resulting from secondary Cl deposition.

The primary deposition takes place along the coast and is significant only in a strip some 100 km wide. The origin of the primary deposition is unquestionably the sea. The secondary deposition varies much less with distance from the sea, as seen from the above equation, and considering its origin, Conway suggests that it may either represent a different state or condition of sea chloride in the atmosphere, with a different diffusion rate, or derive ultimately from volcanic Cl driven into the higher regions of the atmosphere and existing possibly in a different form from sea Cl. Establishing a balance of Cl drainage to the ocean, Conway evaluated the sources of this Cl and found that the primary process accounted for 18%, the secondary process for 26% of total Cl discharged into the sea. In view of the uncertain origin of the secondary Cl, one-half shall here be assumed to derive from the sea. Thus, atmospheric transport of sea-derived Cl is equivalent to 18% + $\frac{1}{2}$ (26%) = 31% of total Cl discharged into the sea.

Total world runoff of Cl can be computed from the data given by Livingstone (1963) as $.25 \times 10^9$ tons/year. The atmospheric Cl transport on this basis becomes $.25 \times 10^9 \times .31 = .078 \times 10^9$ tons/year. If this amount is apportioned in proportion to area, and the areas of the N. Atlantic and the N. Pacific are 11.8% and 21.8% of the world ocean area, the pick-up of wind-borne Cl from the two sources can be determined as $.009 \times 10^9$ and $.017 \times 10^9$ tons/year, respectively.

It is recognized that the Atlantic and the Pacific may not contribute equally by unit area. The production is tied to the bursting of bubbles such as occur in whitecaps and surf, and local weather patterns, average wind strength, etc. will govern the total in any given region. Eriksson (1959) estimates the total production over the sea at 10^9 tons/year. This is some ten times the amount participating in the salt cycle, so it could be assumed that only 10% of the air-borne Cl is deposited on land, while 90% will fall back into the sea, much of it probably close to the point of origin. If such is the case, apportionment on the basis of length of shore line weighted in accordance with an elaborate analysis of prevailing winds might yield better values for the two oceans. In view of the modest quantities of Cl involved, however, the crude apportionment above will be used, with the acknowledgement that the totals might be off by a factor of two or three.

Drifting Ice

Current-Driven Ice

Beside the previously computed runoff, an amount of drifting ice enters the N. Atlantic from the Greenland Sea and the Labrador Sea, a phenomenon without parallel in the Pacific, where the Bering Strait currents do not promote entry. This ice derives partly from the pack covering the North Polar Basin, partly it is of glacial origin as bergs calving off glaciers along the Greenland coasts. The latter have been taken into account under Region E in Table 7.

Assigning quantitative values to this ice transport meets with some difficulty, for a very large spread exists between estimates made so far. Defant (1961) estimates an annual southward import through Denmark Strait and Davis Strait of 20, 000 km^3. Gordienko (1960) and numerous other Russian workers have calculated the amounts anywhere from 10, 000 km^3 through Denmark Strait alone to only 1, 300 km^3 through both Denmark Strait and Davis Strait. Discrepancy grows sizeable because the total transport varies as a function of 1) current speeds, 2) current widths, 3) sea ice thickness, 4) degree of cover, 5) magnitude of wind influence, and 6) glacial contribution. As each of these parameters is subject to individual interpretation within wide limits, it is not surprising that the results fail to agree.

When the data are examined, Koch (1945) appears to have the best-substantiated estimate of East Greenland Current speed: 15-17 km/day. Using U. S. Hydrographic Office observations (1958) and an average thickness estimated at 2 m, Vowinckel (1962) pegs the sea ice import through Denmark Strait and Davis Strait at 1, 180 km^3 and 491 km^3, respectively. These figures will be used in the subsequent chapter dealing with surface currents. The chart in Figure 3 shows paths of ice flow.

Figure 3. Routes of entry of drifting ice through Denmark Strait and Davis Strait. (From Koch)

Wind-Driven Ice

In some recent calculations, Vowinckel (1964) argues persuasively that an amount of ice is wind-driven in southwesterly direction on the seaward side of the East Greenland Current, some 100 km^3/year at 65^oN. This wind-driven part of the sea ice flow will be considered as a separate item. If the sea ice salinity is taken to be 4‰ in accordance with Defant (1961), a Cl contribution is found from the wind-driven sea ice of $100 \times 10^9 \times .004 \times .5525$, or $.221 \times 10^9$ tons per year.

Since a salt budget is interesting primarily when viewed over very long periods of time as part of a steady state condition, it may be appropriate here to mention that Koch (1945) analyzed the ice flows off the East Greenland coast in an attempt to determine whether cyclic variation exists. Using abundant historical and saga material as well as archaeological and meteorological data, he concludes that we in this century are near the cold peak of a cyclic change.

As the ice flow figures used here are near the lowest of recent estimates, the error will be ignored, if indeed one is introduced.

IV. BUDGET CRITERIA

Of the physical mechanisms by which water and Cl are transported into or out of the two ocean basins, all have been taken into account except one: currents. If an estimate is made of the currents that bring both Cl and water into the two oceans under study, it is possible to set up two simultaneous budgets for each of the two oceans, one for water and one for Cl. Both budgets must balance. The uncertainty introduced by incomplete knowledge of the abyssal circulation across the equator is thereby obviated, for while either budget could be made to balance by "adjusting" the estimate up or down, no such effect could be achieved on the two budgets simultaneously. Each current has its own unique salinity, hence equal amounts of any two currents would affect the budgets differently.

For budgeting purposes, Atlantic and Pacific sections must be analayzed located along the geographic delineations as follows:

1) along equator from Africa to S. America, above 1000 m
2) along Arctic Circle through Davis Strait
3) smallest section through Denmark Strait
4) along a line Iceland-Faeroes-Shetlands-Norway
5) smallest section through Gibraltar
6) along equator from Africa to S. America, below 1000 m
7) smallest section through Bering Strait

8) along a line from Batu Belat to Singapore

9) along the equator, Borneo-Celebes-Halmahera

10) along the equator, Halmahera-Equador

V. N. ATLANTIC CURRENTS AND BUDGET

Section 1

There is fairly general agreement that water is transported across the equator by surface currents at the rate of about 6 Sv. This is done by the branch of the South Equatorial Current which is deflected north at Cape San Roque and Atlantis stations #5463-5471 are strung in a line across it off French Guiana (Figure 4), while the equatorial section is covered by Crawford stations #498-504 (Figure 5). The current is shallow, about 80 m according to Sverdrup (1963), and attains speeds of 20 miles per day during June and July. If 25 cm/sec is assumed as an average speed, the width can be computed as 300 km.

The average salinity of this flow is about 36.40‰, and its main body may well be centered in the tongue enclosed by the 36.5 isopleth visible in Figure 5 at the 45-70 m depth. A current flowing at the rate of 1 Sv will transport 17.92×10^9 tons of Cl per year per each 1‰ salinity. We have then a Cl transport of $6 \times 17.92 \times 10^9 \times 36.4 = 3,910 \times 10^9$ tons/year.

Sverdrup (1963) states that an additional 2 Sv cross the equator northward above a depth of 800 m, approximately. A representative part of the entire equatorial section is shown in Figure 6,

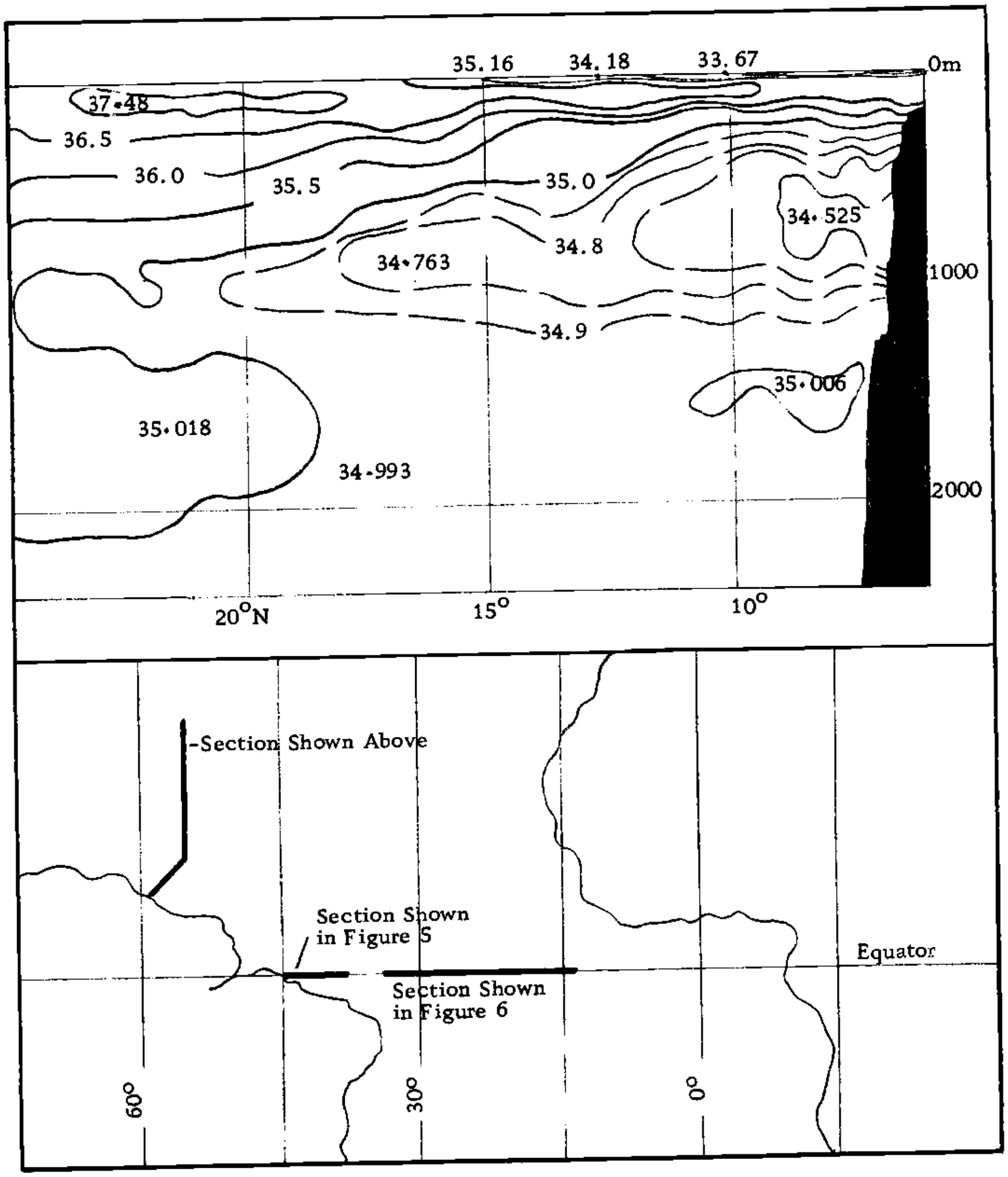

Figure 4. Salinity of upper 2000 m. Data from Atlantis stations #5463-5471. Chart shows locations of Figures 4, 5 and 6.

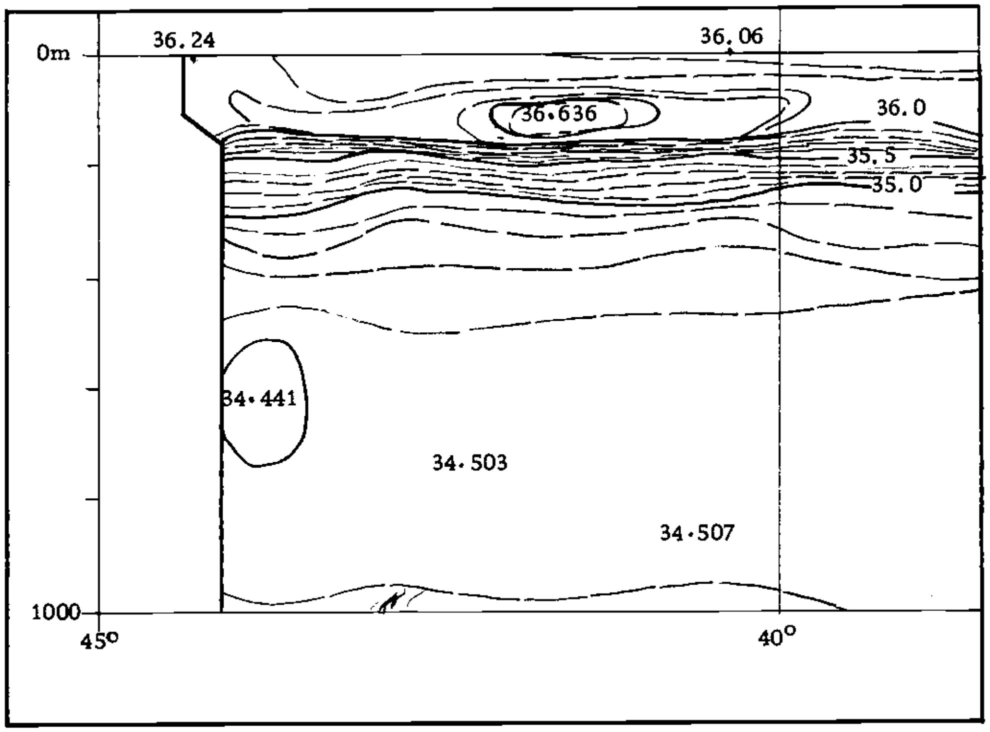

Figure 5. Salinity of upper 1000 m along equator, location shown in Figure 4. Data from Crawford stations #498-504.

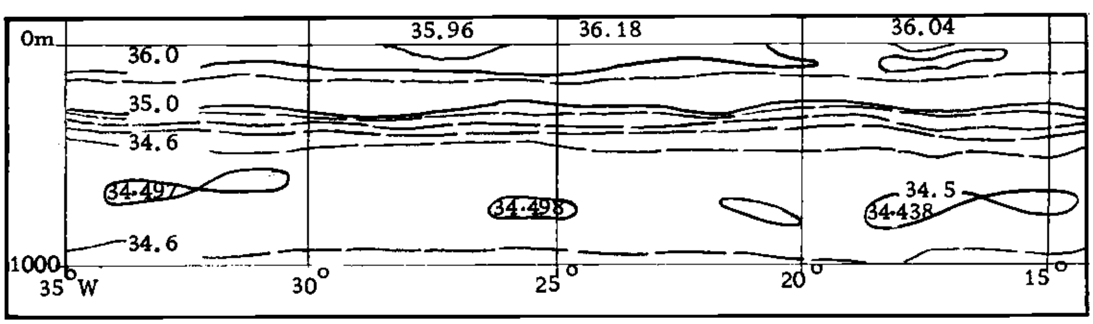

Figure 6. Salinity of upper 1000 m along equator. Location shown in Figure 4. Data from Crawford stations #479-495. (From Fuglister Atlas)

where evidence is found of tongues of Antarctic Intermediate Water moving north. In Figure 4, the same is seen in the N-S plane. If the average salinity is estimated at 34.55‰, the Cl transport amounts to $2 \times 17.92 \times 10^9 \times 34.55 = 1,240 \times 10^9$ tons/year.

Summing up the situation at Section 1, a net import of 8 Sv takes place, bringing with it 5,150 $\times 10^9$ tons of Cl every year.

Section 2

The outflow of water from the North Polar Basin is a continuous process throughout the year. The flow through the Canadian Archipelago has been computed by Collin (1962) as 40×10^{12} m^3/year. Of this, 35×10^{12} m^3 consist of Arctic water of 34.0‰, while the rest is ice and melting water of about 4‰ salinity, giving a Cl import into the N. Atlantic of 650×10^9 tons/year.

Section 3

The East Greenland Current issues from the North Polar Sea between Greenland and Spitsbergen and flows along the Greenland coast, slightly modifying its salinity along the way by admixture of melting water. According to Mosby (1962) no well-established estimate of the transport through Denmark Strait is known to have been made. Mosby estimates the flow at 33.2‰ and 3.69 Sv, taking ice and melting water into consideration. This would correspond to an annual import of Cl in the amount of $3.69 \times 17.92 \times 10^9 \times 33.2 = 2,200 \times 10^9$ tons.

Section 4

This section can be divided into three parts: the shelf between Iceland and the Faeroe Islands; the Faeroe-Shetland Channel; and the shallows of the northern North Sea between the Shetland Islands and Norway.

Between Iceland and the Faeroes, some overflow of deep water from the Norwegian Sea is believed to occur but precise data have not been obtained in quantity due to the highly turbulent nature of the region. Metcalf (1962) mentions 1.4 Sv of pure Norwegian Sea overflow. This is water of 0^o temperature and Arctic salinity in the low 34.90's, giving a Cl import of 880×10^9 tons/year.

Through the Faeroe-Shetland Channel, water flows from the N. Atlantic into the Norwegian Sea. The current is variable but a continuous export takes place throughout the year. Mosby (1962) believes the best estimate to be the means of the results of two investigations, which were carried out over the years 1927-59. The values thus derived are 35.3‰ and 3.6 Sv. This gives a Cl export of $2,280 \times 10^9$ tons/year.

In the third part of Section 4, the area between the Shetland Islands and Norway, only very minor transport is found. A slight eddy motion around the Shetlands occurs from the flow through the channel, and farther to the west the Norwegian Coastal Current carries some water of Baltic origin from the Skagerak north along the coast. The amounts are negligible, however, as shown by Jacobsen (1925), who computes the amount of Baltic water passing through Kattegat as .016 x 10^9 m^3/sec. The net transports through Section 4 are shown in Table 9.

TABLE 9. NET TRANSPORT THROUGH SECTION 4: ICELAND-FAEROES-SHETLANDS-NORWAY.

	Water Sv	Cl tons/year x 10^9
Iceland-Faeroes	+1.4	+880
Faeroe-Shetland Channel	-3.6	-2,280
Section 4 Total	-2.2	-1,400

Section 5

The currents through the Strait of Gibraltar have been computed on the basis of sections published by Schott (1928) and it appears that surface water of 36.25‰ salinity flows east at a rate of 1.75 Sv, while deeper water of 37.75‰ salinity crosses the sill in westward direction at a rate of 1.68 Sv. The currents are predicated on the assumption that no net transport of Cl takes place, and a net water export of .07 Sv is therefore the only result from this section.

Section 6: Balance

Assessment of the transport across the equator below a depth of 1000 m must by necessity be made indirectly. Some direct measurements have been made using Swallow floats but the data are still very few and very far between. The picture that emerges is merely one of variability and apparent randomness. Sverdrup (1963) estimates a northward flow of bottom water of 1 Sv. Bottom salinity is 34.8‰, so we have here a Cl import of 620×10^9 tons/year. The totals from currents so far are listed in Table 10. The mean salinity below the 1000 m level at the equator is about 34.92‰, excluding the bottom water. If $7,220 \times 10^9$ tons of Cl is to be removed by water of this salinity, the water transport can be determined as $7,220 \times 10^9 / 34.92 \times 17.92 \times 10^9 = 11.52$ Sv. This figure is now entered in Table 10, and after addition of runoff, the budget shows an excess of 0.43 Sv, or $13.7 \times 10^{12} m^3$/year. This is, rather surprisingly, precisely the figure Jacobs arrived at for the (E-P) value, as shown in Table 2, page 7, so the result is to some extent corroborated by Jacobs' computations. It is illuminating to note that a change in the (E-P) of 10% would necessitate a change in the salinity of the Section 6 export of more than .3‰, were the budget otherwise to balance.

TABLE 10. BUDGET OF WATER AND Cl TRANSPORTS INTO AND OUT OF N. ATLANTIC, BALANCING THROUGH SECTION 6.

Section	Water import-export Sv	Cl import-export tons/year x 10^9
1	+8.0	+5,150
2	+1.26	+650
3	+3.7	+2,200
4	-2.2	-1,400
5	-0.07	-
Section 6--In	+1.0	+620
Totals	+11.69	+7,220
Section 6--Out	-11.52	-7,220
Runoff	+0.26	-
Excess	+0.43	

It is now of interest to evaluate the quantity of Section 6 export in the light of theoretical analyses of deep water circulation, notably those undertaken by Sverdrup (1963), Stommel (1957, 1958, 1960) and Broecker (1960). Such evaluation is made in Chapter VI.

VI. N. PACIFIC CURRENTS AND BUDGET

Section 7

The U. S. Navy has carried out extensive current measurements in Bering Strait, and Mosby (1962) has published details of the flow which follows a cyclic pattern of 12 months' duration. Over the ten months July-April a northward flow (export) occurs, averaging 0. 835 Sv, while the May-June period shows a southward current (import) averaging 0. 23 Sv. The outgoing and incoming waters are of about equal salinity (Sverdrup, 1963), and it will suffice to use the annual average export of 0. 66 Sv and 32. 5‰ salinity. These figures give an annual Cl export of 380×10^9 tons.

Section 8

This section traverses the southern extremity of the South China Sea. The waters are shallow, less than 200 fm, and the currents according to H. O. Sailing Directions (1962) are variable, wind-induced drifts. In consequence, no water transport of any significance can take place.

Section 9

This section through the East Indian Archipelago includes

Makassar Strait between Borneo and Celebes and the Molucca Sea between Celebes and Halmahera. The numerous deep trenches and troughs in the area are described by van Riel (1934) as being renewed by Pacific Equatorial Water. As a result, bottom water of some 34.65‰ moves generally southward across the equator. The surface currents are of nearly the same salinity and the H. O. Sailing Directions (1962) state that they are variable, depending on the monsoon. The water quantities involved throughout the various parts of the section are minor and may be ignored for budgeting purposes.

Section 10: Balance

The present state of exact knowledge permits only an enumeration of known currents affecting the Pacific equatorial section, but without any certainty that others do not still remain undiscovered. Direct measurements have revealed several surface or near-surface currents, which for the purpose at hand may be described as follows.

The Pacific South Equatorial Current and the Cromwell Current flow westward and eastward, respectively, astride the equator. Since the sources as well as the ultimate destinations and dispositions of the currents are uncertain, no conclusion can be drawn as to their water transport through Section 10, if any. The Peru Coastal Current sends part of its water across the equator during northern summer, while in northern winter the Equatorial

Countercurrent sends a branch south across the equator in the same general area. Theorizing about the quantities, however, would be futile as the data are much too scant. Total transports of water and Cl through the section shall instead be established as the balancing items in a budget, Table 11, as was done for the N. Atlantic.

TABLE 11. BUDGET OF WATER AND Cl INTO AND OUT OF THE N. PACIFIC, BALANCING THROUGH SECTION 10.

Section	Water import-export Sv	Cl import-export $\times 10^9$ tons/year
7	-.66	-380
8-9	-	-
Runoff	+.11	+.030
(E-P)	-.38	-
Totals	-.93	-380
Section 10	+.93	+380

It is readily realized that over the enormous expanse of the Pacific equatorial section, the relatively slight amounts of water and Cl found in Table 11 could be removed by countless combinations of meanderings of current sources or destinations, or by permanent or cyclic water movements. To select any one combination would perforce be idle speculation.

VII. RELATIVE MAGNITUDES OF SALINITY FACTORS

It is now useful to compare the relative magnitudes of the factors bearing upon the exports and imports of Cl and water of the two ocean basins. Table 12 shows the relationships for both water and Cl in either ocean. It is readily seen that the current influence overshadows all other factors to their virtual extinction. The water and Cl values for the incoming Pacific equatorial currents are bracketed, as they represent merely the net inflow that must come about to achieve balance. The +.93 item might for example be the result of 3.93 Sv of water import less 3.00 Sv of water export.

TABLE 12. TABULATION OF IMPORTS AND EXPORTS OF WATER AND Cl FROM ALL MEASUREABLE SOURCES IN THE N. ATLANTIC AND N. PACIFIC OCEANS.

Source	N. Atlantic		N. Pacific	
	Water Sv	Cl x 10^9 t/yr	Water Sv	Cl x 10^9 t/yr
(E-P)	-.43	-	-.38	-
Runoff	+.26	+.042	+.11	+.030
Airborne Cl	-	-.009	-	-.017
Wind-driven Ice	-	+.221	-	-
Currents--In	+13.96	+8,020	(+.93)	(+380)
Currents--Out	-13.79	-8,020	-.66	-380

VIII. DISCUSSION

It is interesting to compare the transports through the equatorial sections of both oceans as here estimated with theoretical results reached by workers approaching the problem in totally different ways. Stommel (1958) has postulated that the ocean basins inevitably develop western boundary currents, basing his deductions on the principles of oceanic circulation enunciated by Hough in 1898 and by Goldsbrough in 1933. The concept involves the thermocline as a causative mechanism in drawing deep water toward the surface and thus regulating the abyssal circulation. The two known deep water source areas in the Weddell Sea and in the N. Atlantic south of Greenland produce in Stommel's calculations 20 Sv each, the water being returned by means of an upward flux spread throughout the ocean.

The net transports across the equator of deep water are 16 Sv southbound for the Atlantic, as shown in Figure 7, and 10 Sv northbound for the Pacific. The corresponding average residence period for the water masses below the thermocline of the N. Atlantic is about 200 years, as computed by King (1962).

Using radiometric techniques Broecker (1960) measured the natural radio-carbon concentration in the dissolved bicarbonate of the major water masses of the Atlantic in order to establish the

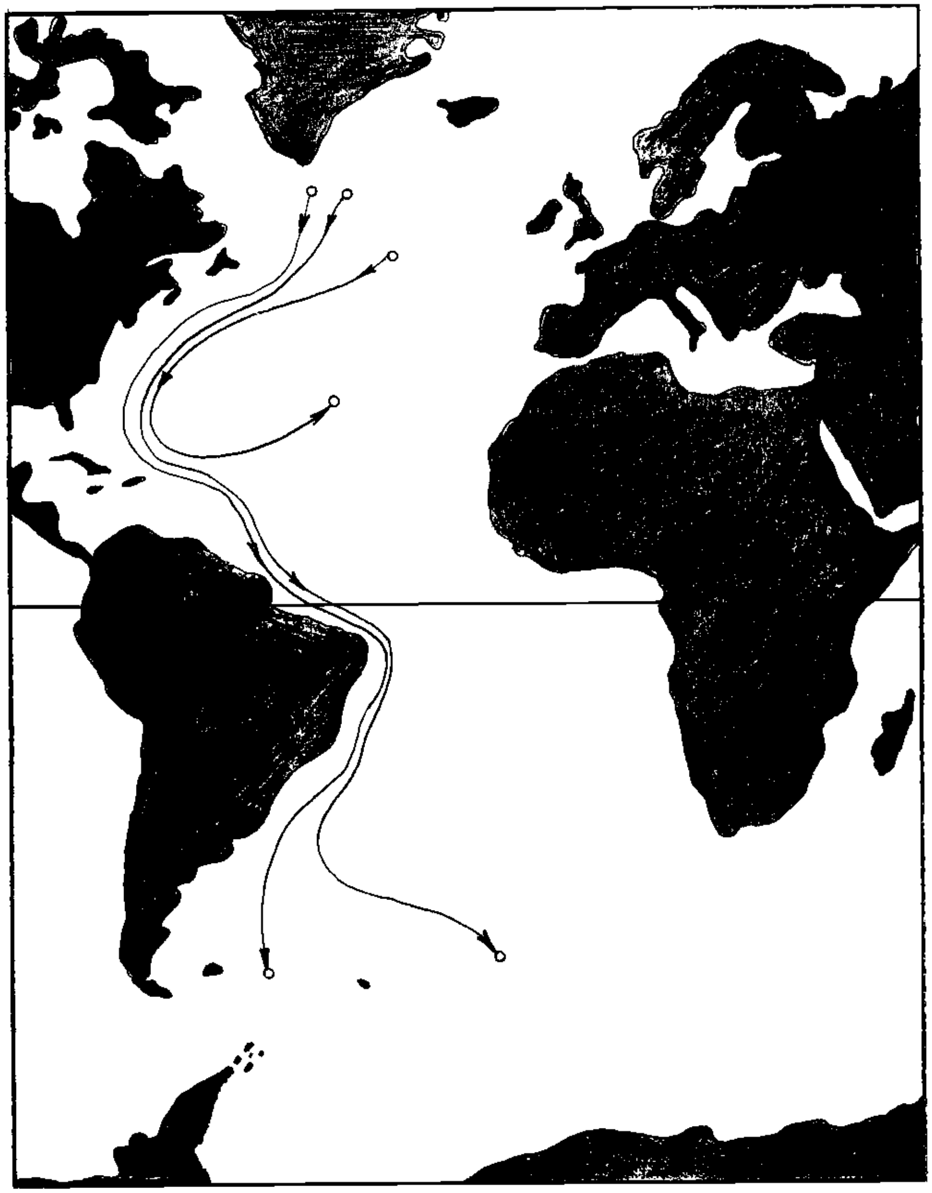

Figure 7. A possible interpretation of total transports in Atlantic bottom layer. Areas of sinking and upwelling are indicated by little circles. Net transport across the equator is 16 Sv. (From Stommel)

absolute rate of overturn of waters in the deep ocean. His results have been graphically summarized in Figure 8 for the N. Atlantic and the totals listed in Table 13 for the purpose of finding an average residence period. The resulting figure of 640 years is no doubt closer to the truth than Stommel's, as it is based on actual direct measurements. It would seem, therefore, that Stommel's upward flux either fails to meet the condition of generalized spreading or that it fails to attain the projected upward velocity component. Hence his abyssal boundary transport is estimated too high.

Sverdrup (1963) estimates that a northward transport of 9 Sv occurs through the equatorial section, distributed as 6 Sv of upper water, 2 Sv of intermediate and 1 Sv of bottom water. Assuming the net transport across the equator to be zero, he then balances by 9 Sv of deep water southbound. The approach used in Table 10 would seem more promising as it takes into account the excess water from (E-P), runoff, import and export through other sections, etc. This view point is justified on the premise that all data used are of very recent date, notably those pertaining to runoff and to currents through the northern approaches to the N. Atlantic. With this qualification, one might accept the figure for the deep equatorial transport (Section 6) in Table 10 as being in good agreement with Sverdrup's.

It has been speculated that the salinity difference between the

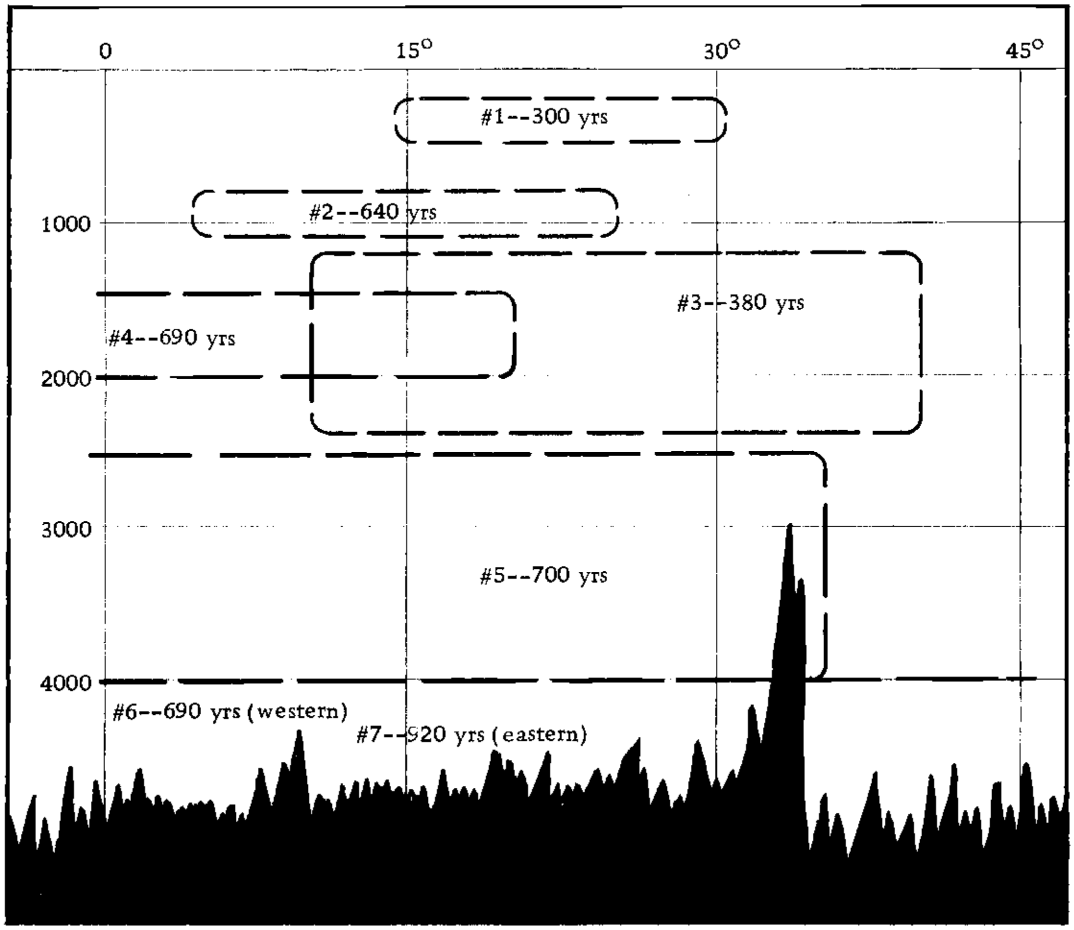

Figure 8. Watermasses in the N. Atlantic age-identified by Broecker through radio-carbon measurements.

TABLE 13. VOLUMES, RESIDENCE PERIODS AND AVERAGE RESIDENCE PERIOD OF WATER MASSES SHOWN IN FIGURE 8.

Water Mass No.	Volume (km^3)	Residence (years)
1	1, 000, 000	300
2	2, 000, 000	640
3	13, 000, 000	380
4	6, 000, 000	690
5	25, 000, 000	700
6	15, 000, 000	690
7	3, 000, 000	920
Weighted average		640

two oceans could be explained by the higher evaporation rate of the Atlantic as compared with the Pacific. In view of the relative magnitudes of the factors shown in Table 13, this would seem a hasty conclusion. The N. Atlantic has (E-P) of the order of .43 Sv and receives runoff at the rate of .26 Sv. The two items taken together give a water loss at the rate of .17 Sv which must be replaced by inflowing ocean water at the rate of .17 Sv. The N. Pacific has an (E-P) rate of .38 Sv and receives runoff at the rate of .11 Sv. Together, the items produce a water deficit at the rate of .27 Sv which must be covered by inflowing ocean water at the rate of .27 Sv. If the replacement waters are of about equal salinity, say 34‰ then we have Cl imports of 104×10^9 and 164×10^9 tons per year. Since the N. Pacific has about twice the mass of the N. Atlantic (Table 1) we have increases that are almost equal: 0.0012‰ salinity increase per year in the N. Atlantic and 0.0010‰ salinity increase in the N. Pacific, ignoring other factors.

As mentioned on page 1, however, the annual salinity change, if any exists, must be less than 0.00025‰, and so it appears that the net effects of Cl transports by currents at least reduce the above increases well below one-fifth of their apparent values, possibly even wipe them out or turn either or both of them into deficit rates.

The conclusion to be drawn from the figures in Table 12 may perhaps be summed up by saying that the effect of all the factors except currents tends to raise the N. Atlantic Cl content relatively more than the N. Pacific Cl content. Since at the same time the importance of the factors dwindles to insignificance when compared with the effect of even slight differences in salinity of the currents feeding and draining the two oceans, the ultimate answer must be gained through greater knowledge of the circulation, particularly in the abyss.

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