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# Transport pathways of polychlorinated biphenyls in Atlantic water

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## ABSTRACT

The distribution of polychlorinated biphenyls (PCBs) in the surface waters of the Atlantic shows concentration maxima in latitudes of high net precipitation and a minimum in the mid-latitudes. Very low PCB concentrations are found in the South Atlantic. Since the nonvolatile inorganic radionuclide distribution in the Atlantic shows no dependence on precipitation patterns, codistillation with evaporating water must be a major factor in determining the distribution of PCBs. Arguments are presented for the net northward migration of PCBs in surface waters with eventual entrainment in the southward North Atlantic Deep Water.

## 1. Introduction

Polychlorobiphenyls (PCBs) are industrial fluids used in many processes and products because of their high resistance to thermal, chemical and biological degradation (Nisbet and Sarofim, 1972). These same properties insure that PCBs, once released to the environment, will be relatively stable and have life times suitable for use as organic geochemical tracers. They are released to the environment, from the products and devices containing them, in various ways and are believed transported to the ocean by the atmosphere mainly in the vapor-aerosol phase (Harvey and Steinhauer, 1974; Bidleman and Olney, 1975; Jernelov, 1974). We believe that a study of the distribution and transport of PCBs within the ocean can be geochemically informative because many of their physical properties, e.g. boiling point, vapor pressure, water solubility and activity coefficients, are intermediate between those of the soluble, nonvolatile inorganic radionuclides, and those of the gaseous fluorocarbons, both of which have been used as tracers on a global scale (Volchok *et al.*, 1971; Wilkniss *et al.*, 1975). Inferences on the large-scale ocean circulation are generally drawn from hydrographic measurements (Fuglister, 1960) or radionuclide data (Bowen *et al.*, 1968) but studies on the distribution of the anthropogenic PCBs can increase our ability to interpret the distributions of some biogenic compounds and, more generally, the cycling of organic carbon in the sea.

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The primary productivity of the ocean is about  $5 \times 10^{16}$  g of carbon per year and is unevenly distributed. Furthermore, the molecular composition and distribution of the resulting organic compounds are poorly understood. Existing methods for determining the total organic carbon content of seawater have not been precise enough to discern major patterns of horizontal transport (Sharpe, 1973). In addition to *in situ* production of organic compounds, Rasmussen and Went (1965) estimate that up to  $4 \times 10^{14}$  g per year of volatile plant terpenes are released on land to the atmosphere. Some of this material must be precipitated into the ocean to form a distribution pattern similar to that of PCBs. However, no data are available.

In addition to recent biogenic inputs of volatile organic compounds into the sea, millions of tons of fossil petroleum are spilled each year. Little is known about its distribution or relocation, because it is very difficult to distinguish what fraction of the total hydrocarbons found at a particular site are of ancient or recent origin (Farrington *et al.*, 1976).

Although no single class of organic compounds can serve as a model tracer for all organics, PCBs offer one solution toward unravelling some of these problems. Because they are produced, used and released exclusively on land, there is no *in situ* input. PCBs are relatively stable and analytically detectable at very low concentrations in air, water, biota and sediments of the open sea by unique chromatographic patterns (Harvey and Steinhauer, 1976). Certain physical properties of PCBs such as their low water solubility or vapor pressure should cause their distribution and transport pathways to be similar to those of many classes of biogenic compounds, e.g. paraffinic and aromatic hydrocarbons, fatty esters, halogenated metabolites and organometallic mercury or arsenic compounds.

Previous descriptions from our laboratory (Harvey *et al.*, 1973; Harvey *et al.*, 1974a) of the open Atlantic distribution of PCBs gave some indication of regional differences in concentration. For example, we had always seen lower concentrations in the Sargasso Sea, an observation confirmed by Bidleman and Olney (1975), and we suggested the possibility of the redistribution of PCBs by codistillation with water from areas of intense evaporation (Harvey and Steinhauer, 1976). However, the data were so widely separated in time and space that intercomparison was difficult. Also, the restrictions on PCB usage which began about 1970 were believed to be causing concentration changes in the Atlantic (Harvey *et al.*, 1974a). Using different collection procedures, Scura and McClure (1975) reported PCB surface concentrations in the Pacific about seven times higher than we measured at the same latitude in the Atlantic in 1974. Furthermore, Scura and McClure observed no decrease with depth. These apparent differences in the depth of PCB penetration in the Atlantic and Pacific are in contrast to our knowledge of  $^{90}\text{Sr}$  and  $^{137}\text{Cs}$  penetration in both oceans (e.g. Pritchard *et al.*, 1971).

Consequently, a set of PCB data was required which had been obtained during a compact time period by a consistent analytical methodology and included a broad

range of latitudes. Those requirements were met between September, 1973 and December, 1975. During that time we were able to measure water concentrations of PCBs in the Atlantic between 54°N and 36°S latitudes on seven separate cruises. The pattern of the distribution and transport pathways of PCBs in the Atlantic that emerged is the subject of this paper.

## 2. Methods

a. *Water collection.* The sampling was accomplished on the following seven cruises:

i) R.V. *Atlantis-II-78*, September-October, 1973, Azores to Barbados, 27°N-09°N.

ii) R.V. *Knorr-33*, September-October, 1973, Woods Hole to Sargasso Sea, 39°N-27°N.

iii) R.V. *Atlantis-II-81*, February, 1974, New England Shelf, 40°N.

iv) R.V. *Atlantis-II-85*, September, 1974, Sargasso Sea, 25°N-29°N.

v) R.V. *Atlantis-II-86*, February, 1975, East of the Antilles, 19°N-14°N.

vi) R.V. *Knorr-51*, September-October, 1975, Scotland to Woods Hole, 54°N-42°N.

vii) R.V. *Atlantis-II-93*, November-December, 1975, Brazil to Republic of South Africa, 11°S-36°S.

Water was collected in an all-metal 65 l sampler (Bodman *et al.*, 1961). In a number of cases a Nansen bottle, fitted with reversing thermometers, was attached 10 m above the Bodman sampler on deep casts. The resulting T-S data from the Nansen and the salinity data from the Bodman were compared to discover possible pretripping or leakage of the large sampler.

Immediately after securing the sampler on the ship the water was drained through hexane rinsed 16 mm copper tubing into 50 l glass carboys, which had been pre-cleaned with hydrofluoric acid and rinsed with hexane. The copper tubing was connected to the sampler faucet with a 5 cm piece of silicone rubber tubing. Extracting and analysis of the silicone tubing showed no interfering contamination as revealed by electron capture gas chromatography.

Immediately after the carboys were filled the seawater was pulled through a column of Amberlite XAD-2 resin (described below) using all copper tubing and a peristaltic pump installed after the column.

b. 1) *Use of Amberlite XAD-2.* The use of Amberlite XAD-2 resin (a crosslinked styrene-divinylbenzene copolymer) for adsorption of chlorinated hydrocarbons from seawater was developed in our laboratory (Harvey, 1972). Since its use has been described only briefly in the literature (Harvey *et al.*, 1973) a full description and rationale is given here.

Because of the low PCB concentrations present in the open sea it is generally

necessary to extract large volumes of seawater, i.e. 50 to 200 l. Solvent extraction is not practical for such large volumes and collection on a solid adsorbant is the preferred method. Several materials, such as polyurethane foam (Uthe *et al.*, 1972), charcoal (Breidenback *et al.*, 1966), undecane coated on chromasorb (Ahling and Jensen, 1970) and polyethylene powder (Harvey, unpublished) have been evaluated in the past. After careful consideration of rate of throughput, efficiency of adsorption and desorption for PCB or DDT, reusability, uniformity, stability and portability of the solid adsorbant, Amberlite XAD-2 was chosen. All adsorption methods, including XAD-2, have the disadvantage of a laborious cleanup of the adsorbant to achieve acceptable blank levels. However, once clean, XAD-2 can be reused at least 20 times. The method which has been used successfully in our laboratory at sea follows.

*b. 2) Cleanup of Amberlite XAD-2 resin.* The commercial resin (20-40 mesh, available from Eastman Chemicals) was placed in a 50 mesh stainless steel sieve and washed with several liters of tap water to remove fines and inorganic contaminants. The resin was air dried and then Soxhlet extracted for 4-8 hours, with one solvent change, with nanograde acetonitrile and for 24 hours with nanograde benzene.

*b. 3) Blank determination.* A 2 cm diameter column was packed with 50 cc of resin, to produce a column with a length/diameter ratio of 6. Higher ratio columns are less efficient. Boiling acetonitrile (200 ml) was poured through the column at full gravity flow into one liter of salt water. The aqueous acetonitrile was extracted with  $2 \times 75$  ml of hexane. The hexane was backwashed once with 25 ml of water, then dried and concentrated to 0.5 ml in a Kuderna-Danish apparatus. Five microliters of the concentrate were injected into a gas chromatograph fitted with a  $2 \text{ m} \times 2 \text{ mm}$  glass column packed with 2% Apiezon L on chromasorb W. An electron capture detector was used. Any resulting peaks which matched the standard Aroclor 1254 were quantified. If the interference was too great the Soxhlet extractions were repeated until the total interference was less than 30 ng for a 100 l sample.

*b. 4) Extraction of seawater.* Seawater (50-200 l) was pumped or gravity fed through the above-described 50 cc column of resin at 250 ml/min. This flow rate of 5 bed volumes per minute is critical. At higher flow rates the contact time is insufficient for PCB or DDT adsorption. At lower flow rates the resin is nondiscriminating and will adsorb even hydrophilic organic matter thus reducing its hydrophobic adsorption properties. At a flow rate of 0.1 bed volumes per minute no dissolved organic carbon elutes from the column until 5 l have passed through (Harvey and Chang, unpublished). Also, at a flow rate of 2 bed volumes per minute 90% of the dissolved humic substances are adsorbed (Stuermer and Harvey, 1976).

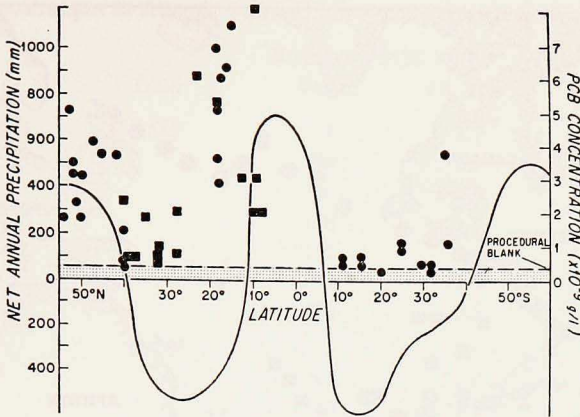


Figure 1. Surface water distribution of PCB in the Atlantic. Squares are for 1973-1974 data and circles are for 1975 data. Solid line represents the net precipitation in mm of water per year.

The column was eluted with acetonitrile and concentrated as described above. The concentrated extract was passed through a 5 cm column of Florisil (60-80 mesh) in a Pasteur pipette. The PCB and DDT family were eluted from the column with one bed volume of 5% diethyl ether in hexane and analyzed by gas chromatography.

*b. 5) Verification of the XAD-2 method.* On several occasions during the development and use of XAD-2 resin for PCB analysis we have verified the reproducibility; duplicate and triplicate analyses of the same sample always agreed within 20%. The variation between separate samples collected at the same station was  $\pm 22\%$  in the South Atlantic and 0-100% in the North Atlantic. The procedural blank was equivalent to 0.0-0.3 ng/l on all seven cruises.

The efficiency of the technique has been checked by simultaneous extraction of a 50 l aliquot of the same sample by hexane, dichloromethane or 5% ethyl ether in hexane. In every case the difference between the results of the XAD-2 method and solvent extraction was less than 20%.

*c. Analysis of PCBs.* Our gas chromatographic quantitation methods have been described in detail previously (Harvey *et al.*, 1974b). However, in all water analyses 12 PCB peaks were used for quantification instead of the six used previously for organisms.

### 3. Results

The concentrations of PCB, plotted by latitude, found in Atlantic surface water

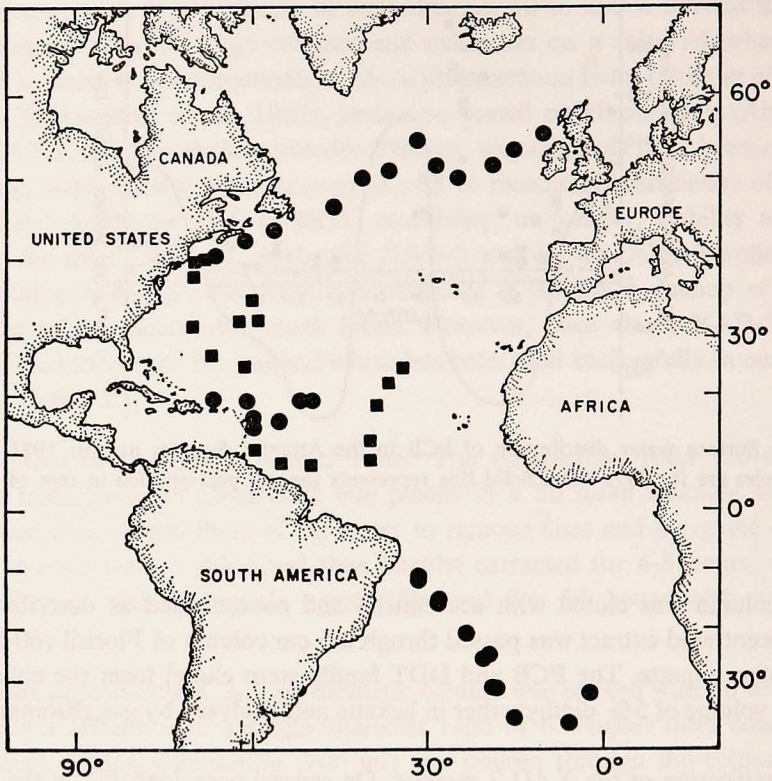


Figure 2. Positions of water stations. Squares are for 1973-1974, circles are for 1975.

between September, 1973 and December, 1975 are presented in Fig. 1. The net annual precipitation (precipitation minus evaporation) by latitude is shown on the same figure. The precipitation-evaporation data were taken from Sverdrup *et al.* (1942) and Starr, *et al.* (1969). PCB concentrations range from  $< 0.3$  ng/l at some sites in the South Atlantic to 8 ng/l in the tropical North Atlantic. Positions of the sampling sites are shown in Fig. 2. Profiles of PCB concentrations in the water column are presented in Tables 1 and 2. The surface water data from which Fig. 1 is derived is presented in Table 3. None of the data presented have been corrected for blanks since they were not determined for every analysis. Conservatively, one could subtract 0.3 ng/l from each determination given in Fig. 1 and Table 3.

In most cases DDT compounds were undetectable by our methods, i.e.  $< 0.1$  ng/l for DDT and  $< 0.03$  ng/l for DDE. However, in the South Atlantic between  $11^{\circ}\text{S}$  and  $15^{\circ}\text{S}$  we observed DDT and DDE concentrations of 0.3 and  $0.1 \times 10^{-9}$  g/l respectively (Table 3). These observations of DDT compounds in the South Atlantic may be accounted for by the increasing use of that insecticide in the Southern Hemisphere, recently characterized by Goldberg (1975) as the "southward tilt."

Table 1. PCB concentrations in Atlantic water within Northeast trades.

Station	Date	Nominal Depth	PCB $\times 10^{-9}$ g/l ( $\pm 20\%$ )	S ‰
09°00N 40°00W	9/73	1	2.7	35.377
		80	1.7	35.703
		100	0.9	35.466
		110	1.8	35.355
		130	1.4	35.197
		200	2.0	34.834
		300	0.8	34.692
09°00N 49°57W	9/73	1	8.0	29.562
		80	1.8	36.460
		80	1.7	—
		100	1.1	36.586
		200	1.6	35.693
		250	1.2	35.466
19°00N 61°15W	2/75	1	3.5	34.765
		50	4.3	35.751
		120	3.9	37.222
		140	4.5	37.169
		180	3.8	36.992
		200	3.9	36.831
18°58N 55°03W	2/75	1	5.0	36.494
		50	8.4	36.872
		130	8.2	37.314
		140	8.7	37.312
		200	6.1	37.066
		850	4.2	34.771

#### 4. Discussion

It is now reasonably established that PCBs are transported to the open sea in the vapor-aerosol state rather than on particulate matter through the atmosphere and that the input from fresh water is negligible (Harvey and Steinhauer, 1974). Thus, one might expect surface water concentrations of PCBs to be highest in those

Table 2. Knorr 51, Leg 4 September-October, 1975. PCB concentration in North Atlantic water at 54°29'N, 31°47'W.

Depth	(PCB) $\times 10^{-9}$ g/l	S ‰
Surface	1.8	34.590
200	1.7	34.766
1000	.8	34.915
2200	.7	34.983
2600	2.4	34.983



Table 3. PCB concentration in Atlantic surface water: 1973-1975.

Station	Date	(PCB) $\times 10^{-9}$ g/l
54°57N 09°30W	9/75	2.5
54°41N 10°27W	9/75	7.1
54°29N 31°47W	9/75	1.8
53°14N 15°19W	9/75	4.8
52°19N 27°48W	9/75	3.5
52°08N 19°00W	9/75	3.1
51°41N 36°04W	10/75	2.2
50°19N 24°31W	9/75	1.2
50°03N 41°41W	10/75	3.2
47°37N 45°57W	10/75	4.2
45°45N 57°02W	10/75	3.8
44°22N 62°34W	10/75	3.9
42°29N 67°07W	10/75	3.6
40°32N 72°44W	2/74	2.3
40°18N 70°48W	2/74	0.4
40°00N 69°00W	2/74	1.4
40°00N 67°00W	2/74	0.4
39°28N 72°29W	10/73	1.1
39°28N 72°13W	10/73	0.6
39°03N 71°35W	10/73	0.6
38°10N 70°50W	10/73	0.6
35°14N 63°36W	9/73	1.8
32°30N 59°40W	9/73	0.9
32°25N 70°20W	10/73	0.6
32°20N 63°01W	9/73	0.6
31°27N 62°10W	9/74	0.7
27°10N 34°20W	9/73	2.0
23°25N 36°16W	9/73	6.5
19°22N 50°47W	2/75	6.8
18°57N 61°18W	2/75	3.5
18°56N 55°01W	2/75	5.0
18°08N 38°12W	9/73	4.2
16°10N 56°14W	2/75	6.1
14°43N 60°00W	2/75	5.8
12°22N 40°00W	9/73	3.1
11°02N 59°17W	9/73	1.2
09°59N 59°17W	9/73	1.8
09°00N 40°00W	9/73	2.7
09°00N 49°57W	9/73	8.0
11°05S 32°14W	12/75	0.5
14°59S 28°56W	12/75	0.5
20°38S 24°31W	12/75	0.4
25°02S 20°52W	12/75	1.1
29°57S 19°23W	12/75	0.5
32°00S 02°58E	12/75	0.3
34°54S 16°09W	12/75	3.7
35°45S 06°49W	12/75	1.1

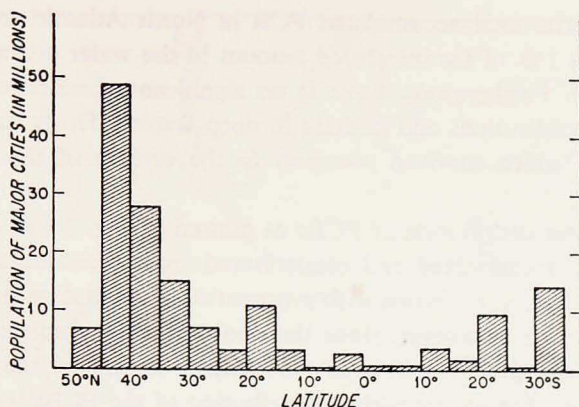


Figure 3. Population in cities on American continents having a census greater than one-half million plotted by 5° latitude bands. Data taken from National Geographic Society World Atlas, 1975.

latitudes in which PCB usage is greatest. The population in cities on the American continents having a census greater than one-half million people is diagrammed in Fig. 3. It is readily seen that 50% of the city population lives between 35° and 45°N latitude. Since the prevailing winds over most of North America are southwesterly one would expect increasing concentrations of PCB in offshore waters from 40°N northward. An examination of the data plotted in Fig. 1 shows this to be the case. However, this correlation based on population and, consequently, industrial density coupled to wind transport does not explain the source of the higher PCB concentrations found between 10° and 20°N. It is unlikely that that PCB is contributed from Europe or Africa by way of the tradewinds since the United States and Japan are the major producers and users. European PCB production is a small fraction of the total (O.E.C.D., 1973).

To understand the observed surface water distribution pattern (Fig. 1) several processes must be considered which could possibly redistribute the PCB after its deposition on the sea surface by wet and dry fallout.

Loss of PCB from surface waters by adsorption on sinking organic debris in areas of high primary productivity does not appear to be important since the mid-latitudes have both low productivity ( $< 100 \text{ mg C/m}^2 \text{ d}$ , FAO, 1972) and low PCB concentrations. Also, unpublished experiments from this laboratory have shown that only about 3% of a mixture of PCBs similar to those found in the ocean (Aroclor 1254, which is mainly pentachlorobiphenyls) is degraded by mixed cultures of marine microorganisms in two months. Most of the degradation occurs within the first two days after introduction of PCB to the system. Geochemical degradation is assumed to be very slow for the reasons cited in the Introduction.

Sedimentation of PCB adsorbed on sinking particles is slow in the time scale

considered here. The total accumulated PCB in North Atlantic sediments is estimated at less than 1% of the integrated amount in the water column (Harvey and Steinhauer, 1976). Furthermore, there is no significant correlation between sedimentary PCB concentrations and latitude in deep waters. These data suggests that most of the PCB which survived transport to the surface of the Atlantic is still being translocated.

The surface water distribution of PCBs as plotted in Fig. 1 can be explained by assuming they are translocated and redistributed from their latitudes of delivery over the Atlantic (Fig. 3) in accord with evaporation-precipitation processes and the major surface currents. However, since the nonvolatile inorganic radionuclides do not show a concentration maxima in the surface waters of the tropical North Atlantic, we assume that atmospheric redistribution of the PCBs is more important than surface currents in explaining their Atlantic distribution.

### **5. Atmospheric transport processes**

The potential importance of evaporation of PCB and other organic compounds from water bodies by codistillation has been pointed out by Mackay and Leinonen (1975). They developed a set of thermodynamic equations which took into account the high activity coefficients of PCBs in water. Although several assumptions were made in deriving their equations which Mackay and Leinonen admit may not reflect conditions in real water bodies, they calculated half-lives of PCBs due to co-evaporation in a one meter water column at 25°C of the order of 10 hours. At lower temperatures, half lives are longer. Although these high evaporative codistillation rates have been verified in the laboratory, Mackay and Leinonen caution that they are not easily confirmed in the natural environment. However, if the relative half-lives of various other compounds calculated by Mackay and Leinonen are correct then one can predict codistillation-translocation patterns of other organic compounds in the sea, such as those mentioned in the Introduction. For example, six naturally occurring aromatic hydrocarbons had half-lives in water similar to PCBs, but the chlorinated cycloaliphatic insecticides Lindane and Dieldrin, which are molecularly similar to many natural products, have half-lives at 25°C of one to two years by codistillation. Octane and 2,2,4-trimethylpentane, which should resemble many of the terrestrial plant volatile terpenes (Rasmussen and Went, 1965), have half-lives of 5 hours, similar to the aromatics.

PCBs probably remain largely in the vapor phase after delivery over the Atlantic in the mid-latitudes where the net precipitation is minimal, especially over the Sargasso Sea. Precipitation fallout of the PCBs north of 40°N would allow them to be carried northward in the North Atlantic Current and southward in the eastern boundary of the central gyre or in the Canaries Current (see Fig. 4). Most PCB carried into the Sargasso Sea by Gulf Stream eddies would be rapidly evaporated and re-entrained in the southwesterlies.

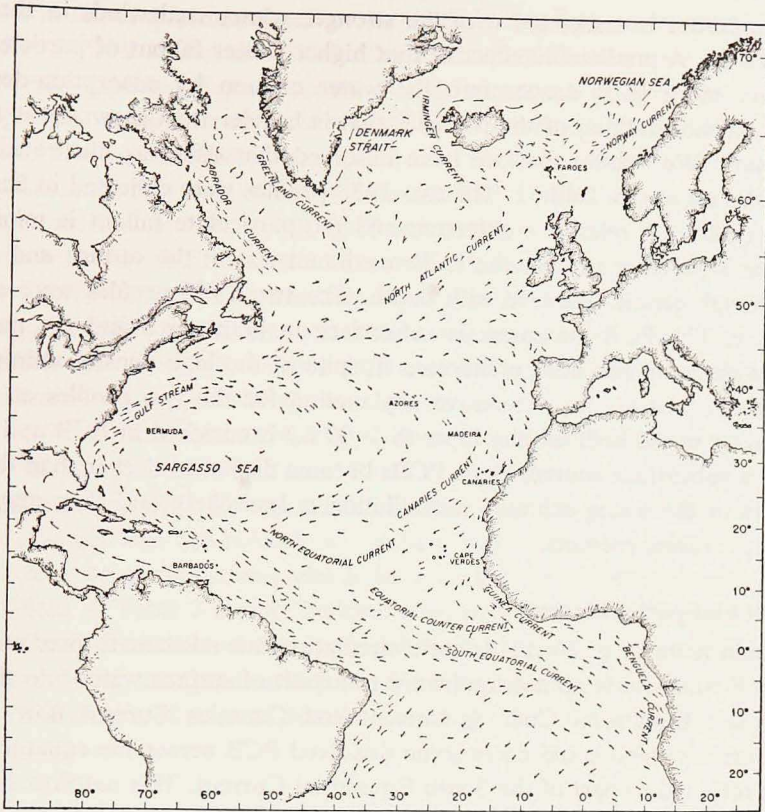


Figure 4. Major surface currents of the Atlantic.

From Fig. 1 it is apparent that very little interhemispheric transport of PCB occurs. The very low PCB concentrations observed between  $10^{\circ}\text{S}$  and  $30^{\circ}\text{S}$  may represent a small amount of atmospheric transport from the North Atlantic but more likely they are due to the industrial cities between those latitudes in Africa and South America (Fig. 3). There is some indication from the two PCB analyses south of  $30^{\circ}\text{S}$  that there is a migration toward the polar region as in the North Atlantic. This same trend of increasing PCB concentrations toward the polar regions is discernible in our data on Atlantic plankton measured in 1971-1972 (Harvey *et al.*, 1974b). It is unfortunate for purposes of comparison with the surface water data that no plankton were collected between  $0^{\circ}$  and  $20^{\circ}\text{N}$  in that work.

We believe that the higher concentrations of PCB found in the tropical North Atlantic are probably transient; this material should be translocated westward and northward both by atmosphere and horizontal water advection. The northeast trade-winds blow steadily throughout the year and the surface water temperature often exceeds  $25^{\circ}$ . Thus, remobilization of the PCBs by evaporative codistillation with water (Mackay and Leinonen, 1975) in seasons of low rainfall is favored. A greater

particulate fallout is associated with the stronger winter tradewinds in the tropics (Folger, 1970). A predictable effect of that higher winter fallout of particles would be to carry more PCB deeper into the water column by adsorption-desorption processes on that fraction of the particles that is heavier than seawater at the time of deposition. We believe that we have observed that effect as illustrated by the PCB profiles set out in Table 1. The two 1973 profiles were collected in September when the trades are relatively quiescent and the particulate fallout is minimal. In both of the September profiles the PCB maximum was at the surface and shows a gradual though erratic decrease with depth. The two 1975 profiles were collected in February. The PCB maximum is subsurface in both cases and the pattern of decrease with depth has been obliterated in spite of the high density salinity maximum at about 140 m. An alternative explanation for the two profiles at 19°N is that the water in the high salinity layer ( $S > 37\text{‰}$ ) is enriched in PCB and is functioning as a subsurface source. Once PCBs become dispersed deeper than the upper few meters of the water column, codistillation is less likely and they may be entrained in the major currents.

## 6. Current transport processes

Two main features of North Atlantic circulation are relevant to predicting PCB transport. First, there is no net southward transport of surface water into the South Atlantic. The Equatorial Counter Current and Canaries Current flow into the Guinea Current which could carry some dissolved PCB across the equator but this would be returned as part of the South Equatorial Current. This net flow of surface water to the north is balanced only by the southward deep currents (Stommel and Arons, 1960). Thus, PCBs could be entrained in the great clockwise gyre between 10° and 45°N. The only escape from this circulation is northward with the North Atlantic Current which flows about Iceland as the Irminger Current or continues into the Norwegian Sea above the Arctic Circle. At high latitudes the low water and air temperatures would greatly reduce codistillation, a process directly proportional to temperature (Mackay and Leinonen, 1975). The low temperatures coupled with the prevailing precipitation would help to keep the PCB in the water column at high latitudes. However, it is precisely at these latitudes that the deep southward return of cold water begins by sinking over the sills of the Denmark Strait or the Iceland-Scotland ridge. In this way the PCB can move with the North Atlantic Deep Water (NADW) eventually into the deep South Atlantic and Pacific. The southward migration of bomb tritium and radiocarbon introduced to the NADW in this way was detected to at least 40°N in 1972 during the Atlantic GEOSECS expedition (Ostlund *et al.*, 1974). The physical-chemical properties of oceanic tritium and radiocarbon are quite different from those of PCB. Consequently, we would not expect the advective transport of PCB within the water column to be the same. We do have one indicative profile that PCB may be advected

southward in the deep return water to the southern hemisphere. A five point profile collected at 54°N is shown in Table 2. The PCB are well mixed in the upper 200 m and show the expected higher concentrations than at an intermediate depth. The two deep water samples with a salinity of 34.983‰ are in Iceland-Scotland overflow water. The higher PCB concentration seen in the 2600 m bottom sample may represent material that was at the surface prior to 1970. In contrast, tritium concentrations are low in the Iceland-Scotland overflow water and show subsurface maxima only in the NADW west of the mid-Atlantic ridge. The profile in Table 2 was taken in the ridge. We do not know what the PCB concentrations were before 1972 north of 50°N but in that year they were at least ten times higher than in 1975 (Harvey *et al.*, 1974). Typical PCB profiles measured during the past three years between 10°N and 30°N show a regular decrease from surface to about 500 m followed by a detectable ( $> 0.3$  ng/l) but uniform concentration to the bottom (Harvey and Steinhauer, 1976). In 1975 PCB concentrations in the South Atlantic were undetectable below 200 m. Clearly, a study of the penetration of PCB into the deep Atlantic with the NADW would be a fruitful area of research to complement the data on radionuclides which have entirely different physical properties. The brief data of Table 2 merely indicate what may be found.

From the previous discussion a crude scheme of the transport pathways of PCBs within the Atlantic emerges in which the ideas presented do not conflict with existing data. The proposed scheme has the advantage that it can be tested by further work.

## 7. Transport pathways of PCB in the Atlantic

PCB enters the open Atlantic mainly between 40° and 45°N in the prevailing southwesterlies from the United States. The airborne PCB is washed out into the surface water along the entire course of their northeast trajectory. That portion which is precipitated between 40° and 50°N can be transported northward into the Norwegian Sea-Denmark Strait regions, or southward with the North Atlantic gyre or the Canaries Current. Accumulation of PCB in the surface water is least in the mid-latitude where net evaporation is highest. Some accumulation will occur in high latitudes mainly because the water temperatures are unfavorable for codistillation, and in the low latitudes where the high net rainfall tends to keep the PCB in the water by frequent washout. However, the warm surface water and the steady northeast tradewinds in the tropical Atlantic favor codistillation of PCB especially during periods of low rainfall. The fate of this PCB is unknown but washout in the western Caribbean and on the eastern slopes of the continental divide of Central America is a possibility. That portion of the PCB in the tropical waters which does not evaporate will be carried northeasterly by the North Atlantic gyre and be returned to the tropics in a few years at most (Bowen *et al.*, 1968). It can escape the gyre by being evaporated while passing through the mid-latitudes, or carried north-

ward into the Denmark Strait and Norwegian Sea with the North Atlantic Current and added to the PCB carried there directly from North America. In these regions the PCB can eventually be entrained with the large sinking water masses which form the southward flowing NADW. This material will be diffused throughout the deep waters of the southern hemisphere.

Undoubtedly, this description could be refined by measuring PCB in the atmosphere and in the NADW along a meridian such as 50°W in the North Atlantic, and by following the PCBs in the northeast trades and underlying water into the western Caribbean.

*Acknowledgments.* We thank the officers and crews of R.V. *Atlantis II* and *Knorr* for their outstanding cooperation during this work. We are especially indebted to V. T. Bowen who provided ship time, advice and criticism throughout the work. R. Oldershaw assisted with the sampling and analyses in the South Atlantic. This work was supported by the National Science Foundation, International Decade of Ocean Exploration under Grants GX-35212 and GX-6435, the Energy Resources and Development Administration under Grant AT (11-1) 3563.00 and the Rockefeller Foundation. Contribution number 3768 from the Woods Hole Oceanographic Institution.

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