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# TRACERS AND MODELING

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The major tracer activity of the last four years was the completion in 1983 of a survey of the North and Tropical Atlantic begun in 1981 as part of the Transient Tracers in the Ocean (TTO) project (Brewer, et al., 1985). An early set of papers (Brewer et al., 1983, and Swift, 1984) discussed evidence from these observations for the freshening of the North Atlantic due to cessation of overflow across the Iceland-Scotland ridge in the period between Geosecs and TTO. Broecker et al. (1985a) examined observations further south within the deep Northeastern Atlantic and showed that there was no change of nutrient contents in this region during the same time span, consistent with their conclusion that there is no ventilation of this region from the north. Kawase and Sarmiento (1985 and 1986) used the TTO data to produce a series of nutrient and salinity maps and property-property plots on density surfaces in the thermocline and middepth waters. Of particular interest in these studies is the evidence from silica-salinity observations of strong cross-isopycnal mixing and advection in the equatorial region.

The latter part of the TTO North Atlantic Study and the entire Tropical Atlantic Study saw the first major chlorofluorocarbon data sets obtained in the Atlantic Ocean. The solubilities of the oceanographically interesting CFC-11 and CFC-12 were determined in laboratory studies by Wisegarver and Cline (1985) and Warner and Weiss (1985), thus allowing the boundary conditions for these tracers to be specified more precisely. Bullister and Weiss (1983) used measurements in the Greenland and Norwegian Seas to estimate ventilation rates in this region, and Weiss et al. (1985) combined data from the North Atlantic with data from the Tropical Atlantic to show that chlorofluorocarbons in the upper North Atlantic Deep Water have arrived all the way from the Labrador Sea to the equator and crossed it on a time scale of order 23 years, suffering a dilution of only a factor of 5 in transit.

The behavior of western boundary currents in the North American Basin was also dicussed by Olson et al. (1986) using tritium and hydrographic observations. The data analyzed in this study imply rapid variations in the formation and spread of North Atlantic Deep Water, presenting a picture which is more complex than that depicted by the freon observations. Recently there have been a series of more detailed surveys of the western boundary including tracer observations (e.g., Hogg et al., 1986) which should help in further understanding these boundary transport processes.



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Dating of waters using freon measurements makes use of the fact that the CFC-11 to CFC-12 ratio in the surface ocean changed significantly through time prior to 1975. Since 1975 the ratio has remained constant. However, the ratio of CFC-11 and CRC-12 to krypton-85, a radioactive isotope with a half-life of 10.76 years which is produced by fission reactions, has not remained constant. Smethie and Mathieu (1986) developed a laboratory facility for measuring this isotope in the oceans and obtained a large number of samples during the TTO program. Early results from these measurements have been used by Smethie et al. (1986) along with tritium, carbon-14, and argon-39, to study the ventilation of the Greenland and Norwegian Seas. They estimate residence times of 24-34 years for deep Greenland Sea with respect to the surface waters, compared with the 35-42 year chlorofluorcarbon based estimate of Bullister and Weiss (1983); and 19-30 years for the deep Norwegian Sea with respect to the deep Greenland Sea, compared with the Bullister and Weiss result of 10-28 years. Further work of interest in the area has been that of Livingston et al. (1985) which showed that in the period from 1972 to 1981 there was an increase of tritium due to atmospheric hydrological recycling and of cesium-137 from European reprocessing plants. These new additions take of the order of two years after entry into the surface waters of the Greenland and Iceland Seas to appear in the Denmark Strait Overflow.

Radioisotopes from the Windscale plant on the Irish Sea have also been observed in the Arctic Ocean at depths of 1500 m (Livington et al., 1984), indicating a transit time of 8 to 10 years. Ostlund and Hut (1984) have shown from tritium and oxygen-18 isotopes as well as salinity that surface and halocline waters of the Arctic have a residence time of 10 years.

Samples for the measurement of carbon-14, tritium, and helium-3, were also collected during the TTO program. Ostlund (1985) gave a preliminary account of the changes in carbon-14 and tritium distributions that have occured along the western Atlantic Geosecs track between Geosecs and TTO. Additional measurements are still being completed in various laboratories.

Reid, D.F. (1984) showed significant variability in radium isotopes measured in the Gulf of Mexico due to transport and mixing of shelf waters into the interior. Radium-224, which has a 3.64 day half life, was used by Levy and Moore (1985) to study mixing processes on the shelf off North Carolina and Georgia, and Chapman et al. (1986) used oxygen isotopes to study flow in the Middle Atlantic Bight. Additional work in the Gulf of Mexico (Morrisong et al. 1983) separated various water types in this region using hydrography and nutrients and also showed an input of bomb produced $^{14}C$ to the deep waters, presumably through dissolution of carbonate particles. Pearcy and Stuiver (1983) used the increase in radiocarbon of deep dwelling organisms in the Pacific to estimate that the organic carbon pool of these organisms has a mean life of about 35 years.

Measurements of tritium and radiocarbon in the Southern Ocean (Jenkins et al., 1983; Chen and Rodman, 1985; and Michel, 1984) showed that Antarctic Bottom and Intermediate waters have had surface contact more recently than the Deep Waters. Tritium values are very low. Jenkins et al. (1983) have used larger samples to reduce the tritium detection limits to .001 TU.

Tracer studies in the Pacific have concentrated on the Tropics where new tracer data to supplement the Geosecs work has been obtained as part of the North Pacific Experiment (Norpax), Equatorial Pacific Ocean Climate Studies (Epocs) and Pacific Equatorial Ocean Dynamics (Pequod) programs. Fine et al. (1983) showed from tritium observations that there was a significant cross-equatorial transport with a southwards transport of the order of $3 \times 10^6$ $m^3 s^{-1}$ into the equatorial region from the northern hemisphere. Upwelling at the equator was suggested to occur above the $\sigma_\theta = 26.0$ surface. In a subsequent paper, Quay et al. (1983) used $^{14}C$ as well as tritium, $\Sigma CO_2, O_2$, and salinity observations to constrain a multilayer mixing model that gave an equatorial upwelling rate of $47 \times 10^6 m^3 s^{-1}$ and a maximum depth of upwelling of $\sigma_\theta = 26.5$. Recently, Fine et al. (in press) have given a more detailed discussion of the mechanism of entry of tritium from northern latitudes into the equator.

Feely et al. (in press) showed that the cessation of upwelling during the El Nino event of 1982-83 had a dramatic impact on $pCO_2$ and chlorofluorocarbon-11 saturation levels in surface waters of the central equatorial Pacific. $pCO_2$ was reduced from its usual level of supersaturation to saturation and CFC-11 increased from its usual level of undersaturation. The release of $pCO_2$ into the atmosphere when upwelling was reinitiated was seen as a significant pulse in atmospheric $CO_2$ levels.

$CO_2$ fluxes in and out of the ocean were also studied by Smethie et al. (1985) using radon-222 deficit measurements to obtain gas exchange rates. Sarmiento and Biscaye 1986 used measurements of radon-222 excesses in the Hatteras Abyssal Plains area to study how benthic mixed layers exchange with the interior.

Two studies by Fine (1985) and Toggweiler and Trumbore (1985) explored evidence from tritium and $^{90}Sr$ bomb-test fallout for flow from the Pacific into the Indian Ocean through the Indonesian straits. Geosecs tritium observations show that there is a transport of order $5 \times 10^6 m^3 s^{-1}$ (Fine, 1985). The Toggweiler and Trumbore study makes use of measurements of bomb-test $^{90}Sr$ recorded in corals, which show large localized inputs due to close-in fallout. The use of $^{90}Sr$ observations to study ocean circulation problems, particularly for the higher latitude Northern Hemisphere, will be facilitated by the study of Sarmiento and Gwinn (1986), which analyzed $^{90}Sr$ observations from the atmosphere and in precipitation to develop a model for prediction of the fallout.

Druffel (1983) has also made use of long term records of isotopes in corals to study long-term variability, in this case of the surface North Atlantic. Her study, which included measurements of oxygen isotopes and $^{14}C$, showed that the Atlantic was $\sim 1^oC$ colder and had higher $^{14}C$ during the Maunder minimum.

The continuing analysis of Geosecs measurements led to several papers during this quadrennium. Broecker et al. (1985) and Broecker el al. (in press) summarized the bomb radiocarbon and tritium inventories on a global scale and compared them with estimated inputs in order to study the redistribution of these tracers by lateral exchange processes. Stuiver and Ostlund (1983) completed the radiocarbon program with a paper summarizing the Indian Ocean and Mediterranean measurements. Stuiver et al. (1983) used the global $^{14}C$ data set to estimate replacement times of 510, 210, and 275 years for the waters below 1500 meters in the Pacific, Indian, and Atlantic Oceans, respectively; and 500 years for the world ocean. Kroopnick (1985) reported on the $^{13}C$ measurements made during the Geosecs program. Moore and Santschi (1986) discussed their Indian Ocean radium-228 measurements.

There was significant additional work on using inverse modeling techniques for constrain-ocean transport. Wunsch (1984) showed that radiocarbon observations in the Atlantic equatorial region significantly constrained an estimate of upwelling. Fiadeiro and Veronis (1984) examined the inverse technique using idealized tracer distributions calculated by a model. They concluded that the inversion of an undetermined system gave results which did not resemble the real flow. These results were challenged by Wunsch (1985) in a debate which is still continuing. The problem of using transient tracers in inverse modeling is examined in a recent paper by Wunsch (in press)

The modeling study of Musgrave (1985) examined how mixing and western boundary currents affect the homogenization of a tracer in a gyre. Sarmiento (1983) carried out a three-dimensional simulation of tritium entry into the Atlantic which illustrated many of the processes that have been inferred from the observations discussed above. Modeling studies are likely to play an increasingly important role in the following quadrennium with the availability of a full three-dimensional data set from the TTO North and Tropical Atlantic Studies. Also planned for 1987 is a major tracer study of the South Atlantic.

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