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Conveyor Belt

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surface extent of the SST-anomaly fields can be carried out with the use of satellite measurements and drifters. Sea-level signatures can be investigated with tide gauges and satellite sea-surface altimetric studies. In both cases, however, these methods provide only a portion of the information required to understand these features.

In order to measure the overall ocean heat content in these regions, it is suggested that a network of heat-content monitoring instruments be considered. Multi-year deployment of a widely-spaced array of instruments capable of monitoring water-column heat content (e.g. inverted echo sounders, IES in a region of with a history of strong SST anomalies, is recommended.) Real-time reporting of IES data may be possible by 'dumping' the data to VOS ships. However, so little is known today about heat storage changes that it is not obvious where the key areas to monitor may lie. The SST-anomaly region off St. Johns, Newfoundland, the SST-anomaly site south of the equator between Brazil and Africa, as well as the various boundaries of the Atlantic discussed above, are potential sites.

Coupling these data with the ongoing model studies, and other observations both local (SST, heat content in the upper 500 m, altimetric surface-height observations from satellite) and remote (e.g., severity of winter conditions in bottom-water formation areas, mean surface pressure field), offers an entirely new diagnostic tool for the study of climate variations.

Recommended:

Monitoring of heat content of the water column in regions with strong SST anomalies that may have a strong effect of atmospheric circulation.

Further Information

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EX 138

ACCP

Executive Summary

The rate at which greenhouse warming will take place is a critical unknown in mankind's ability to react to climate change. Predictions based on atmospheric models indicate a global warming ranging from 1.5° C. to 4.0° C. in response to a doubling of greenhouse gases. Whether this warming takes place in 50 years or 100 years is still not certain. Part of this uncertainty is due to the natural background variability in the climate system associated with the complex interaction between the atmosphere and the global ocean. The instrumental record extending back over the past century reveals substantial climate variations. Outstanding examples are the prolonged droughts on the Great Plains of North America during the 1930's and the African Sahel drought in more recent times. The credibility of model projections of greenhouse warming into the next century depends on gaining a better understanding of these significant climate variations in the recent past.

Due to the enormous heat capacity of the ocean, and the large fluxes of heat across the air-sea interface, all climate variations of more than a few years time-scale must involve the ocean in a very significant way. In recent years there has been real progress in understanding the interaction between the equatorial Pacific and the global atmosphere which constitutes the El Nino phenomenon. A research program is gradually evolving into a practical monitoring system, providing information on a regular basis to the world weather services. There are indications from models and empirical data that the Atlantic may also play an important role in climate variability.

Relative to the Pacific, the Atlantic extends to much higher northern latitudes, and the cooling of relatively saline waters of Southern origin leads to deep mixing in the vicinity of Greenland. The Atlantic may be thought of as an inverted estuary. Surface waters become increasingly saline as they flow in from the Southern Ocean, and the inflowing waters are compensated-for by the outflow of deep relatively fresh deep water. This process has been dubbed the "Atlantic conveyor belt." For a short period in the 1960's, the deep convection near Greenland that contributes to the long term maintenance of the "conveyor belt" was interrupted by a surface layer of very fresh water, which after a few years drifted off to the east. It has been hypothesized that fluctuations in the intensity of the "conveyor belt" could at least in part be responsible for persistent sea-surface-temperature anomalies in the Atlantic. The goal of the Atlantic Climate Change Program (ACCP) is to study the links between the conveyor belt, sea-surface temperature and salinity, and the global response of the atmosphere.

Atmospheric models have already indicated significant connections between Atlantic sea-surface temperature patterns and large-scale atmospheric circulation changes. An important part of the program will be to extend the modeling results to obtain a deeper understanding of the atmospheric response. Historical data-sets based on the record of the past century contain a rich source of information on Atlantic variability. The study of these data sets based on a detailed comparison with ocean and atmospheric model results will represent another element of the program. The third element of the program will be aimed at the design of an effective field program to monitor changes in the Atlantic temperature, salinity, and velocity structures important in producing sea-surface-temperature anomalies.

A large number of field measurements taken by satellites, ships of opportunity, and research groups will be available in the Atlantic during the next decade. ACCP plans a substantial effort to assimilate as much of this data as possible on a real-time basis. Field measurements required to design a long-term, cost-effective monitoring system will only be taken where the goals of ACCP cannot be met with the observations already being planned as part of international programs already in place. The experience gained in the NOAA/STACS program in monitoring the Florida Straits will serve as an important building-block for designing long-term monitoring strategies at other sites.

Advances in modeling and real-time data assimilation provide powerful tools for studying basin-wide processes and designing monitoring grids. There is no more urgent problem connected with climate change than the explanation of the natural variability in the climate record. The timing is appropriate to launch an Atlantic Climate Change Program (ACCP).

Preface

On April 18-19, 1989 an *ad hoc* NOAA panel met at GFDL in Princeton to consider a program to study global climate variability related to thermohaline processes in the Atlantic Ocean. A consensus was reached on a joint undertaking by atmospheric scientists and oceanographers, based on modeling, examination of data sets, and long-term measurements of thermohaline processes in the Atlantic Ocean. It is envisioned that the program should consist of a balanced effort in each of these three areas.

Recent geological findings and coupled ocean-atmosphere model results have provided new insights into the sensitivity of global climate to Atlantic thermohaline processes, which are primarily associated with fluxes of heat and fresh water through the ocean surface. Preliminary experiments with atmospheric models have shown significant response in the global atmosphere to realistic sea-surface-temperature anomalies in the Atlantic. An initial emphasis of the program should be to confirm these atmospheric results and provide more detail. Observations show that sea-surface-temperature anomalies in the Northwest Atlantic are modulated by wind and irregular seasonal thermohaline convection. A particularly important question is why these anomalies persist over many years. The low heat-capacity of the atmosphere implies that these anomalies are intimately tied to changes in the thermocline structure of the ocean and its feedbacks to the atmosphere. The focus here is therefore on the thermohaline circulation and its interaction with the atmosphere. The focus on thermohaline circulation in the Atlantic is deliberate. The signal is strong and the historical data-base is superior to that existing in any other region of thermohaline convection.

The scope of the atmospheric component of the program must be global, while the oceanographic monitoring and measurements would be restricted to the Atlantic in view of indications that this region of the ocean plays a major role in long-term climate variability.

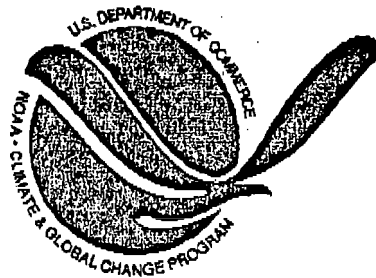
On July 25-27, 1989 a second meeting of the panel and a larger group of invited experts was held at Lamont-Doherty Geological Observatory of Columbia University. A list of members of the *ad hoc* panel which met at Princeton in April and of the attendees of the second meeting at Lamont-Doherty are given in Appendix A. At the Lamont-Doherty meeting the following goals of the Atlantic Climate Change Program were agreed upon:

1. To determine the response of the global atmosphere to persistent SST and sea-ice anomalies in the Atlantic Ocean and to develop coupled ocean-atmosphere models to simulate and predict seasonal-to-decadal change over and around the Atlantic Basin.
2. To monitor, describe, and model the space-time variability of the large-scale meridional circulation of the Atlantic and its relation to variability of SST, sea ice, and salinity over the Atlantic Ocean on seasonal, annual, and interannual time scales.
3. To design an observing program to monitor the changes in the conveyor belt, and to develop a suitable modeling program to assimilate available observations to help understand the mechanisms that determine the fluctuation of the Atlantic thermohaline conveyor belt.

This report is based on the contributions of the participants of these two meetings. Air-sea interaction involving the Atlantic is very poorly understood. At this point it is not possible to make a detailed implementation plan. This report aims to provide the concept of the program based on modeling, analysis of historical data, and field monitoring.

Atlantic Climate Change Program Science Plan

Prepared by the
Atlantic Climate Change Science Working Group



Produced by the
University Corporation for Atmospheric Research

April 1990

ENVIRONMENTAL DEFENSE FUND

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No. of Pages: (5) (including cover)

Comments: Katy - you asked for information

on Salinity changes in

the North Atlantic. This

study was put together

to monitor such changes.

I don't know if they've

found any trends yet.

All the best,

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10.8.91 - Program Dir. NOAA Admin. Climate 301-427-
Tel. Conf. w/ David Goddard 2089 x 38

{ Arnold Gordon - Oceanographer at NOAA
Kurt Bryan - GFDL
→ co-chairs for

Chlorocero

- Fairman & CFC's = tracers
just starting to

measure in 1980's
locations where ocean has come into
touch w/ atmos.

if find in water, know it has
been exposed to atmos

Can see plumes coming down
where they were cored & plotting

only way can produce observations is
if there's a large body of water.

haven't had deep connections

* we don't know how long the
influence has been going on - only have data since
8

Broecker - look at paleoclimatic - deep

cores in N. Atlantic.

Borecher - Younger Dryas consistent
w/ observations in deep water when
see deep water shuts down -
can happen on time scale
of couple decades.

Cold - warm - cold ^{from 1960}
30's early 40's → corresponds to dust bowl

Corresponds w/ SST see in No. Atlantic

Salt & fresh water -

palaeoclimate - switch on & off
problem is that hydrologic cycle &

Manabe at GFDL

"halocline catastrophe"

searching for models to show either a deep
thermohaline circulation (a) to
switch to a mode where fresh water
comes in & shut down conveyor belt
then

Is Hadley Circulation

overdrup 10⁹ cu meters? —

Drum - November on a Norwegian
passel incl. Labrador, Greenland &
Norwegian seas

→ full scale monitoring of
Smelt in northern waters
not necessarily all same as in **grinon**
or Greenland

Off bottom bottom water & deep
water → ^{up} oceanographic
characteristics by which they
come from
can trace

[Antarctic bottom water forms
off Weddell sea

→ densest & coldest & saltiest
will be in deepest part of
basin & will tend also toward
western boundary (heads North
up the Atlantic)
& deep water form in N Atlantic
comes down ~~from~~ along western boundary ^{also}

more No. Atlantic deep water than
Antarctic in most parts of

Antarctic perimeter. H₂O } Sandwich
No. Atlantic deep }
Antarctic bottom H₂O.

relatively few places in world ocean
where deep water formed -- signifying
to climate change where have
formation horizontal exchange

W. Atlantic & Weddell Sea

V. little in the Pacific -- rather
poignant in terms of vertical
circulation

can tell alot of the heat loss
in track of surface

Pacific on shorter time scales
extremely active

ex. El Niño

upper 100-200 m of ocean &
atmos.

the warm pool in the Western Tropical

Pacific

Warming up & cooling off of W. trop. Pac.
= global IR sea from space.

El Niño's wouldn't happen w/o an ocean &
an atmosp. working together.

Atlantic is a North/South flow
Pacific

Western boundaries of oceans are
more active than Eastern side
of pattern of jets!
Coriolis force.

Full stream goes into N. Atlantic
current.

make foli → Conveyer Belt
put in Glob. Wm.
drawer.

The Great Global Conveyor

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Submitted to
Oceanography
1991

INTRODUCTION

A diagram depicting the ocean's "conveyor belt" has been widely adopted as a logo for the Global Change research initiative. This diagram (see figure 1) first appeared as an illustration in an article about the Younger Dryas event which appeared in the November 1987 issue of Natural History. It was designed as a cartoon to help the largely lay readership of this magazine to comprehend one of the elements of the deep sea's circulation system. Had I suspected that it would be widely adopted as a logo, I would have tried to "improve" its accuracy. In hindsight such repairs would likely have ruined the diagram both for the readers of Natural History and for use as a logo.

The lure of this logo is that it symbolizes the importance of linkages between realms of the Earth's climate system. The ocean's conveyor is driven by the salt left behind as the result of the transport of water vapor through the atmosphere from the Atlantic Basin to the Pacific Basin. A byproduct of its operation is the heat which maintains the anomalously warm winter air temperatures enjoyed by northern Europe. A millinnum of very cold conditions known as the Younger Dryas appears to have been the result of a temporary shutdown of the conveyor. Thus the conveyor logo portrays the concern which led to the launching of the Global Change research initiatives; namely devilishly complex interconnections among the elements of our Earth's climate system will greatly complicate our task of predicting the consequences of global pollution.

The objective of this paper is to provide a readable summary, from my prospective, of the conveyor's operation present and past.

IT'S PATH

The main problem with the logo is that it implies that if one were to inject a tracer substance into one of the conveyor's segments it would travel around the loop as a neat package eventually returning to its starting point. As we all know this is hardly the case.

Other circulation "loops" exist in the ocean and mixing occurs among the waters traveling along these intersecting pathways. The logo symbolizes a far more complex situation.

To understand the logo's message, let's start at the point of origin of its lower limb and work our way around the ocean. Waters in the vicinity of Iceland are cooled through contact with the cold winter air masses which sweep in from the Canadian Arctic. The cooling densifies the surface water to the point where it can sink to the abyss and flow southward forming the conveyor's lower limb. In the logo this flow is depicted as a ribbon of water which jets its way through the deep Atlantic from the vicinity of Iceland to the tip of Africa. In reality it is a sluggish mass which fills most of the deep Atlantic. Its flow is more akin to that in a slow moving river than to that in a fast moving mountain stream. This water mass, known to oceanographers as the North Atlantic Deep Water (NADW), stands out as a tongue of high salinity, low nutrient content and high $^{14}\text{C}/^{12}\text{C}$ ratio water in sections drawn along the Atlantic's length (see Figure 2). Its only competitor for space in the deep Atlantic is a wedge of Antarctic Bottom Water (AABW) which underrides the NADW mass. This intruding water is mixed upward into the southward flowing NADW, increasing the transport by the conveyor's lower limb.

Southward of 30°S the lower limb of the conveyor joins a rapidly moving deep current which encircles the Antarctic continent. This current serves as the great mix-master of the world ocean. It blends the NADW exiting the Atlantic with new deep water generated along the perimeter of the Antarctic continent and also with old deep waters recirculated back into the Antarctic from the deep Pacific and Indian Oceans. So efficient is this blending that the NADW entering from the Atlantic loses its identity before it passes even one half of a revolution around the Antarctic!

A rough quantification of the contribution of NADW to the deep waters of world ocean is provided by a property called PO_4^* (Broecker, et al., 1991) which is defined as follows

$$PO_4^* = PO_4 + \frac{O_2}{175} - 1.95 \mu\text{m/kg}$$

where PO_4 and O_2 are the measured phosphate and dissolved oxygen gas concentrations in a given water sample. The coefficient, 175 is the global Redfield coefficient relating O_2 consumption to PO_4 release during respiration (Broecker, et al., 1985) and the coefficient 1.95 is arbitrarily introduced in order to bring the values of PO_4^* into the range of deep water PO_4 concentrations. To the extent that the respiration coefficient is a constant, PO_4^* constitutes a conservative property of any given deep water parcel; the increase in PO_4 due to the oxidation of organic material is exactly balanced by the decrease in $O_2/175$. PO_4^* is attractive as an indicator of the contribution of NADW because deep waters formed in the northern Atlantic have much lower PO_4^* values than those formed in the Southern Ocean. Further the range of PO_4^* values for the northern source waters (0.73 ± 0.03) and for southern source waters (1.67 ± 0.10) is small compared to the difference between the means for these end member values ($1.67 - 0.73 = 0.94$). The nomogram in figure 3 permits the conversion of deep sea PO_4^* values into percentage contribution of NADW.

As can be seen in the map in figure 4, at a depth of 3 kilometers the contribution of NADW to the deep water mix remains strong throughout the Atlantic, but after the conveyor's lower limb passes around the southern tip of Africa into the Antarctic it rapidly becomes blended with the high PO_4^* deep water generated along the edge of the Antarctic continent. In this way an ambient deep water mix with a PO_4^* value of 1.37 is produced (see histograms in figure 4). This blend which consists of 1 part deep water produced in the northern Atlantic with about 2 parts of deep water produced in the Antarctic floods the deep Pacific and Indian Oceans.

A more complete picture of the geometry of the blending process is given by the PO_4^* sections in figure 5. As can be seen, the more dense and higher PO_4^* waters produced in the Antarctic mix upward and northward into the less dense and lower PO_4^* waters entering from the Atlantic. By the time the water reaches the deep Indian, the deep Pacific and the Drake Passage, these endmember waters have been well blended.

As depicted in the logo the lower limb water returns to the surface in the northern Indian and Pacific Oceans. In reality this upwelling is widely spread with a large amount taking place in the Antarctic. The logo also suggests that the major route for return flow to the Atlantic (i.e the conveyor's upper limb) is through the Indonesian archipelago and around the tip of Africa. This view was impressed on my brain by enthusiastic presentations by our society's president who stressed the role of the Agulhas current in global circulation (Gordon and Piola, 1983; Gordon, 1985 and 1986). As discussed below, this route probably accounts for only about one quarter of the return flow. A more important pathway is that through the Antarctic via the Drake Passage into the South Atlantic. These additional upwelling and return flow pathways are portrayed in figure 6.

ITS FLUX

It is my view that the magnitude of transport by the conveyor is best constrained by radiocarbon measurements on samples of deep water from the Atlantic Ocean. Some physical oceanographers might dispute this claim and opt instead for estimates derived from a combination of current meter measurements and geostrophic flow calculations. Fortunately the two approaches yield similar answers.

The radiocarbon based estimate of the flux of NADW into the deep Atlantic is obtained by dividing the volume of water contained in the deep Atlantic by the radiodecay based mean residence time. This estimate must be corrected for the contribution made by

AABW to the conveyor's lower limb. It must also be corrected for the impact of temporal changes in the $^{14}\text{C}/\text{C}$ ratio for atmospheric CO_2 .

The major obstacle to calculation from radiocarbon measurements of residence times for water in the deep Atlantic is the determination of the initial $^{14}\text{C}/\text{C}$ ratio for each parcel. The reason is that all waters in the deep Atlantic are mixtures of northern component water with a comparatively high $^{14}\text{C}/\text{C}$ ratio ($\Delta^{14}\text{C} = -68\text{‰}$) and of southern component water with a comparatively low $^{14}\text{C}/\text{C}$ ratio ($\Delta^{14}\text{C} = -158\text{‰}$). Because of the large difference in the $\Delta^{14}\text{C}$ values for these end members much of the variation in $^{14}\text{C}/\text{C}$ ratio within the deep Atlantic is created by differences in the end member blend. As shown by Broecker et al. (1991a), PO_4^* provides a quite accurate means of establishing the proportions of northern and southern component water in the sample analyzed for radiocarbon. The measured radiocarbon concentration is then subtracted from the initial concentration calculated for the mixture yielding the deficiency attributable to radiodecay. An example of this calculation is shown in Table 1. The radiocarbon measurements used in this analysis were made in the laboratories of Gote Ostlund at the University of Miami and Minze Stuiver at the University of Washington.

Water column averages for radiodecay deficiencies are shown in figure 7 for all the stations occupied during the GEOSECS, TTO, TAS and SAVE expeditions. Little information is lost by this vertical averaging because significant trends with depth are not found for any of the stations. The vertically averaged deficiencies do however show a pronounced geographic trend. The lowest values ($<10\text{‰}$) are found along the western margin of the Atlantic and the highest values ($>30\text{‰}$) along the eastern margin. As radiocarbon decays by 1‰ in 8.27 years, the isolation times corresponding to these radiocarbon deficiencies range from near zero for the western boundary in North Atlantic to as high as 300 years along the eastern boundary. This suggests rapid ventilation from both

ends of the Atlantic along the western boundary coupled with more leisurely dispersion into the interior. The radiocarbon deficiency for the entire deep Atlantic averages about 22‰. This corresponds to a residence time of about 180 years.

The volume of the deep Atlantic reservoir is $1.55 \times 10^{17} \text{ m}^3$ (i.e., 2500m mean thickness with an area of $6.2 \times 10^{13} \text{ m}^2$). Hence to achieve this residence time requires a ventilation flux of $8.6 \times 10^{14} \text{ m}^3/\text{yr}$ or 27 Sverdrups (1 Sverdrup = $10^6 \text{ m}^3/\text{sec}$). As the flux of AABW is about 4 Sverdrups, the flux of NADW is estimated to be 23 Sverdrups.

This calculation assumes the system to be at steady state. While we have no way to know whether this is true for the water fluxes, we do know that the atmosphere's $^{14}\text{C}/\text{C}$ ratio has changed with time. When these changes are taken into account, the flux has to be reduced by a factor of about 0.88 (Broecker et al. 1991b). Hence, we get a flux of close to 20 Sverdrups for the northern component (i.e., NADW). It is difficult to assess the error in this estimate but it is probably on the order of 25% (i.e., ± 5 Sverdrups). To appreciate the immense magnitude of this flux it is important to be reminded that it is 20 times the combined flow of all the world's river and somewhat larger than the rainfall over the entire globe!

ITS DRIVE

My contention is that the conveyor is driven by the excess salt left behind in the Atlantic as the result of vapor export (Broecker, et al., 1985). As can be seen from the map in figure 8, the surface waters of the Atlantic are on the average 1 gm/liter higher in salt content than those in the Pacific. For sea water with temperatures in the range of those constituting the NADW mass (i.e. 2 to 4°C) one gram per liter extra salt has the same impact on the water's density as a cooling of 2 to 3°C. The salinity contrast between surface waters in the northern Atlantic and those at comparable latitudes in the northern Pacific is even larger, ranging from 2 to 3 grams per liter. This difference is so large that

surface waters in the northern Pacific even when cooled to their freezing point (i.e -1.8°C), sink to a depth of only a few hundred meters before reaching their buoyancy limit. Hence no deep water can form in the northern Pacific.

Three means are available by which the magnitude of the vapor export flux can be estimated. The first approach is based on the water budget for the Atlantic Ocean and its continental drainage basin (see figure 9). Baumgartner and Reichel (1975) have constructed a water budget based on estimates of rainfall and evaporation over the Atlantic Ocean and runoff from its drainage basin. Their result is that vapor is being lost from the Atlantic basin at a rate averaging 0.45 Sverdrups.

A second approach is to estimate the vapor export necessary to maintain the salinity differences in the sea against mixing among the ocean's water masses which tends to homogenize the sea's salt. If the mixing rates within can be determined and incorporated into an ocean mixing model, the fresh water budget for any region of the ocean can be determined. Broecker et al., (1990a) adopted this approach. Using a radiocarbon calibrated ocean box model they obtain a flux of 0.25 Sverdrups. The Princeton ocean GCM yields a water vapor loss of 0.45 Sverdrups (Manabe and Stauffer, 1988) and the Hamburg ocean GCM 0.20 Sverdrups (Ernst Maier-Reimer, personal communication).

The third approach involves the determination of the net fluxes of water vapor across segments of boundary separating the Atlantic's drainage basin from the remainder of the world. To do this, Zaucker and Broecker (in press) have used wind and humidity data summarized by Oort (1983) to calculate vertically integrated and annually averaged vapor transports for all positions on the globe (using the $4^{\circ} \times 5^{\circ}$ grid 11 level eggcrate geometry employed by GISS). They obtain in this way a net vapor loss from the Atlantic of 0.32 Sverdrups. In addition to providing an estimate of the magnitude of the vapor loss, this approach also yields the routes for this loss. As is shown in figure 10, vapor loss occurs

both in the belt of northern hemispheres westerlies and in the belt of tropical easterlies. For the westerlies substantially more vapor is exported across Eurasia than is imported across the North American cordillera. For the easterlies substantially more vapor is exported across Central America than is imported across Africa.

Based on these results we estimate that the rate of vapor loss from the Atlantic basin is 0.35 ± 0.12 Sverdrups. To put this flux in context it helps to be reminded that it is about twice that for the Amazon River. Over the course of a year vapor export removes an amount of water equal to that in a 15 cm. thick layer covering the entire Atlantic!

ITS SALT BUDGET

Adopting a 20 Sverdrup export rate for lower limb water and an 0.35 Sverdrup fresh water loss from the Atlantic, it is of interest to see what combination of return flow water could balance the Atlantic's salt budget. As the outgoing lower limb water has a salinity of about 34.9‰ and the outgoing water vapor a salinity of 0.0‰, the aggregate salinity of the return flow water must be about 34.3‰ (see figure 11) or 0.6‰ lower than that of the outflowing lower limb water. Thus the salinity contrast between sea water and water vapor is about 60 times larger than the salinity contrast between the waters being traded between the Atlantic and the remainder of the ocean! It is for this reason that a measly 0.35 Sverdrup vapor loss can drive a mighty 20 Sverdrup ocean current! It should be kept in mind in this regard that were the salt buildup to go uncompensated, the salinity of the entire Atlantic would increase at the rate of about 1.4 gm/liter per millennium. As we shall see below, the conveyor appears to have been running more or less as it does today for the last 9000 years. Had the salt buildup not been compensated, the Atlantic's salinity would have increased during that time by a staggering 13‰. Clearly this can not have been the case. Rather, on the average over this period of time the export of salt via the conveyor's lower limb must have balanced the enrichment of salt by vapor loss.

The "remainder water," which feeds the upper limb of the Atlantic, has three components; Antarctic surface waters passing through the Drake Passage ($S \cong 33.8\text{‰}$), Indian surface water passing around the tip of Africa via the Agulhas Current ($S \cong 35.1\text{‰}$) and intermediate waters formed at the northern perimeter of the Atlantic segment of the Antarctic ($S \cong 34.3\text{‰}$). The salinity of the intermediate water matches that required to achieve salt balance. However this salinity could also be achieved by mixing 1.6 parts Drake Passage surface water with 1 part Agulhas water. So, based on salinity alone it is not possible to say how much of the remainder water enters the South Atlantic at intermediate depth and how much enters at the surface.

A rough idea of the proportions of intermediate water on one hand and the Drake-Agulhas mix on the other can be obtained by invoking another constraint, namely, that the element phosphorus be conserved within the Atlantic. The reason is that the residence time of phosphorus in the ocean (several tens of thousands of years) is roughly 100 times the residence time of water in the Atlantic (several hundreds of years). Hence, there can be no significant gain or loss of phosphorus during a single ventilation cycle; in other words, the phosphorus contained in the exported water must match that contained in the imported water. Before employing this constraint I must point out that it has a possible flaw. While we assume in our calculations that phosphorus is transported only in inorganic form (i.e., PO_4), the finding by Suzuki, et al., 1985, that sizable amounts of organic nitrogen are contained in low nutrient surface waters, opens the possibility that phosphorus is contained in the large molecules or fine particles thought to carry the organic nitrogen. If phosphorus is being shuttled back and forth between organic and inorganic forms, then the constraint suggested here becomes invalid.

The phosphorus constraint stems from the fact that only Agulhas Water carries less PO_4 than outgoing lower limb water; the other contributors to the return flow have 20 to

50% higher phosphate concentrations. Agulhas water carries no PO_4 and Drake Passage water carries about $1.5 \mu\text{m/kg}$ PO_4 ; hence the Agulhas-Drake Passage mix required to yield the right salinity (1 part to 1.6 parts) carries about $0.9 \mu\text{m/kg}$. Intermediate water carries about $1.8 \mu\text{m/kg}$ of PO_4 . Hence to match the $1.3 \mu\text{m/kg}$ of PO_4 carried by the outgoing lower limb water requires a mix of about 56% Agulhas-Drake Passage component and about 44% intermediate water. This then suggests that the 15.35 Sverdrups of remainder water is made up of 6.7 Sverdrups intermediate water, 5.3 Sverdrups of Drake Passage water and 3.3 Sverdrups of Agulhas water. However because of the many simplifications required in order to make this calculation, these fluxes must be taken with a grain of salt (and perhaps also a dram of phosphorus).

ITS BENEFITS

The benefit provided by the conveyor is the heat it releases to the atmosphere over the northern Atlantic. This heat is responsible for Europe's surprisingly mild winters. The amount of heat released to the atmosphere is given by the product of the conveyor's flux and the temperature change required to convert upper limb water to lower limb water (i.e., to create NADW). The temperature of NADW averages about 3°C . As will be shown below, the temperature of the upper limb water averages about 10°C . Thus each cubic centimeter of upper limb water releases 7 calories of heat to the atmosphere during its conversion to deep water. At an average flux of 20 Sverdrups this totals 4×10^{21} calories each year, an amount of heat equal to 35% of that received from Sun by the Atlantic north of 40° latitude!

Manabe and Stauffer (1988) have shown that indeed the thermohaline circulation of the Atlantic maintains high surface water temperatures in the northern Atlantic. Using the GFDL ocean GCM, they demonstrate that circulation in the Atlantic can assume two quite different modes; one with a strong thermohaline component akin to the conveyor and one

with no thermohaline circulation. The difference between surface water temperatures maintained by these modes is shown in figure 12. As can be seen when the conveyor is operative, the temperature of surface waters in the northern Atlantic average 5°C warmer than when it is off. Considering that strength of the thermohaline circulation in the Manabe and Stauffers' conveyor-on mode is only 12 Sverdrups, this warming should be even greater in the real ocean with its 20 Sverdrup thermohaline circulation.

Rind et al., (1986) have used the GISS atmospheric GCM to estimate the geographical pattern of the winter air temperature change supported by the conveyors heat output. They adopted for the surface water temperature difference between the conveyor-on and conveyor-off modes that reconstructed by the CLIMAP group for glacial surface water relative to today's. As shown in figure 13, the air temperature anomaly obtained in this way extends across Europe into Siberia. As we will discuss below this geographic pattern matches very nicely that for the Younger Dryas cooling.

Now let us return to the problem of estimating the temperature of the upper limb water supplying deep water formation in the northern Atlantic. The major supplier of water to the region of deep water formation is the Gulf Stream. As the roots of this great current extend to a depth of 1500 or so meters, the properties of the water supplied to the NADW source region depend strongly on the depth at which the major transport takes place. A large contrast exists between the water from depths of less than 500 meters and water from depths of greater 800 meters (see figure 14). For example, the upper waters have too high a salinity and the deep waters too low a salinity to match that needed to generate NADW. As summarized in figure 15, when the inputs into the northern region of low salinity Bering Sea water and of fresh water (through river runoff and the excess of precipitation over evaporation) are taken into account the salinity of the aggregate upper limb supply water must be about 35.6‰. This value is intermediate between those for upper and lower

Gulf Stream water. A similar situation exists for the nutrient constituents phosphate and silica. The deeper portion of the Gulf Stream carries too high concentrations and the upper portion too low concentrations to match that in outgoing NADW. Thus it appears that a mixture of upper and lower Gulf Stream water is required to create the salinity and nutrient content of new NADW.

Radiocarbon provides a crosscheck on this conclusion (see Broecker, in press a). The pre-nuclear $\Delta^{14}\text{C}$ value for new NADW was close to -66‰ . The feed water for NADW production should have a value 6‰ more negative than this (i.e., $-66 - 6 = -72\text{‰}$). The reason is that CO_2 exchange with the atmosphere adds more radiocarbon to the source region than is lost by radiodecay during residence in the source region. CO_2 exchange raises the $\Delta^{14}\text{C}$ value by 11‰ while radiodecay lowers it by only 5‰ . The pre-nuclear $\Delta^{14}\text{C}$ value for Gulf Stream water was about -50‰ ; and that for lower Gulf stream water about -80‰ . In order to obtain the desired input value of -72‰ requires that about 1 part upper Gulf Stream water be mixed with 2 parts thermocline water carried beneath the Gulf Stream. These proportions match reasonably well those required to create the phosphate and silicate contents of new NADW.

While the proportions of upper and lower Gulf Stream water necessary to achieve the salinity nutrient and radiocarbon contents of new NADW are not well defined, the temperature of the input water should lie between that of about 18°C for the upper water and that of about 6°C for the lower water. A 1 parts upper - 2 parts lower water mixture would have a temperature of 10°C .

ITS ACHILLES HEEL

The addition of fresh water to the northern Atlantic poses a constant threat to the conveyor. Northward of 40°N in the Atlantic precipitation and continental runoff exceed evaporation by about 0.30 Sverdrups (Baumgartner and Reichel, 1975). In addition, the 1 Sverdrup of low salinity ($S \approx 33.0\text{‰}$) water entering the Arctic arm of the Atlantic through the Bering Straits contributes the equivalent of 0.06 Sverdrups of fresh water bringing the total to 0.36 Sverdrups. When the conveyor is running at its current strength of 20 Sverdrups, this fresh water is efficiently swept away causing only an 0.63‰ reduction in the conveyor water's salinity as it passes through the northern Atlantic. If the conveyor were to progressively weaken, this salinity reduction would grow. It would be 0.94‰ at 15 Sverdrups, 1.26‰ at 10 Sverdrups... At some point the salinity reduction would become so large that deep water could no longer form. The conveyor would shut down. Were this to happen, fresh water would pool at the surface of the northern Atlantic much as it currently does in the northern Pacific creating a severe barrier to deep water formation.

Ocean GCM simulations by Manabe and Stauffer (1988) clearly demonstrates the role of this fresh water input. As shown in figure 12, for the conveyor-off mode pooling of fresh waters reduces the salinity surface waters in the northern Atlantic by about 3‰. Maier Reimer and Mikolajewicz, 1989, using the Hamburg ocean GCM show that a modest dose of excess fresh water to the source region of NADW can kill the model's thermohaline circulation. Furthermore, the demise is abrupt occurring on the time scale of a few decades. The rapidity of this response is not surprising for it depends on the residence time of water in the source region. At a flushing rate of 20 Sverdrups the entire volume of water contained in the Atlantic north of 45°N can be replaced in two decades!

We know of no ocean GCM experiment which shows how the conveyor circulation might be restarted. Because of the strong barrier created by the pooling of fresh water, this

may prove to be a tricky task. Microprocesses such as densification through brine formation beneath sea ice may have to be invoked.

ITS HISTORY

The best indicator of the past operation of the conveyor is the air temperature in the northern Atlantic basin. The reason is that as we have already shown turning on and off the conveyor causes 5 to 8°C changes in the air temperatures over Greenland and Europe. The most detailed record of air temperature in the northern Atlantic basin is the isotope record preserved in the Greenland ice cap. This record (see figures 16 and 17) had different character during the last period of glaciation than during the present period of interglaciation (Dansgaard et al., 1971, Hammer et al., 1985). During glacial time air temperatures over Greenland underwent excursions of the magnitude and abruptness expected if the conveyor were turning on and off on an millennial time scale. By contrast, during the 9 or so thousand years since the period of glaciation came to a close, Greenland's air temperature has remained nearly constant. The impression I get from this is that a frenetic glacial conveyor became firmly locked in the on-position at the beginning of post glacial time and has remained so ever since.

A possible explanation for the behavior of the conveyor during glacial time is that when the northern end of the Atlantic Basin is surrounded by ice sheets, stable operation of Atlantic's circulation system is not possible (Broecker, et al., 1990b). Rather, because the ice sheets constitute a tremendous source of fresh water, circulation in the Atlantic tends to flip back and forth between the conveyor-on and conveyor-off modes.. When the conveyor is operative its heat output tends to melt back the ice releasing large amounts of fresh water to the Atlantic. The conveyor also efficiently exports excess salt from the Atlantic. The combination of meltwater dilution and salt export drives down the density of waters in the Atlantic until the point is reached where the conveyor can no longer function.

It goes off. With the conveyor inoperative, the export of salt and the dilution with meltwater are reduced to the point where water vapor export once again begins to enrich salt in the Atlantic. The salt content and hence also the density of Atlantic waters steadily rise until the conveyor turns on again. This cycle repeats over and over again.

Although a rigorous demonstration that such an oscillator did operate is not possible, the facts we do have lend strong support to this scenario. First of all, we know that the 40 million cubic kilometers of excess ice present in the ice sheets of the northern hemisphere during peak glacial time began to melt about 13,000 years ago and was gone by about 8000 years ago. Thus the average flux of meltwater during this interval must have been about 0.25 Sverdrups. Assuming this to be the magnitude of the melting rate during the proposed conveyor-on episodes then the dilution of salt due to meltwater would have been comparable to today's rate of vapor export. If the assumption is made that then as now the conveyor was exporting salt at a rate comparable to the rate it was being enriched through vapor export, then during the conveyor-on episodes, salt would have been diluted at a rate corresponding to the input of meltwater. When the conveyor was off the dominant important term in the salt budget would be vapor export. As yet we do not have an adequate estimate of the rate of water vapor export in the presence of an ice sheet. However, since vapor export is dictated by the interaction of planetary winds with mountain ranges, the rate may not have been very different from today's.

Additional support comes from the observation that the average duration of individual warm and cold episodes recorded in Greenland ice ranges from about one half to two millennia. This spacing is consistent with that expected from the salt oscillation hypothesis. A vapor loss of 0.35 Sverdrups removes a layer 15 cm thick from the Atlantic each year. If uncompensated by salt export, the salt content of Atlantic waters will rise 1.4 gm/liter per millennium! As a salt buildup or reduction of 1 to 2 gm/liter for the Atlantic is

about what is needed to tip the balance between conveyor-on and conveyor-off, a match exists between the observed timing and that predicted timing (Birchfield and Broecker, 1990). This is a strong point in favor of the oscillator hypothesis!

For an oscillator to function requires a combination of a long time constant drift (in this case the buildup or drawdown of salt) and a short time constant stabilization mechanism. In the previous section it was shown that a tendency exists for fresh water to pool at the surface of the northern Atlantic. When the conveyor comes on this pool is quickly destroyed raising the salinity in NADW source region. This stabilizes the conveyor in its on-position. Similarly when the conveyor stops the pool quickly reappears stabilizing the conveyor in its off position.

As can be seen in figure 17, many of the Greenland temperature cycles are characterized by abrupt warmings followed by more gradual coolings. The salt oscillator hypothesis provides a natural explanation for this shape (see Broecker, in press b). The abrupt warmings are caused by turn-ons of the conveyor. Immediately following such a reinitiation, the conveyor runs with extra vigor. The reason is that in order to overcome the fresh water pool present in the northern Atlantic when the conveyor is inoperative, the salinity of the Atlantic would have to rise above the level required for steady state operation. Thus when the conveyor comes on the buoyancy contrast between deep water formed in the northern Atlantic and deep water present in the remainder of the ocean will be unusually large. This excess density will drive the conveyor at an unusually high rate. As a consequence, a greater amount of heat will be released to the atmosphere over the north Atlantic. However, once operative, the conveyor's strength will steadily wane. The reason is that the combination of dilution with meltwater and export of excess salt will lessen the buoyancy contrast between deep waters inside and outside the Atlantic. As the strength of the conveyor wanes, the amount of heat given off to the atmosphere over the

northern Atlantic will also decrease causing air temperatures to drop. Eventually the conveyor will shut down abruptly cutting off the supply of ocean heat. The atmospheric temperature cycle generated in this way resembles that seen in the ice core record (see figure 18).

Only for the most recent of these cycles do we have sufficient auxiliary evidence to add muscle to this scenario. The abrupt warmings at about 12,700 and at about 10,000 radiocarbon years ago, provide smoking guns in this regard. Not only the oxygen isotope record in ice cores (Dansgaard, et al., 1989) but also that in lake sediments on the European continent (Lötter and Zbinden, 1989) demonstrate that both of these warmings were accomplished in only 50 years! Further, the geographic pattern of these temperature changes associated with Younger Dryas is as expected if they were caused by conveyor turn ons. Pronounced changes are confined to latitudes greater than 40°N and extend from the maritime provinces of Canada and the ice cap of Greenland on the west across the northern Atlantic, the British Isles and Scandinavia into Russia on the east (see Rind, et al., 1986 for summary). Finally, Boyle and Keigwin 1987, have shown based on carbon isotope and cadmium concentration measurements on benthic foraminifera shells from a deep sea core from the vicinity of Bermuda that water of Antarctic origin flooded the western basin of deep Atlantic during Younger Dryas time, confirming that a shutdown of deep water formation accompanied this cold event.

ITS FUTURE

When the Natural History article containing the great global conveyor belt diagram appeared, the editor put a sales "stimulator" on the cover which stated "Europe beware: the big chill may be coming." At the time I was much annoyed because no mention of the conveyor's future was made in the article. To make matters worse, even after reading the article itself, many people were left with the impression that I was warning of an imminent

conveyor shutdown. The fact is that at that time I thought that the coming greenhouse warming would, if anything, strengthen the conveyor by increasing the rate of vapor loss from the Atlantic Basin. I had not given serious thought to the question as to whether any changes associated with man's activities might threaten the conveyor.

The first activity which comes to mind in this regard is the rerouting of water for agricultural use. Irrigation projects increase the recycling of water on the continents and thereby change the point at which a given water molecule reenters the ocean. Of particular interest in this regard is the Russian proposal to divert the great northward flowing Siberian Rivers to the south for agricultural use. The result of such a diversion would be to increase the vapor loss from the Atlantic Basin for instead of flowing out of river mouths into the Arctic, the water would move through the atmosphere across Asia into the Pacific Basin. The longterm result would be to strengthen the conveyor.

In addition to increasing vapor export from the Atlantic Basin, the greenhouse warming will increase the transport of fresh water to the northern Atlantic. On the short term (i.e. decades), the salinity decrease created in northern surface waters would be more important than the Atlantic-wide salinity increase caused by increased vapor loss from the Atlantic Basin. The reason is that the replacement time for waters in the northern Atlantic is shorter than the replacement time for waters in the upper limb of the conveyor. So if a threat to the conveyor is in the making, it is most likely to come in this way. To be on guard we should pay close attention to the climate and oceanography of the northern Atlantic Basin. The finding by Brewer et al., 1983 that the salinity of Atlantic deep waters to the north of 50°N declined between 1972 and 1981 and the finding by Schlosser et al., 1991 that deep ventilation of the Greenland Sea was shutdown during the 1980's are indications that changes do occur. Unfortunately we have no way to tell whether these changes signal natural fluctuations or anthropogenically driven trends.

CONCLUSIONS

The conveyor is only one of many elements which together constitute the Earth's climatic system. It stands out because of its dramatic impact on the climate of a single region on our planet. We must keep in mind however, that the abrupt global warmings which heralded the termination of the last major glaciation can certainly not be explained by the conveyor alone (Broecker and Denton, 1989, 1990). Rather, elements of the system, such as the Hadley cell, which influence cloudiness and atmospheric water vapor content must also have been involved. The challenge of the Global Change Research Initiative is to understand the complex web of interactions which tie together the operation of these diverse elements.

ACKNOWLEDGEMENTS

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Table 1. Example of radiocarbon deficiency calculation

GEOSECS STATION 113 (11°N, 20°W, 4741m)

O ₂ μm/kg	PO ₄ μm/kg	Δ ¹⁴ C ‰
239	0.91	-120

$$\begin{aligned} \text{PO}_4^* &= \frac{\text{O}_2}{175} + \text{PO}_4 - 195 \\ &= \frac{239}{175} + 0.91 - 1.95 \\ &= 0.91 \text{ } \mu\text{m/kg} \end{aligned}$$

$$\begin{aligned} \text{frac. no. comp.} &= \frac{1.67 - \text{PO}_4^*}{1.67 - 0.73} = \frac{1.67 - 0.91}{1.67 - 0.73} \\ &= 0.81 \end{aligned}$$

$$\begin{aligned} \text{frac. so. comp.} &= 1 - 0.81 \\ &= 0.19 \end{aligned}$$

$$\begin{aligned} \Delta^{14}\text{C}_{\text{initial}} &= 0.81(-68) + 0.19(-158) \\ &= -84\text{‰} \end{aligned}$$

$$\begin{aligned} \Delta\Delta^{14}\text{C} &= \Delta^{14}\text{C}_{\text{initial}} - \Delta^{14}\text{C}_{\text{measured}} \\ &= (-84) - (-120) \\ &= 36\text{‰} \end{aligned}$$

$$\begin{aligned} \text{apparent age} &= 36\text{‰} \times 8.27 \text{ yr/‰} \\ &\cong 300 \text{ years} \end{aligned}$$

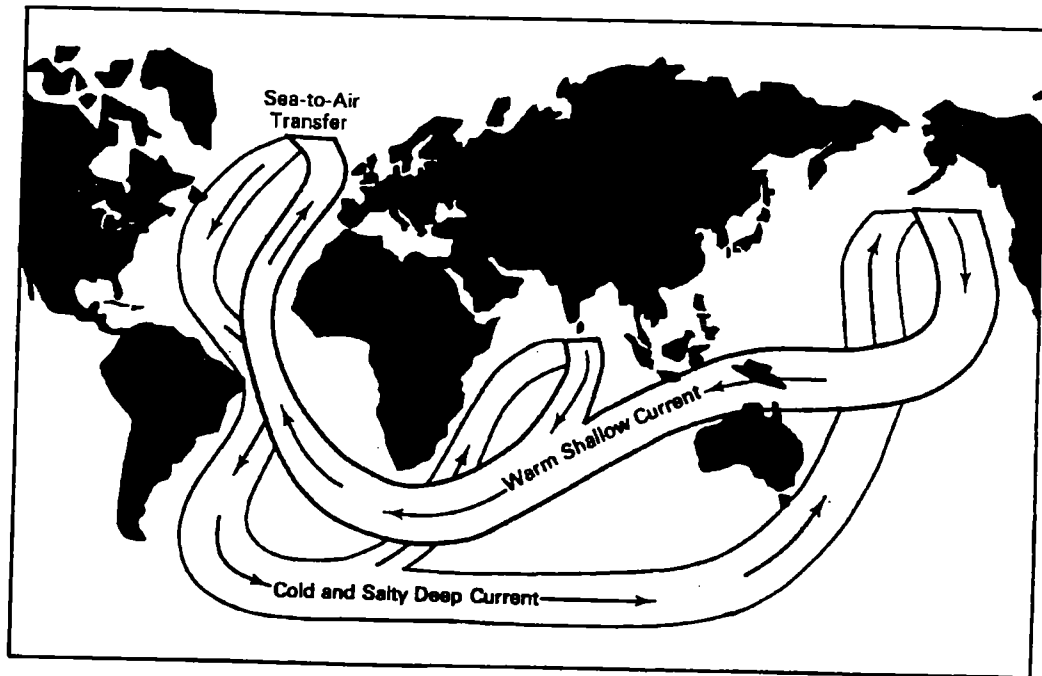


Figure 1. The great ocean conveyor logo (Broecker, 1987).

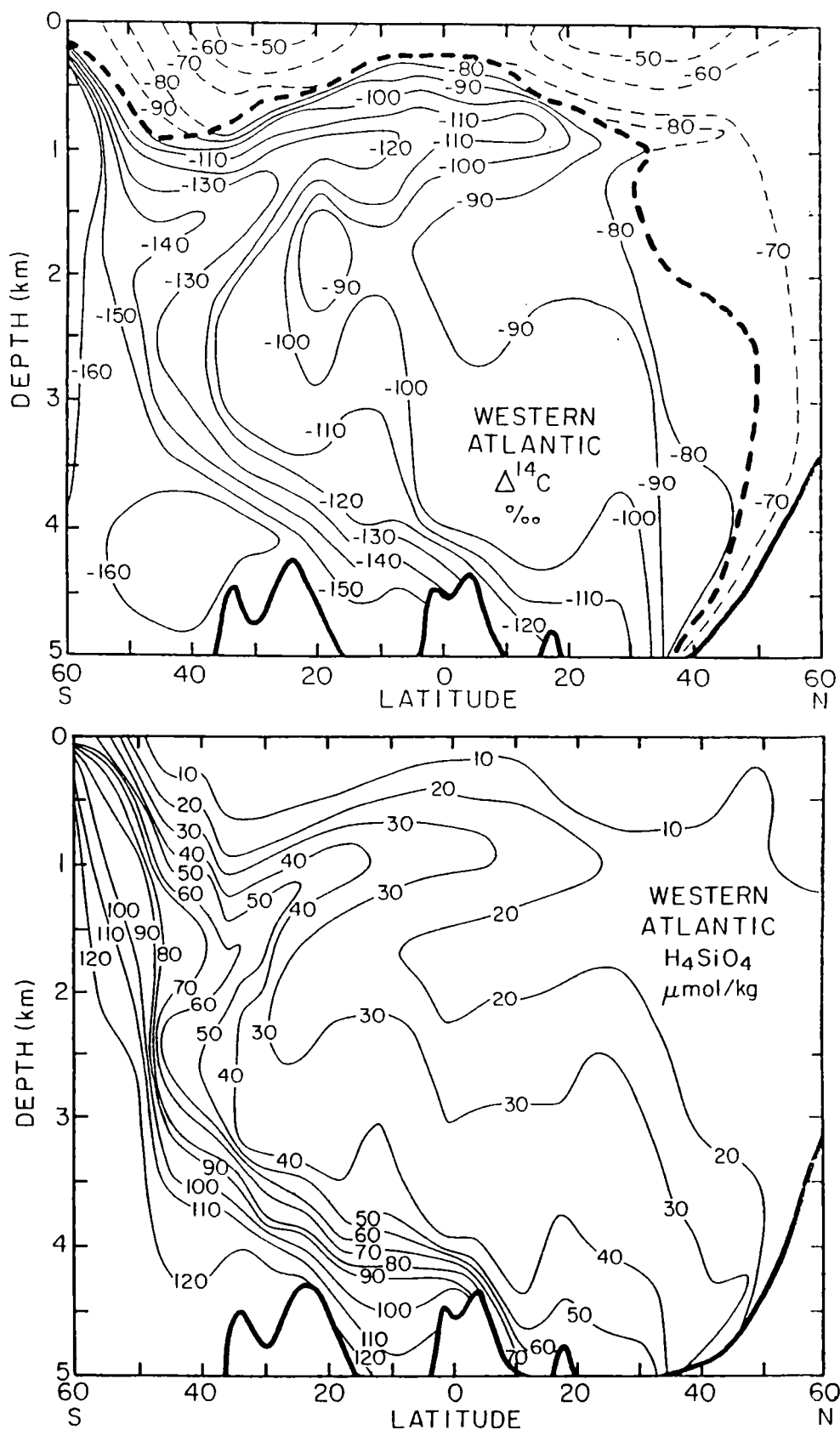
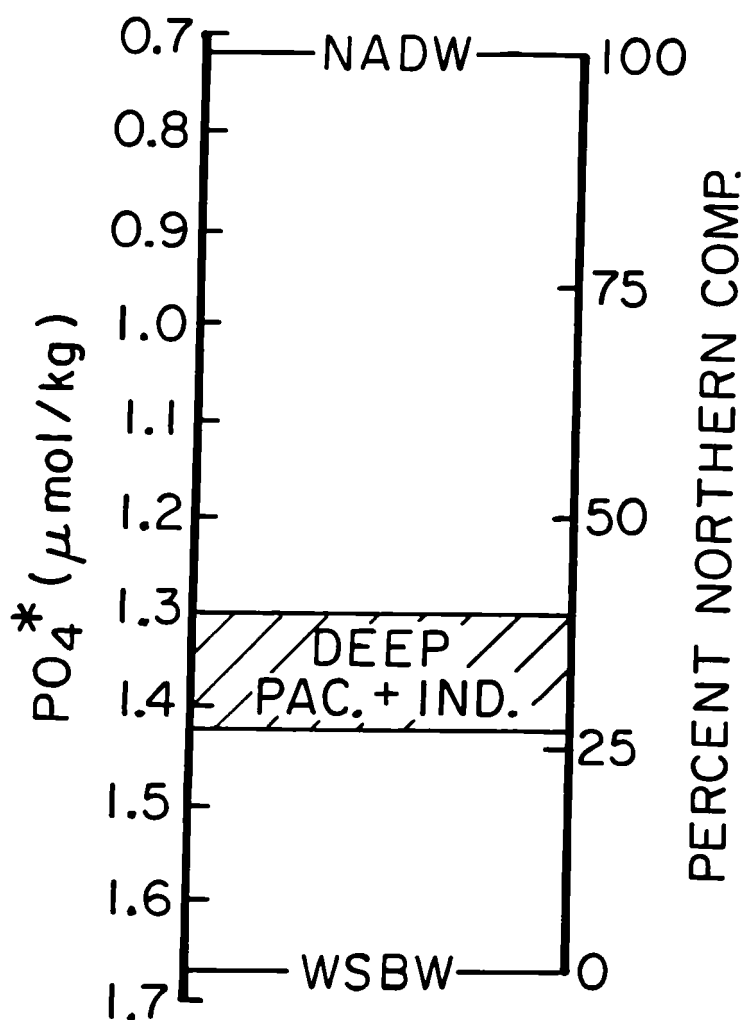


Figure 2. Sections of radiocarbon and of dissolved silicate in the western Atlantic based on measurements made as part of the GEOSECS program. In both the North Atlantic Deep Water clearly stands out from the over and underlying waters of Antarctic origin. The intermediate and bottom waters which enter the Atlantic from the Antarctic have higher in silica concentrations and lower $^{14}\text{C}/\text{C}$ ratios than the NADW which constitutes the conveyor's lower limb.



$$PO_4^* = PO_4 + \frac{O_2}{175} - 1.95$$

Figure 3. Nomogram showing the relationship between PO_4^* value (Broecker, et al., 1991a) and the percentage contribution of NADW to waters in the deep sea mix. Deep waters formed in the northern Atlantic have nearly uniform low PO_4^* values (0.73 ± 0.03 μm/kg). Those which form around the Antarctic continent have high values (between 1.6 and 1.7 μm/kg). Bottom water formed in the Weddell Sea (WSBW) has a PO_4^* value close to 1.67 μm/kg. The deep Pacific and Indian Oceans are flooded with a nearly uniform mix of these two end members (33% NADW + 67% WSBW).

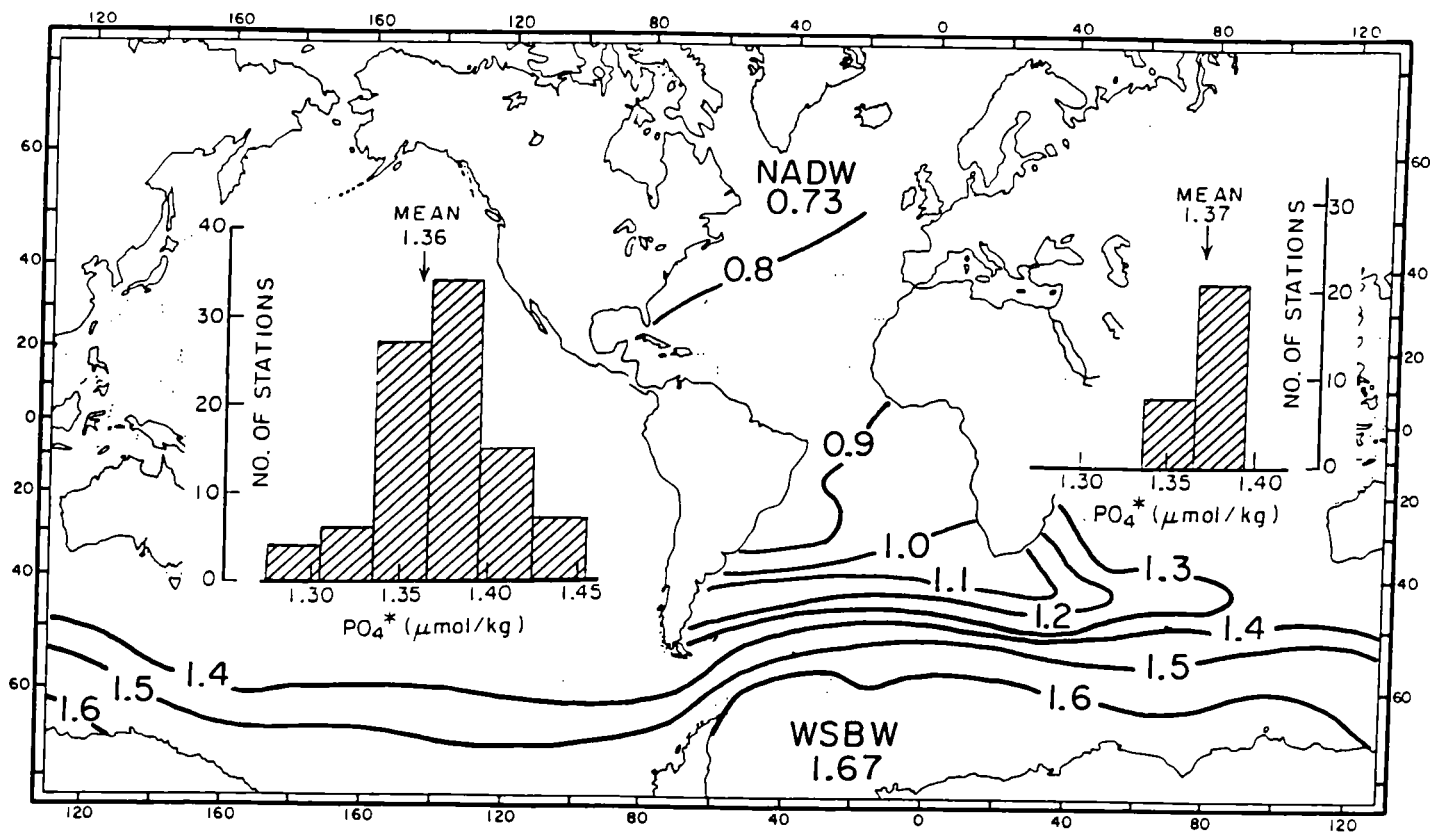


Figure 4. Map of PO_4^* values at 3 kilometers depth. The deep water source in the northern Atlantic has a PO_4^* value of $0.73 \mu\text{mol/kg}$, and that in the Antarctic a value of about $1.67 \mu\text{mol/kg}$. As shown by the histograms, waters on this depth horizon in the Indian and Pacific Oceans have nearly constant PO_4^* values. Although the Pacific GEOSECS stations shows a range of PO_4^* values, the lack of geographic coherence suggests that this spread is the result of station to station shifts in the calibration of the nutrient analyses system.

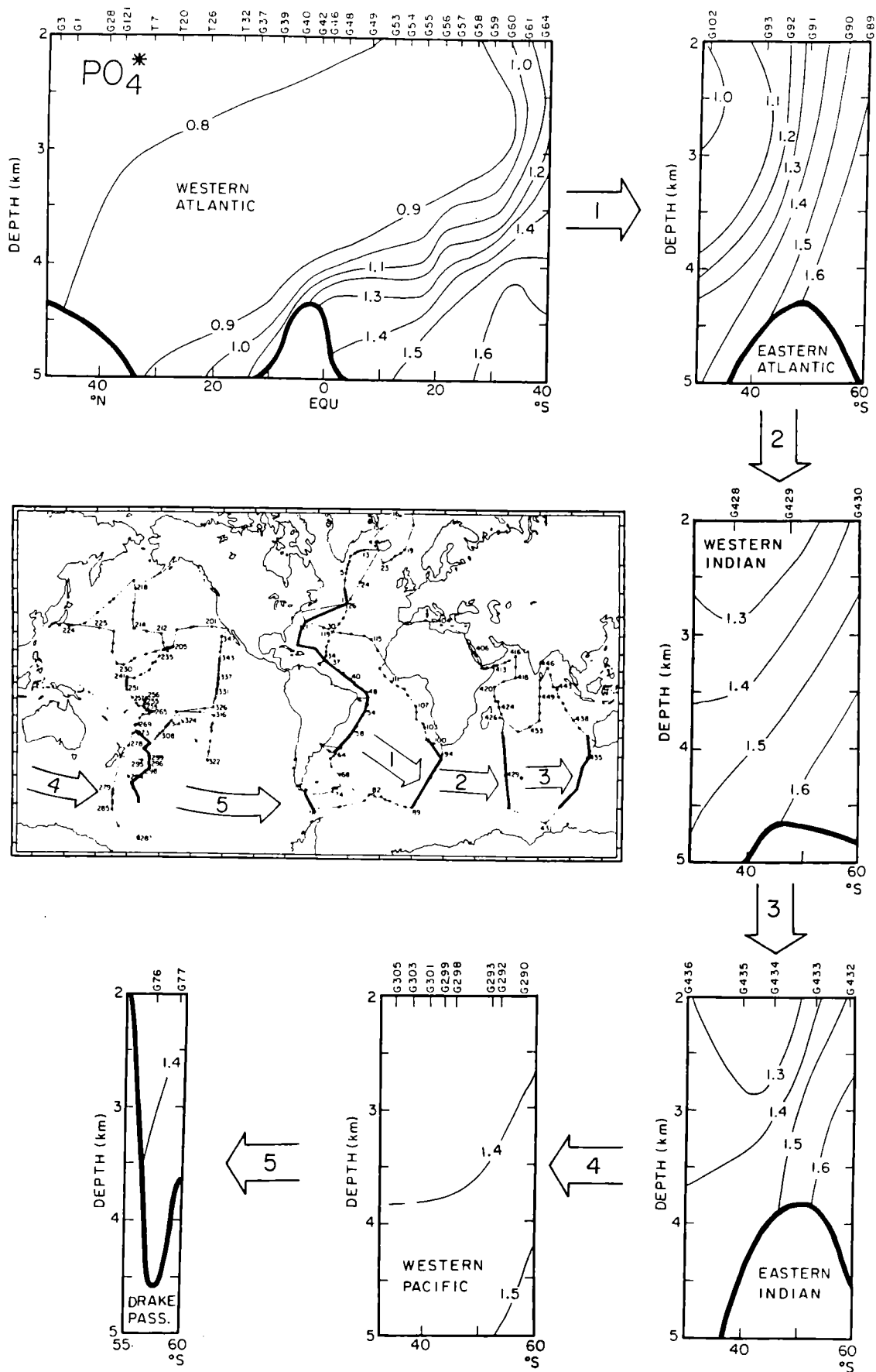


Figure 5. Sections of PO_4^* down the western basin of the Atlantic and around the Southern Ocean. The map shows the location of the GEOSECS stations and of the sections. Note how the $<1.3 \mu\text{m/kg}$ and the $>1.6 \mu\text{m/kg}$ waters blend as they move around the Antarctic continent eventually producing a nearly uniform mix with a PO_4^* value close to $1.4 \mu\text{m/kg}$.

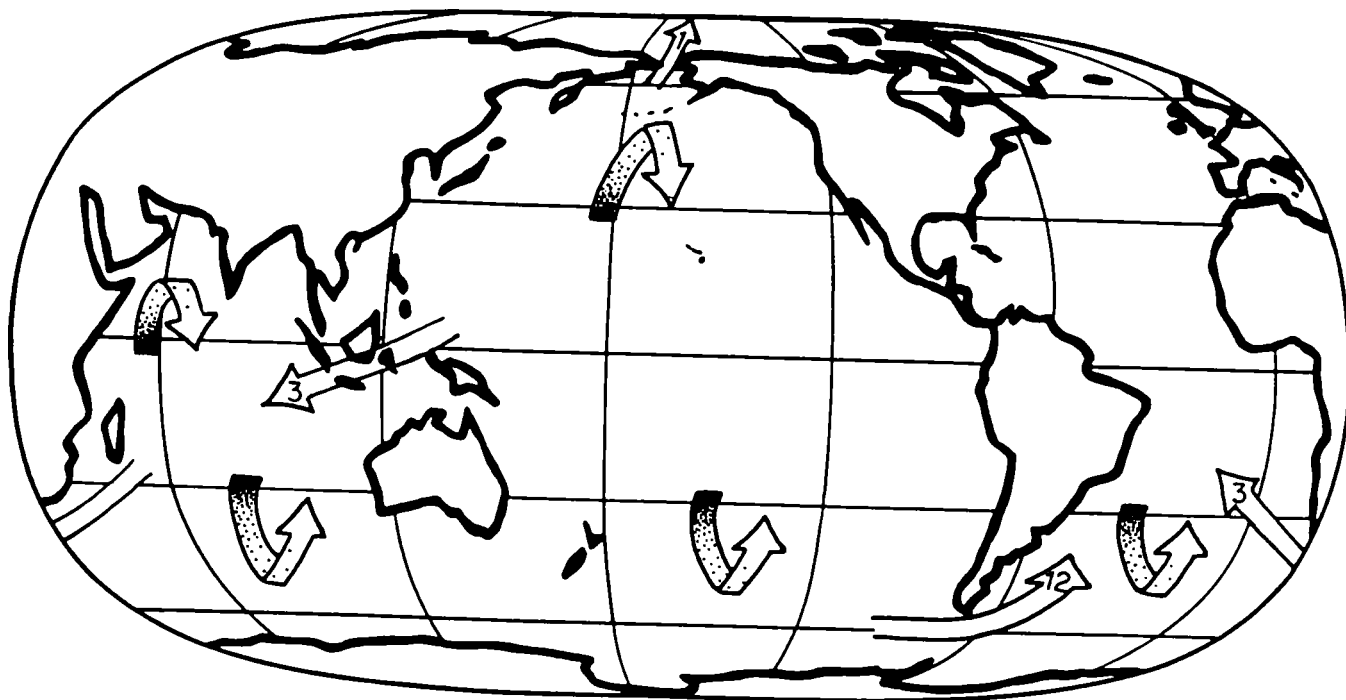


Figure 6. The dotted arrows show the location where intense upwelling of deep water occurs. The clear arrows show the upper ocean routes of return flow which balance the outflow from the Atlantic of lower limb water. The numbers in the arrowheads represent the rough estimates of the magnitude of the fluxes (in Sverdrups). In addition to the features portrayed by the logo, this diagram shows that much of the upwelling occurs in the Antarctic and that much of the return flow occurs through Drake Passage.

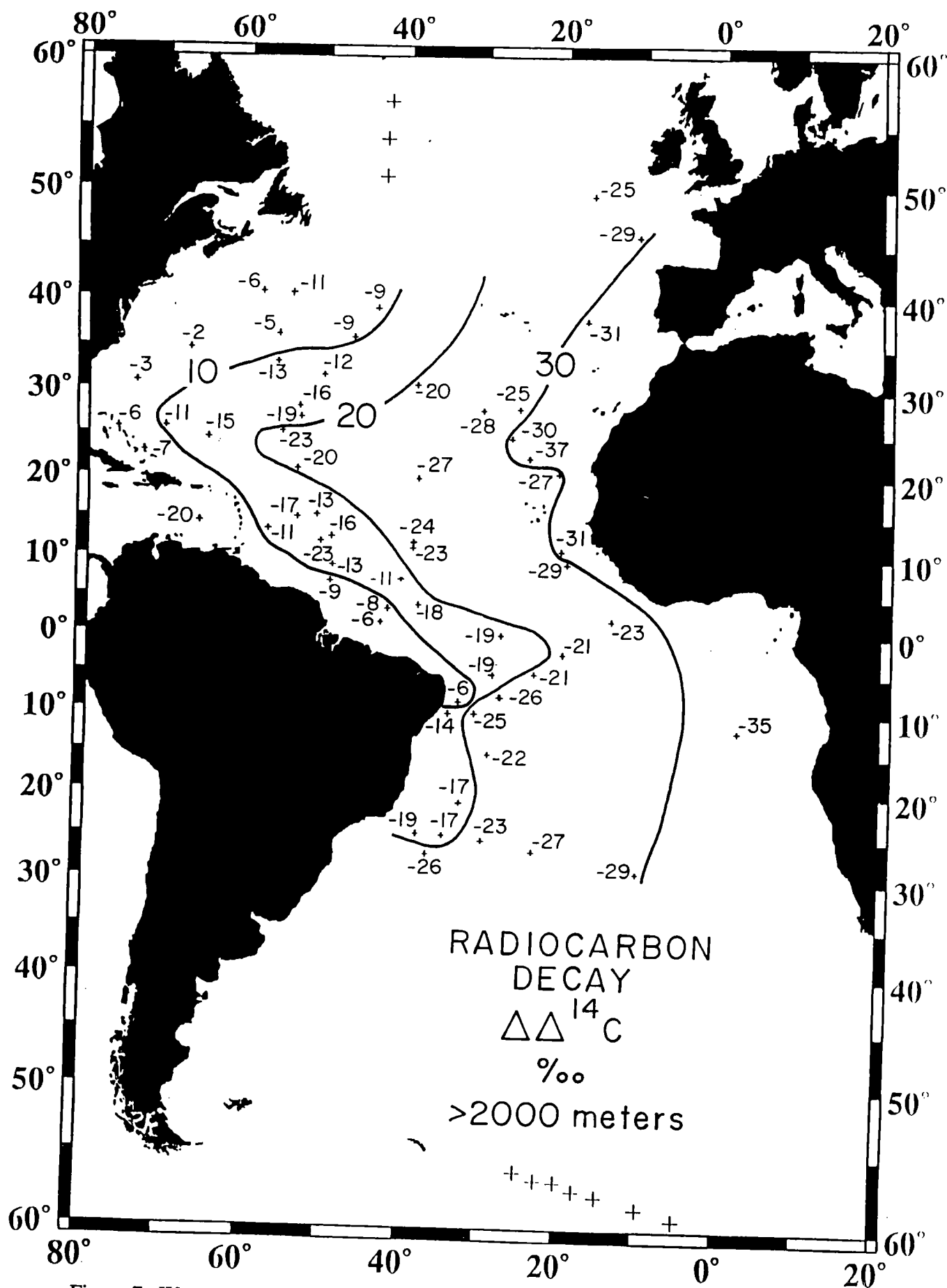


Figure 7. Water column averages for the radiodecay induced ^{14}C deficiency (Broecker, et al., 1991a) at stations occupied during the GEOSECS, TTO, TAS and SAVE expeditions. The major gradient is from low deficiencies along the western margin to high deficiencies along the eastern margin. The residence times corresponding to the 10, 20 and 30‰ deficiency contours are respectively 83, 166 and 249 years. The mean deficiency for this entire region of the Atlantic is estimated to be 22‰ which corresponds to an isolation time of about 180 years.

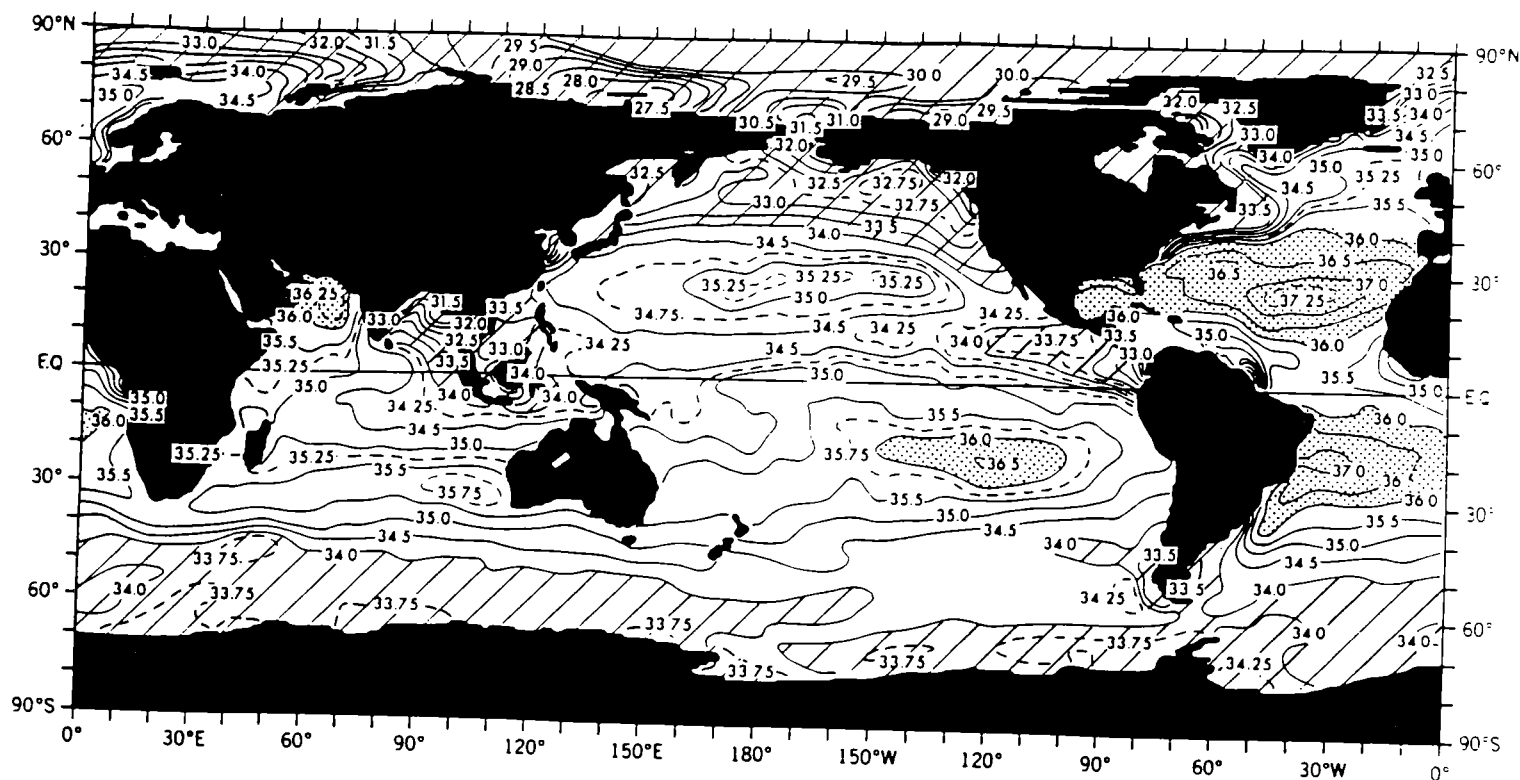


Figure 8. Map of surface ocean salinity (Levitus, 1982). Regions of low salinity (i.e. $S < 34\text{‰}$) are cross hatched. Regions of high salinity (i.e. $S > 36\text{‰}$) are dotted. Note that on the average surface waters in the Atlantic are about 1‰ higher in salinity than their Pacific counterparts. For the high northern latitudes the difference is even larger averaging about 2‰ .

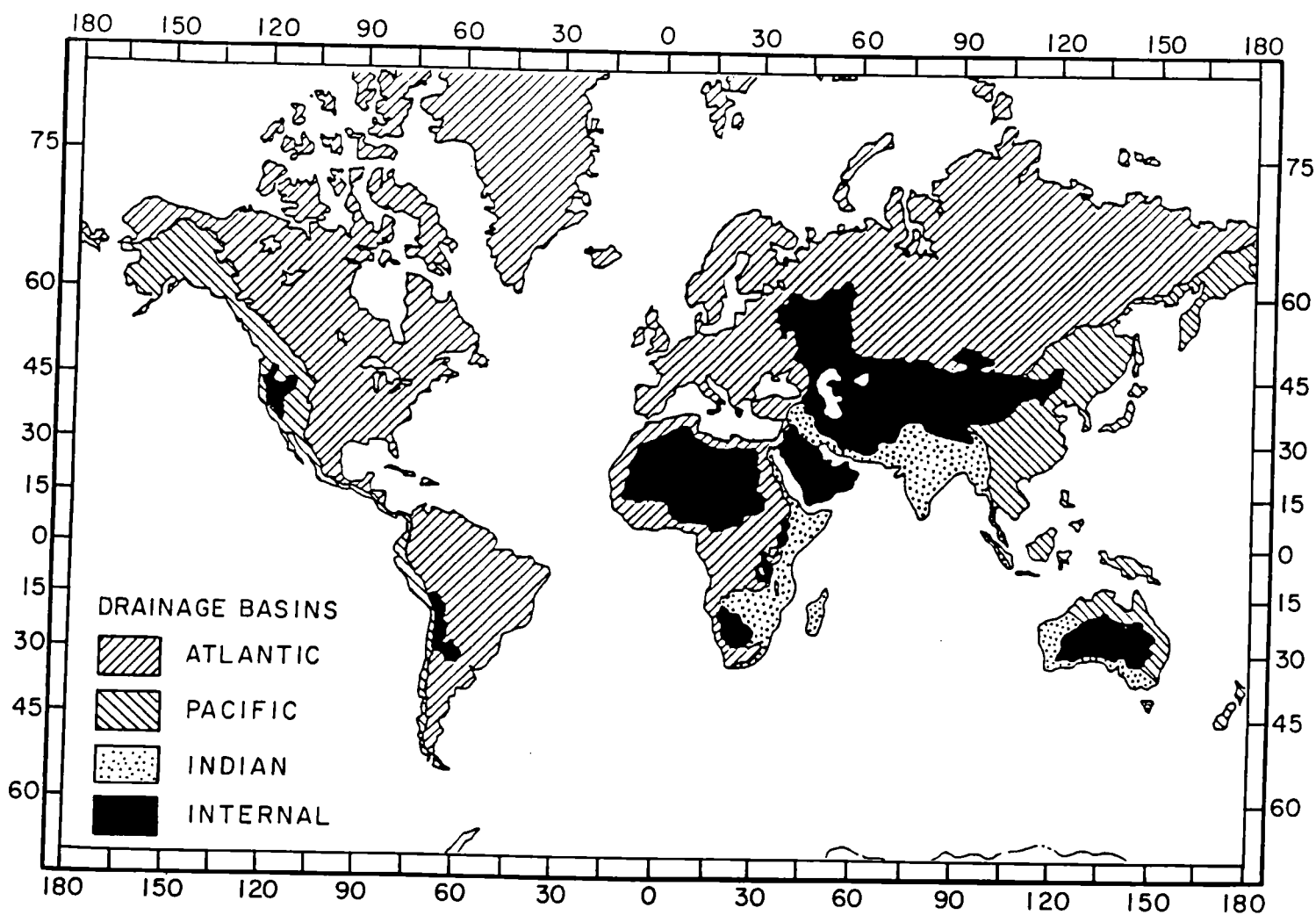


Figure 9. Map showing continental areas whose drainage reaches the Atlantic, Pacific and Indian Oceans. The black areas are deserts from which no drainage to the sea occurs. About 0.35 Sverdrups of fresh water are transported from the Atlantic to the Pacific Ocean moving as vapor in part across Central America and in part across Africa.

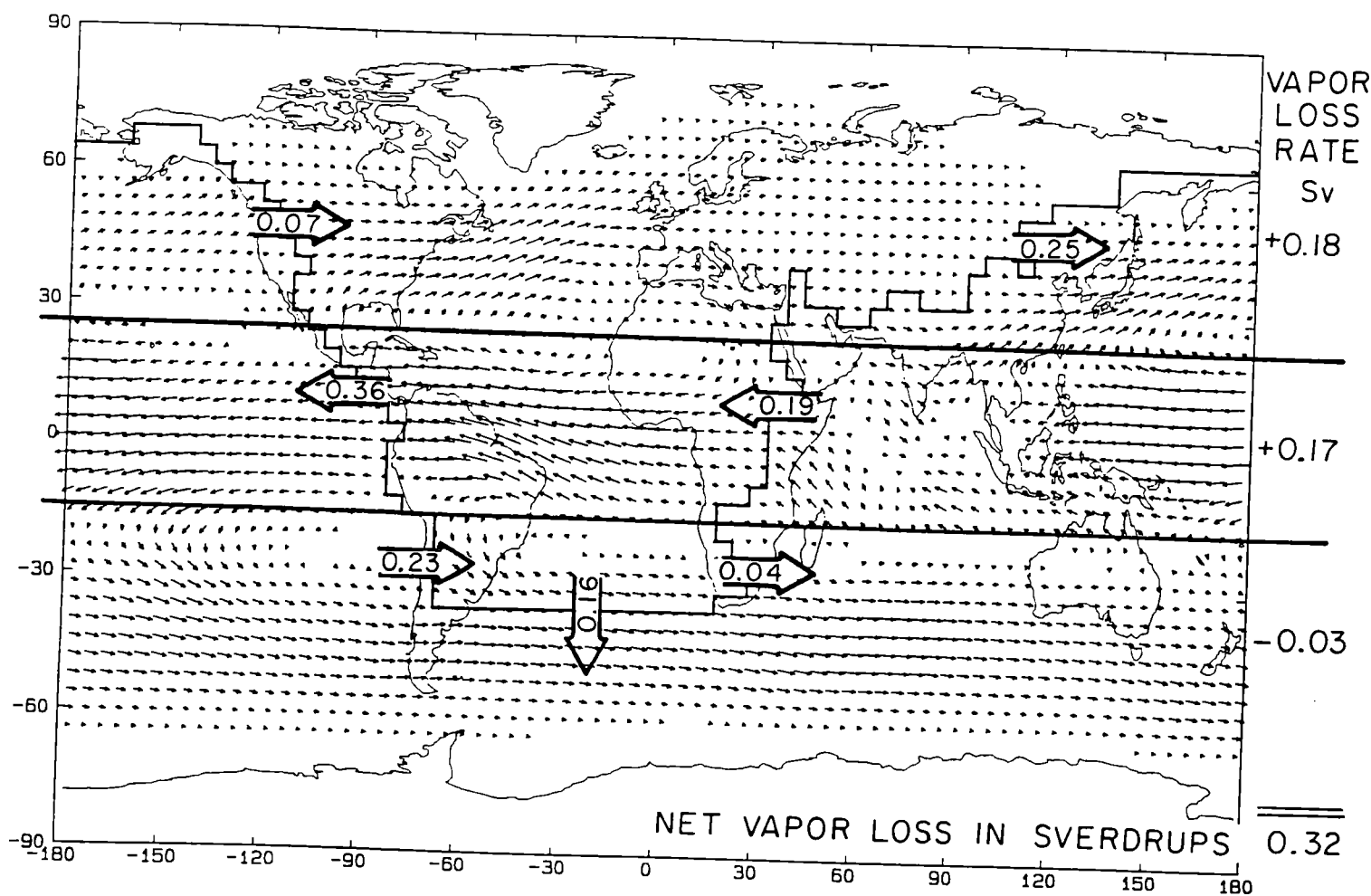
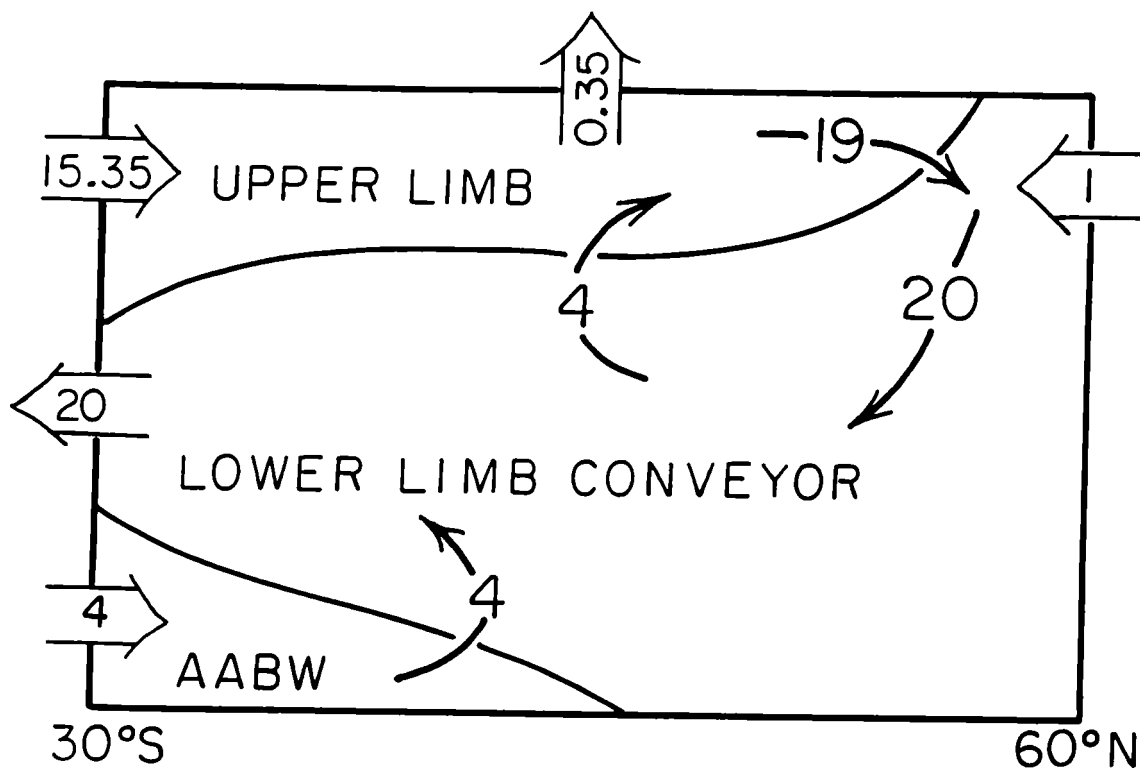


Figure 10. Map showing vertically integrated and annually average water vapor flux vectors compiled by Oort (1983). Also shown is the boundary of the Atlantic's drainage basin and net fluxes across segments of this boundary. The tropical easterlies carry out more water vapor of the Atlantic basin across Central America than they bring in via Africa. So also do the northern westerlies; more water escapes across Asia than enters across the American cordillera. For the entire basin the rate of water vapor loss is 0.32 Sverdrups (see Zaucker and Broecker, in press).



ATLANTIC'S SALT BUDGET

	SALINITY ‰	FLUX Sv
OUT		
NADW	34.9	20.0
VAPOR	0.0	0.35
<u>TOTAL</u>	<u>34.3</u>	<u>20.35</u>
IN		
BERING STS	33.0	1.0
AABW	34.7	4.0
REMAINDER	34.3	15.35
<u>TOTAL</u>	<u>34.3</u>	<u>20.35</u>

Figure 11. Approximate water and salt budget for the Atlantic Ocean. The fluxes of Bering Sea surface water and of AABW are independently determined. The remainder water must then have a flux of 19.35 minus the amount of NADW recirculated within the Atlantic. With the guess of 4 Sverdrups recirculation adopted here the remainder water flux becomes 15.35 Sverdrups. The aggregate return water must have a salinity of 34.3‰ to balance the Atlantic's salt budget. Since the combined Bering Sea (Coachman and Aagaard, 1988) and AABW inputs have a salinity of 34.3‰, the remainder water must also have this salinity.

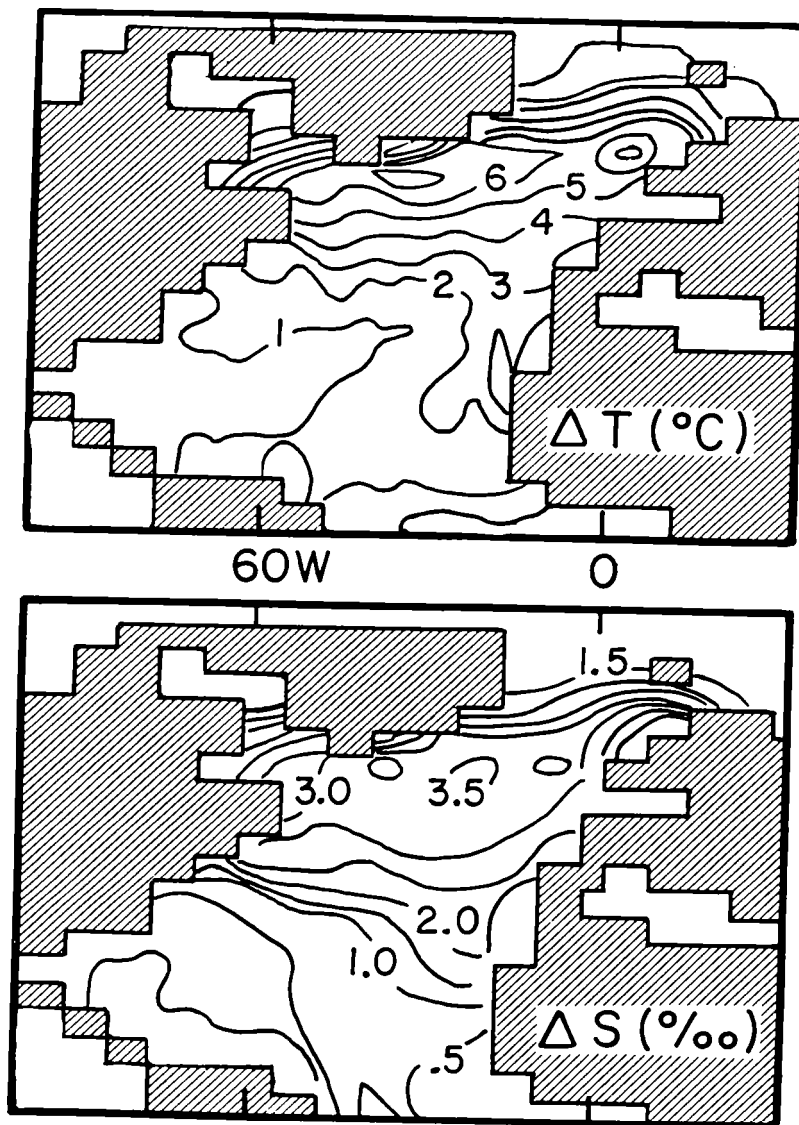


Figure 12. Maps showing the difference in North Atlantic surface water temperature (upper) and surface water salinity (lower) between the Manabe and Stauffer (1988) model circulation schemes with and without thermohaline circulation. As can be seen, a turnoff of thermohaline circulation leads to a pronounced cooling and freshening of the waters in the northern Atlantic.

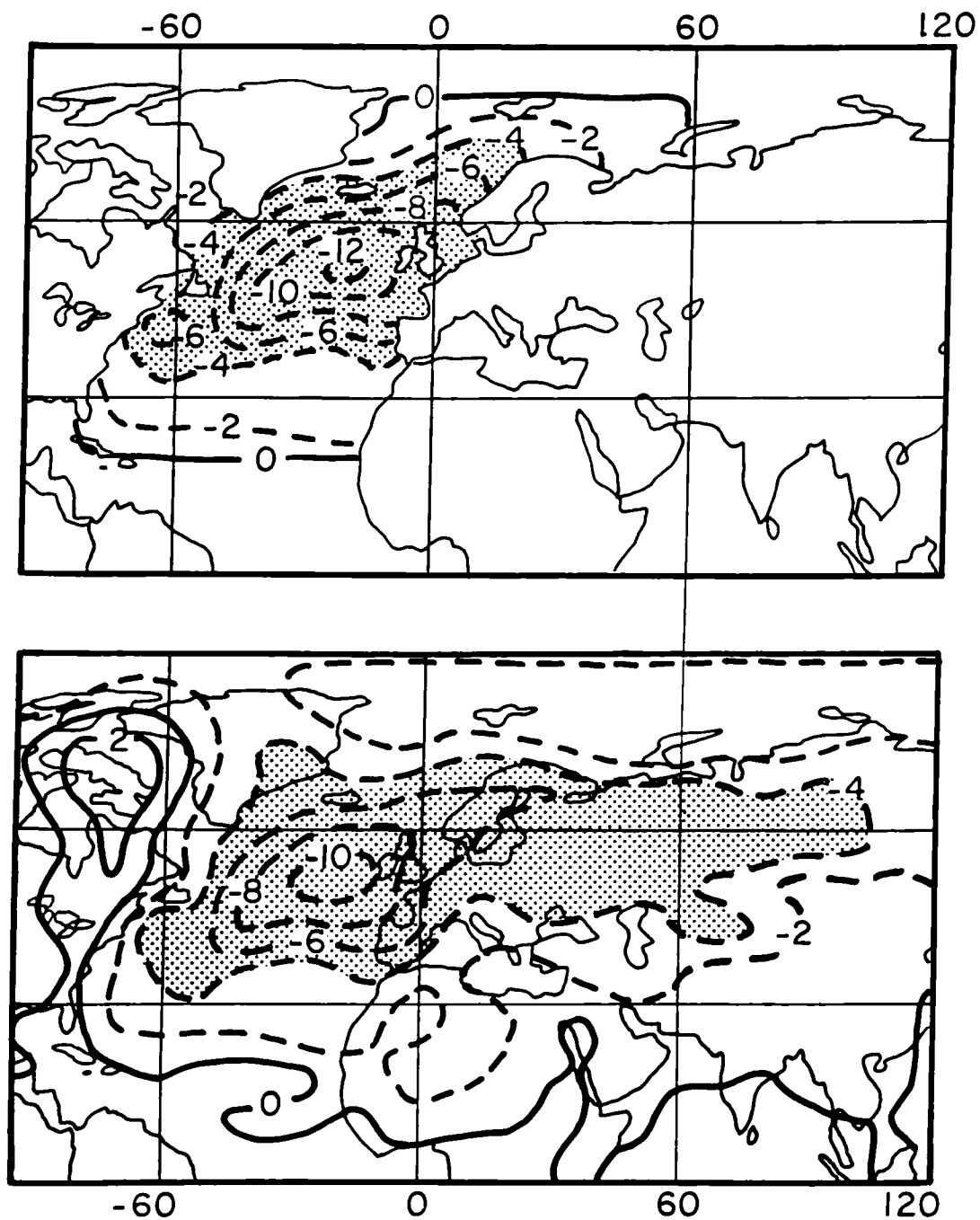


Figure 13. Results of an experiment carried out using the GISS atmospheric GCM (Rind et. al, 1986). Two runs were made which differed only in the surface ocean temperature assigned to the northern Atlantic (see upper panel). The resulting winter air temperature change produced by this ocean temperature change is shown in the lower panel.

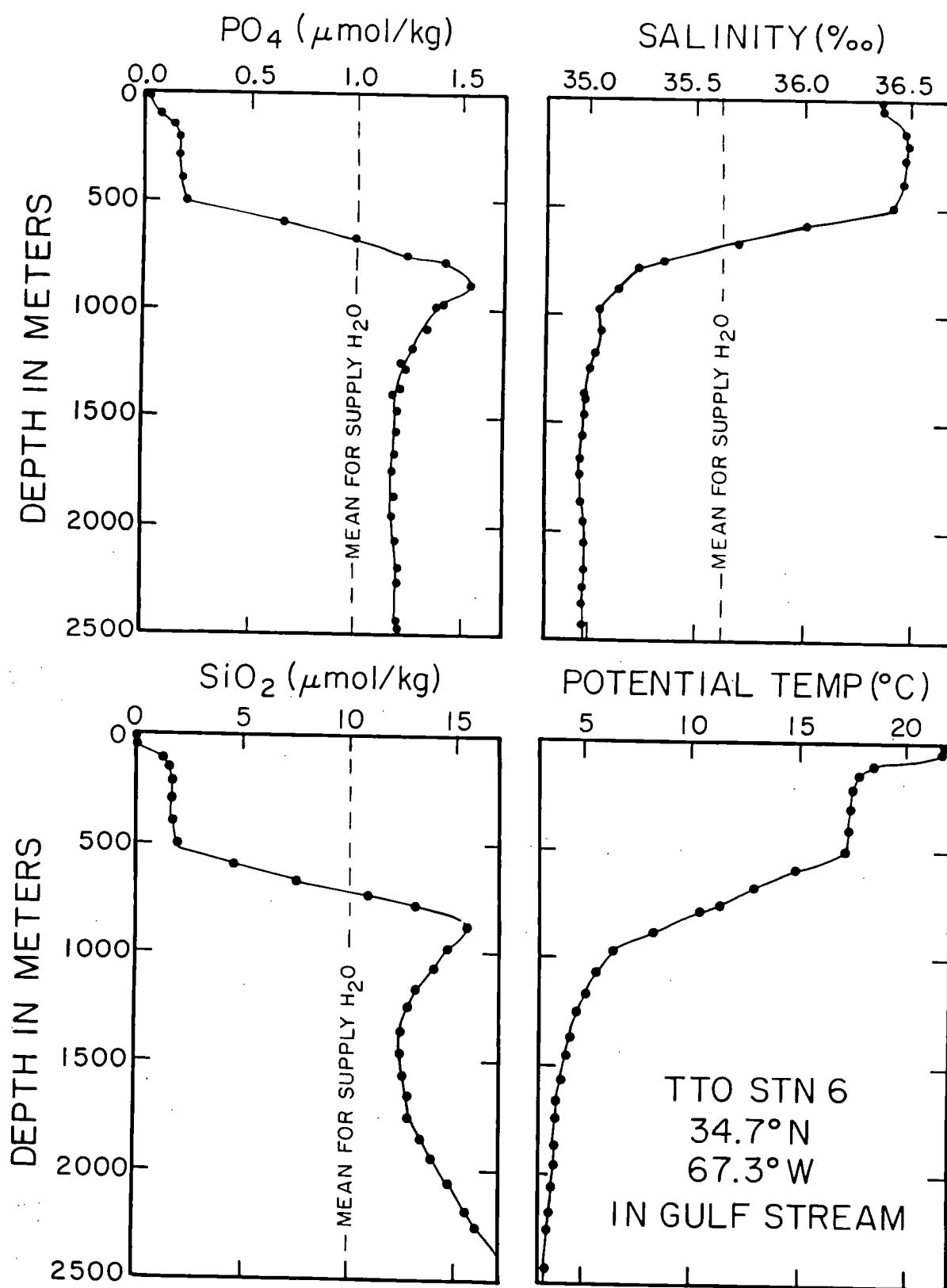
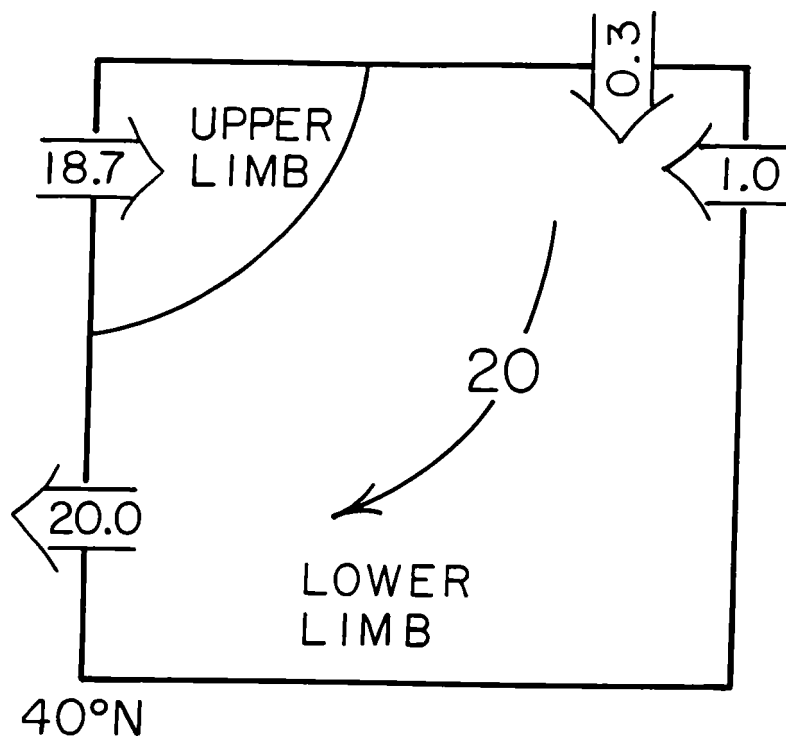


Figure 14. Phosphate, silica, salinity and potential temperature profiles at TTO station 6 in the Gulf Stream. Shown for comparison are the average values for these constituents required for the water constituting the upper limb source for NADW production (vertical dashed line).



NORTHERN ATLANTIC'S SALT BUDGET

	SALINITY	FLUX
OUT	‰	Sv
<u>NADW</u>	<u>34.95</u>	<u>20.0</u>
TOTAL	34.95	20.0
IN		
BERING STS	33.0	1.0
VAPOR	0.0	0.3
<u>UPPER LIMB</u>	<u>35.6</u>	<u>18.7</u>
TOTAL	34.95	20.0

Figure 15. Water and salt budgets for the region in the northern Atlantic where NADW forms. The fluxes and salinities of new NADW, Bering Straits input and fresh water input are known. The water flux and salinity for the upper limb are obtained by difference.

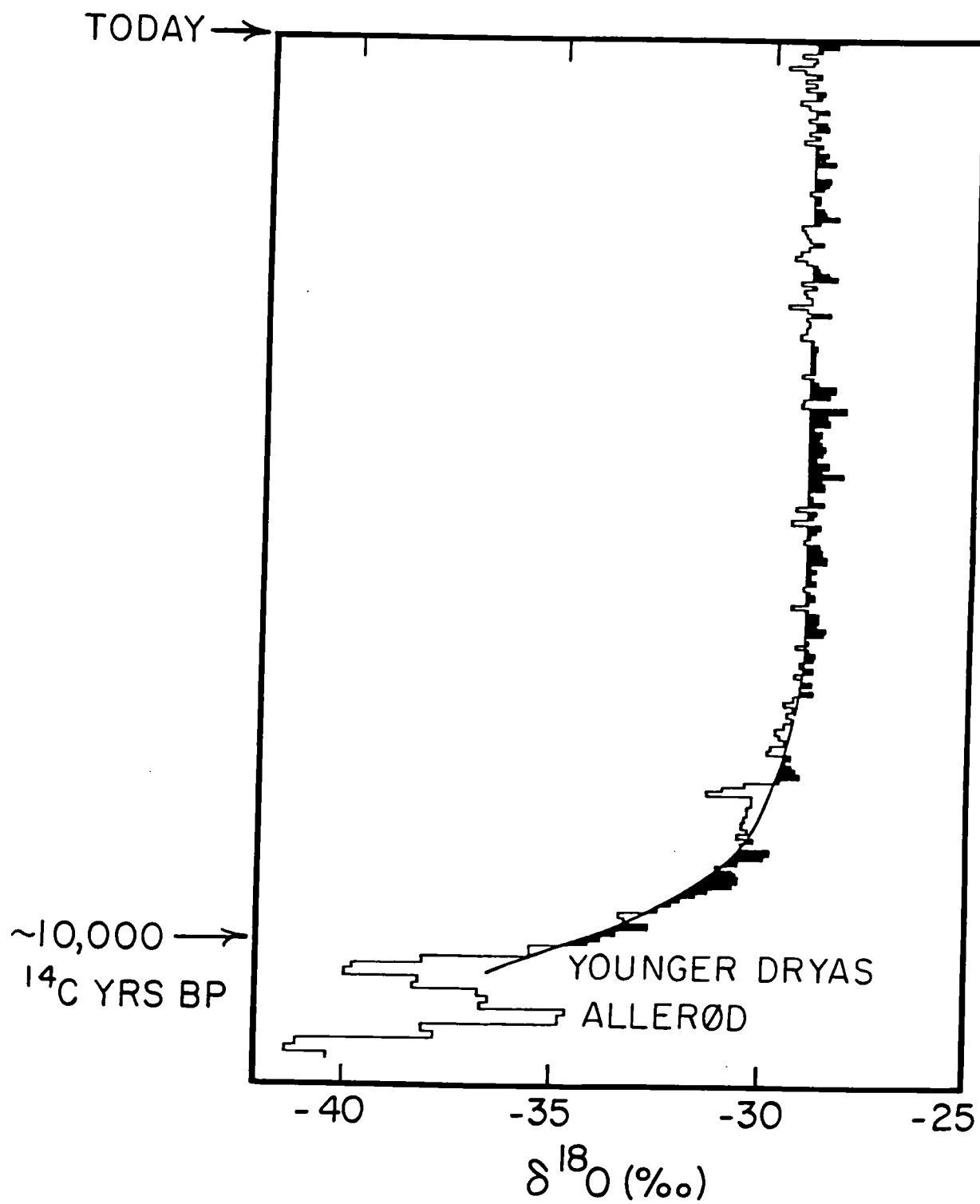


Figure 16. Oxygen isotope record for the Camp Century Greenland ice core (Dansgaard et al., 1971) covering the period from about 13,000 radiocarbon years B.P. to the present.

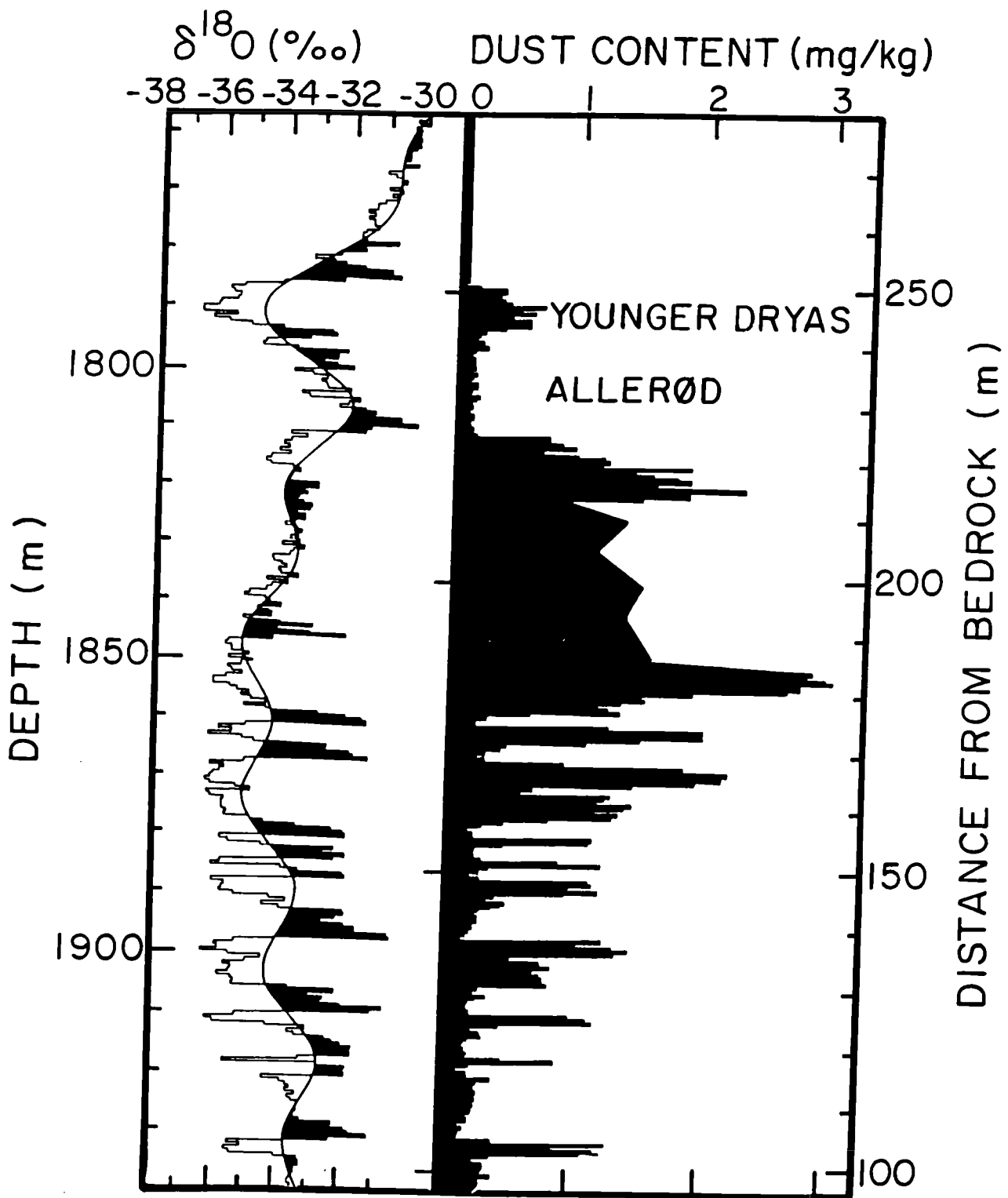


Figure 17. Oxygen isotope and dust records for that part of the Dye 3 Greenland ice core covering the time period ~45,000 to ~8000 years B.P. (Hammer et al., 1985). Note that many of the oxygen isotope events are characterized by rapid warmings followed by more gradual coolings.

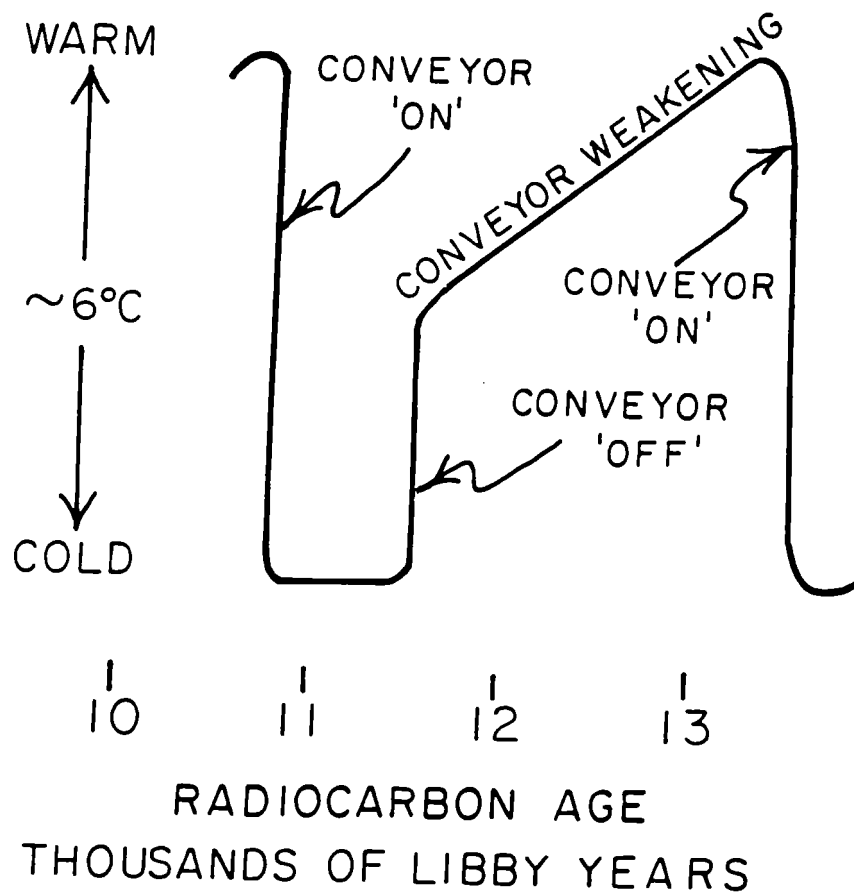


Figure 18. Diagrammatic representation of the temperature record for the northern Atlantic basin from just before 13,000 to just after 10,000 radiocarbon years before present. The features shown in this diagram appear in records of ^{18}O in ice, of ^{18}O in lake sediment, of ocean planktonic foraminifera (Ruddiman and McIntyre, 1981), of pollen and of beetles (Atkinson et al., 1987). Of particular interest is rapidity of the warmings at 12,700 years BP and at 10,000 years BP. Detailed measurements in the Dye 3 ice core and in varved lake sediments reveal that these warmings took place in about 50 years!

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