CHAPTER 4 - THERMOHALINE CIRCULATION

A. Introduction

Oceanography is an applied science in that the ocean provides a problem area for applying basic skills acquired during training in physics, chemistry, biology, botany, zoology, engineering, mathematics, etc.

Physical Oceanography is the subarea of oceanography that deals with the physics of ocean circulation, waves, air-sea interaction, and sound propagation.

The Goals of Physical Oceanography

(1) To obtain a quantitative <u>description</u> of the characteristics and circulation patterns of ocean waters; and

(2) To explain <u>dynamics</u> of the ocean – that is the causes the water movement and ultimate distribution of properties in terms of the relevant forces.

The most important <u>dynamic property</u> of the ocean is its <u>density</u>. Consider the role of density from two points of view, namely

<u>Descriptive</u>:	The distribution of density (as well as temperature and salt) can be <u>used to infer</u> water motion.
<u>Dynamic</u>:	The non-uniform distribution of density causes motion.

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Relation of Physical Oceanography to Other Disciplines

The <u>traditional viewpoint</u> of oceanographers holds that chemical and biological constituents are basically <u>advected</u> with the water as it moves. Therefore any attempt to make predictive models for biological and chemical processes must be firmly based in a context of the relevant physical oceanography.

Historically however, physical oceanographers have been slow in providing the relevant physical oceanography in a usable form to biologists and chemists. Being impatient, the non-physical oceanographers have charged ahead in their studies of the ocean; doing some of the basic physical oceanography themselves. The activities of biological and chemical oceanographers can perhaps provide at least two classes of benefits for physical oceanographers.

Class 1 - Distributions

Traditional descriptive biological oceanography involves describing **space/time distributions** of the different phytoplankton and zooplankton. For example during the 20's and 30's, Henry Bryant Bigelow used drift bottle-derived estimates ocean current patterns and extensive data on the distribution of larval herring to infer the circulation patterns in the Gulf of Maine.

Class 2 - Model Results

This class of benefits relates to the construction and **validation of biological models.** More specifically, if the physical inputs are improperly described or parameterized it is unlikely that any amount of tuning of a biochemical model will produce a match between prediction and the real world. Negative or positive results from such experiments can help the physical oceanographers.

While the above approaches are now being used by interdisciplinary teams of oceanographers, we will not use the latter two approaches to studies of physical oceanography in this course. The principal emphasis will be on the two points of view in which the physical study of the oceans is carried out.

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First a word about terminology:

(1) Synoptic or Descriptive Oceanography

(a) This is the branch of oceanographic studies implied by the term oceanography – the root of which is Graphos or **"**description of**"**

(b) Observations are characterized by sets of features.

(2) Dynamical Oceanography

(a) The term oceanology - the root of which is logos or "logic of" or "science of" is probably is more applicable to the dynamical approach to physical oceanography.

(b) Observations provide clues as to the important processes which should be included in simple theoretical models. The observations are then compared with the predictions of the models.

(c) Theoretical ocean circulation models are nothing more than simplified forms of Newton's second law of motion for a fluid i.e., a balance of

- the "appropriate" forces; and
- accelerations of the fluid.

(d) The discrepancies between the predictions of the model and observations of real world provide a basis for modifying the theoretical model.

B. Thermohaline Circulation

Thermohaline circulation is primarily meridional circulation caused by temperature/salinity differences between global climatic belts with modifications due to wind-induced circulation (Figure 4.1). The T/S distributions in the ocean reveal much about the thermohaline component of the global circulation.

The results of the first systematic study of the deep T/S distributions in the Atlantic were reported by G. Wüst - a German - in 1935. The pioneering work conducted by the

R.V. Meteor in the 1920's and 30's. The original work was motivated by an interest in finding and "mining" gold in the ocean to help a World War I reparation-starved Germany pay its debt when its originator Fritz Haber died early on the first expedition Wüst assumed the leadership of the program.

T/S Property Distribution and Deep Circulation

The deep circulation, below the thermocline, is complicated by the number of water masses involved. The difficulty in obtaining accurate measurements of current in the deep ocean is considerable - the temperature and salinity are nearly constant, and slowly varying flows related to density changes are masked by high energy transient motions. Thus indirect means involving knowledge of water distributions that must be used to infer deep ocean transport. Water mass analysis is useful in knowing deep thermohaline flows.

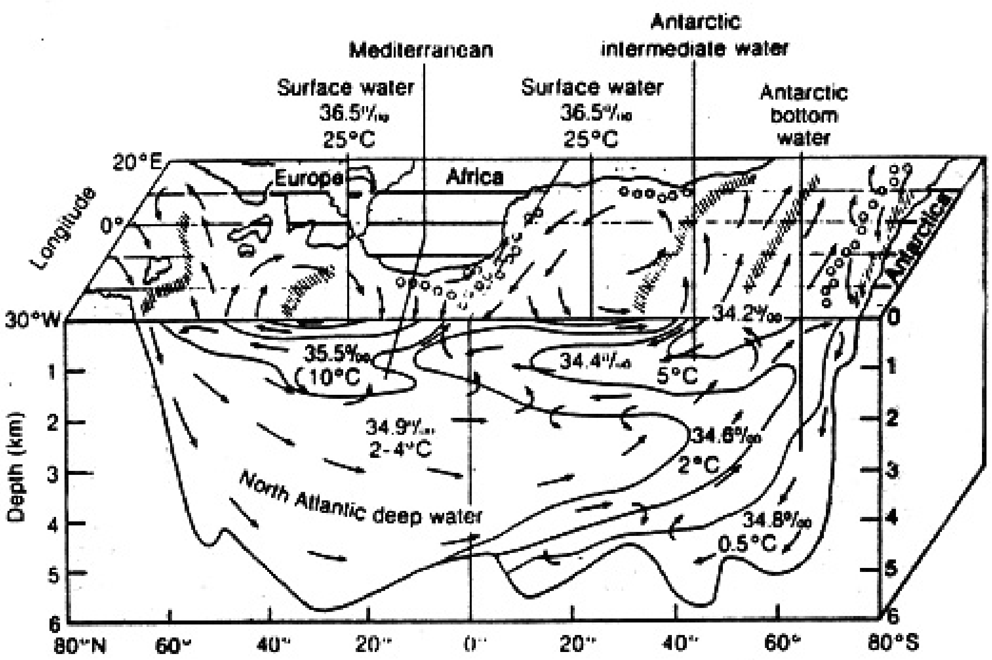

Figure 4.1. A vertical section of the Atlantic Ocean properties in perspective showing density-driven meridional flows and wind-driven altitudinal surface flows. (Duxbury and Duxbury, 1984)

C. Elements of Water Mass Analysis

Important information about circulation and mixing in the ocean can be inferred from the distribution of salinity and temperature. In some cases water mass analysis can be used to determine to origin, mixing history and flow rates. This oceanographic technique, used effectively by Wüst, is based upon the following two assumptions:

(1) The temperature and salinity of a water parcel is affected by heat exchange processes only at the sea surface.

(2) Once out of the direct influence of the surface heat exchange processes (i.e. below about 200 m) the temperature and salinity of a water parcel is changed only by mixing with water masses of different properties.

The latter statement operationally requires that q and S properties of a water parcel are conserved at depth.

Terminology Used In Water Mass Analysis.

Water Type: a parcel of water which is characterized by a q, S pair and thus is represented by a point on a q/S diagram (see Figure 4.2).

Water Mass: A cluster of water types from the same geographical areas undergo similar histories and are found in a reasonably well-defined area on a q/S diagram.

Examples -

(1) A homogeneous ocean is well mixed and thus has the same q, S everywhere (Figure 4.2) and is therefore represented by a single water type (i.e. point) on a q-S diagram.

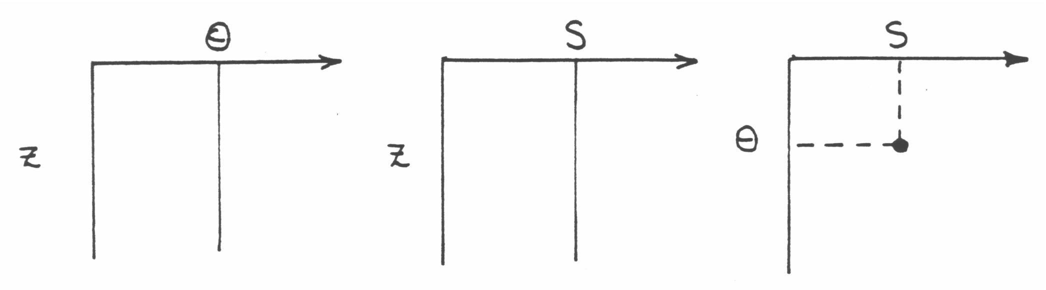

Figure 4.2. A homogeneous ocean with uniform profiles of ? and S (left/middle) is a pure water type (right).

(2) A <u>two-layered</u> ocean is initially composed of two different homogeneous water masses (or types) separated by an impermeable membrane to inhibit mixing (Figure 4.3a). The water mass configuration is stable and its water types are represented on a T-S diagram as the two dots, respectively; water type I (T_1, S_1) and water type II (T_2, S_2). (*Note:* to be accurate in the deep ocean potential temperature must be used)

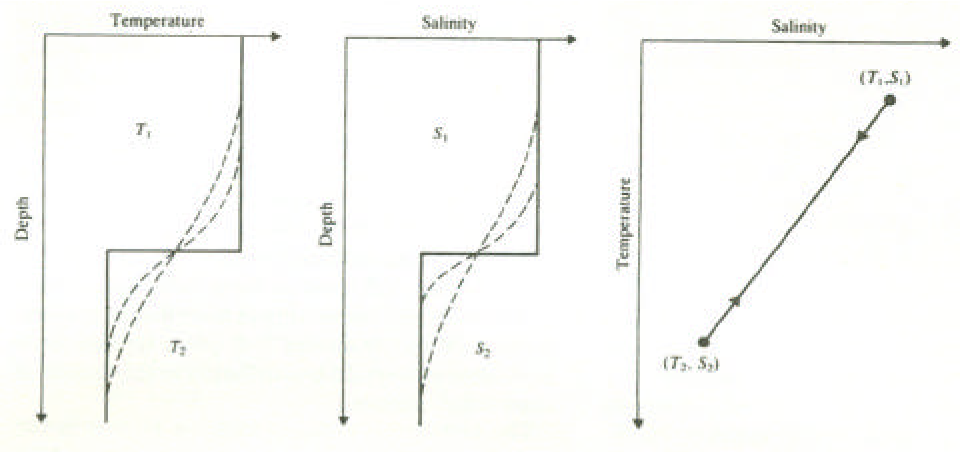

Figure 4.3a. A two layer ocean that is initially composed of 2 pure water types (T_1, $S_1$and T_2, S_2) is defined by the solid line (left) temperature profiles (middle) salinity profiles, and (right) dots on the T/S diagram. With time, the 2 water types will gradually mix through turbulent processes on the interface, yielding successive dashed profiles, and forming *all mixtures* of the end member water types –dots- along the straight line on the T/S diagram.

After the membrane is removed from between the 2 initial pure water types, turbulent mixing processes will diffuse heat and salt across the originally sharp interface to produce the successive dashed line profiles; with increasing time. In the process, the water column properties will take on the continuum of water property T, S values that lie along the straight line between the end member water types.

The proportions of water types I and II, used to form a particular mixture R, can be found from the following relation:

$$\frac{m_I}{m_{II}} = \frac{b}{a}$$

where $\frac{m_I}{m_{II}}$ is the <u>mass ratio</u> of mixing members and **b** and **a** are the length of the line segments shown on the T-S diagram (Figure 4.3b). This computation can be done graphically or analytically depending upon the precision required.

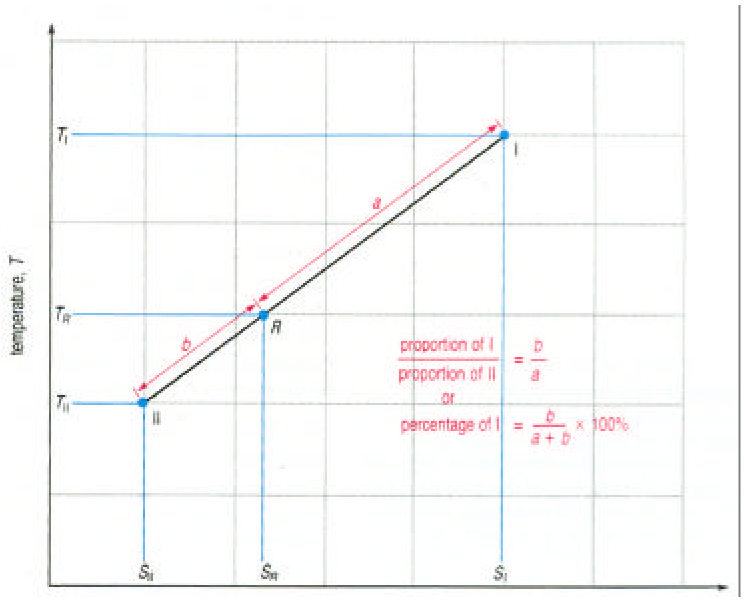

Figure 4.3b. The proportions of water types I and II that make up an arbitrary mixture R can be determined by the indicated linear mixing relationship.

Example of Water Mass Analysis: Wüst’s Core Technique

Consider the classic case of the evolution of a 3-layer ocean consisting of homogenous layers of a cold, fresh water lying between an upper layer of warm, salty water and a deeper layer of cold, salty water as indicated by a trio of hydrographic station “measurements” shown above in the Figure 4.4. Wüst’s core technique, which allows for transport across density surfaces through mixing, involves the use of T/S (or q /S) diagrams and temperature/salinity profiles to infer the most likely paths of water parcel movements movement.

The results of 3 hydrographic (or CTD) stations have been plotted on q -S diagram in Figure 4.4. At station 1 there are pure A, B and C water types bracketed with the appropriate mixtures at the edges. At station 2 there is no pure type B left; only types A and C and a mixture of water types A, B and C. At station 3 only pure type A, pure type C and a mixture of types A and C are detected. These q -S results can be interpreted in terms of the formation of water type B in the source area region. Because of its intermediate density (between that of A and C) it mixes with its neighbors as it sinks and moves laterally.

D. Water Mass Formation Processes

(1) Surface Water Mass Formation

Heat and mass transfer processes at the air/sea interface (Figure 4.5) can produce deep ocean water masses through;

- Cooling with a corresponding increase in density
- Freezing with a corresponding increase of salinity and thus density

When these processes are strong enough, gravitational instability and large scale sinking will result.

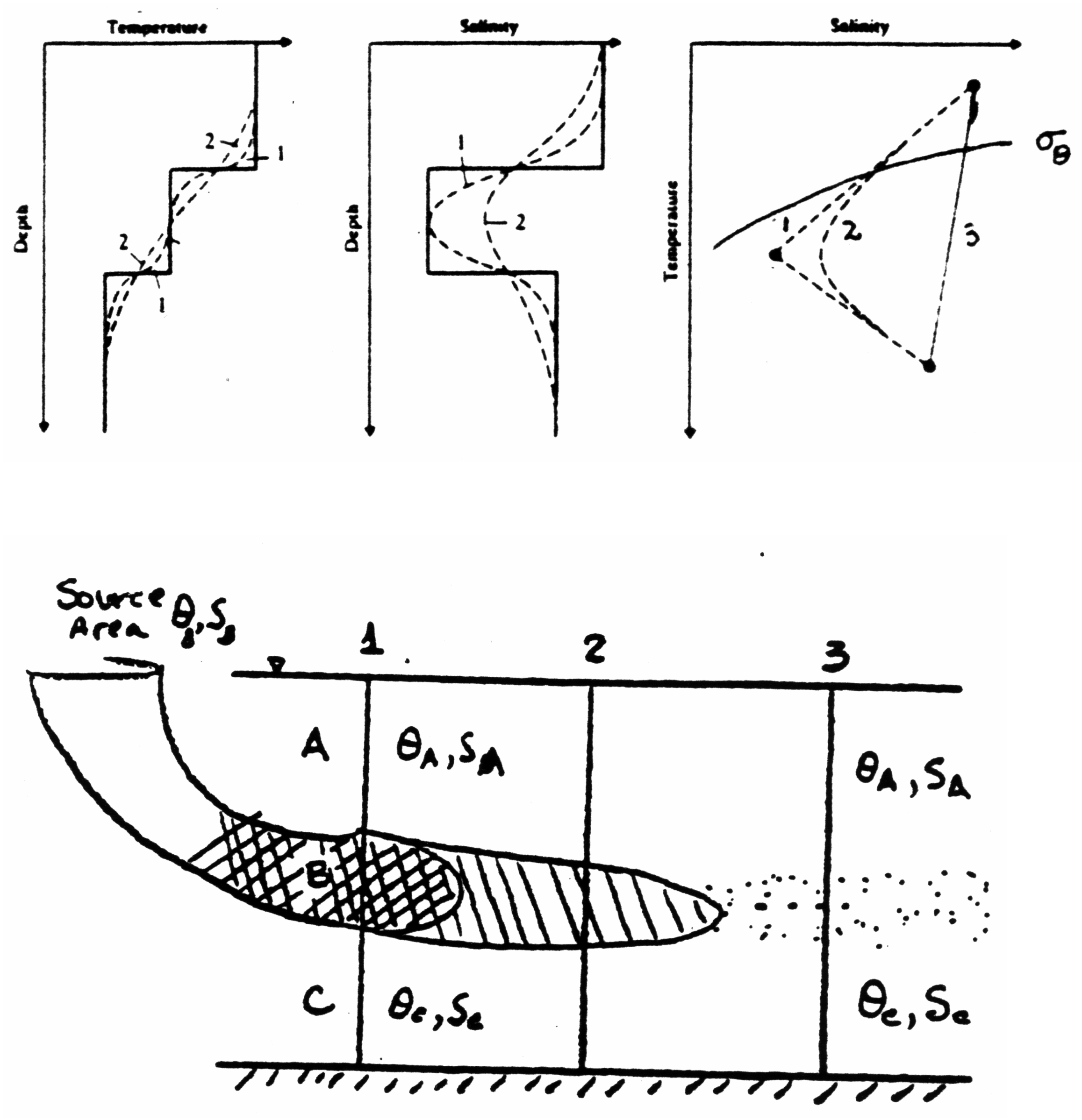

Figure 4.4. The application of the Wüst core technique to the interpretation of three hypothetical hydrographic stations in an idealized 3-layer ocean. (above) The potential temperature θ profiles, salinity S profiles, and θ/S curves for the 3 hydrographic stations. (below) The three-layer ocean with three pure parent water types A, B and C at hydro station 1; At hydro station 2, layers of pure water types A and C are separated by an intermediate layer of mixtures of A, B and C; At hydro station 3, pure water types A and C layers are separated by a layer of mixtures of only water types A and C. (Tolmazin, 1985)

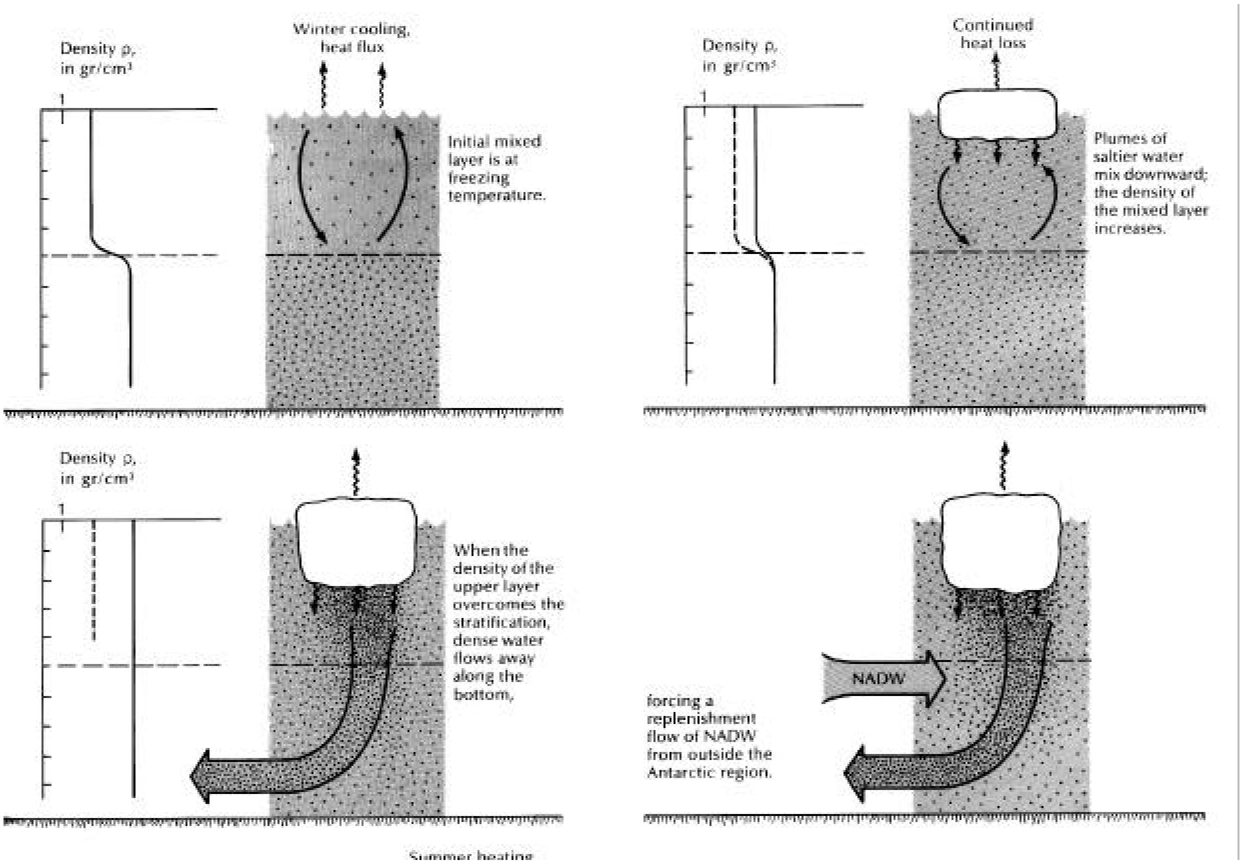

Figure 4.5 Water mass formation process in the Antarctica ; (upper left) Initial winter mixed layer at freezing temperature; (upper right) ice formation increases salinity and hence density; (lower left) mixed layer becomes unstable and sinks; (d) sinking water replenished by NADW. (Neshyba, 1987)

(2) Internal Water Mass Formation

Because density (s_q) is a non-linear function of q and S, mixing between adjacent water masses can locally produce a new anomalously dense water mass which will sink relative to surroundings (Figure 4.6).

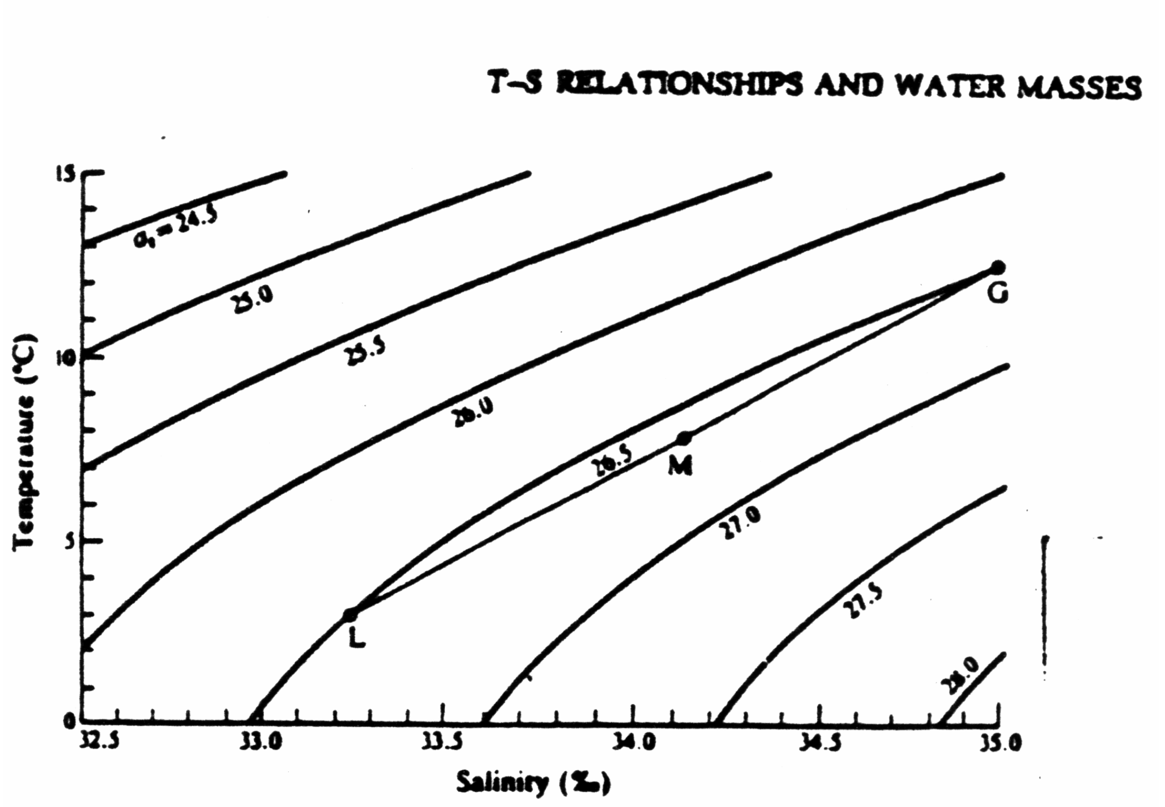

Figure 4.6. The result when two adjacent water types of equal density (s_t=26.5), L (Labrador Current) and G (Gulf Stream), are mixed in equal proportions. The mixture M lies on the straight line connecting these points and has density s_t=26.65. (Tolmazin, 1984)

(3) Thermohaline Convection and Water Mass Modification

Overlying water masses of similar densities but different salinities and temperatures can undergo modification through mixing at their interfaces to produce different several forms of thermohaline convection. Consider the following conceptual models.

A Classic Case: Salt Fountain

Consider a what will happen if long narrow heat-conducting pipe is inserted vertically into a region of ocean where warm, salty water overlies colder, fresher (and slightly denser – Figure 4.7) water. (Note that in this case temperature stabilizes and salinity destabilizes the water column.)

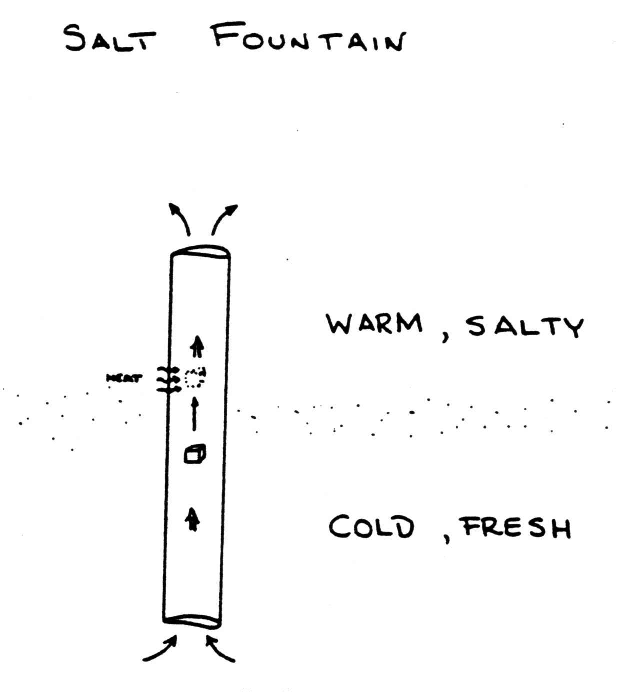

Figure 4.7. A salt fountain in a stratified ocean.

If somehow a parcel of water is displaced upward (by natural ocean turbulence), then it will become warmed (via heat conduction through the pipe). Because it is fresher than the surrounding water it will be buoyant relative to its surroundings and will continue to rise thus initiating a "salt fountain". The continuous upward flow of water in the pipe will persist as long as there is a vertical gradient of salt to supply the potential energy.

A Classic Case: Thermohaline Yo-Yo

Consider a water parcel that is isolated from its surroundings by a thin, neutrally-buoyant, conducting shell, situated in an "ocean" composed of a layer of warm, salty water underlying a layer of colder, fresher (and less dense) water. When the water parcel is displaced upwards, then it will lose heat (but not salt) via conduction to the surrounding cold water. The parcel will sink as it becomes denser. The sinking will cease as it re-warms (via conduction) in the warmer water below - but not before it overshoots its neutrally stable position. Thus, an oscillation will result.

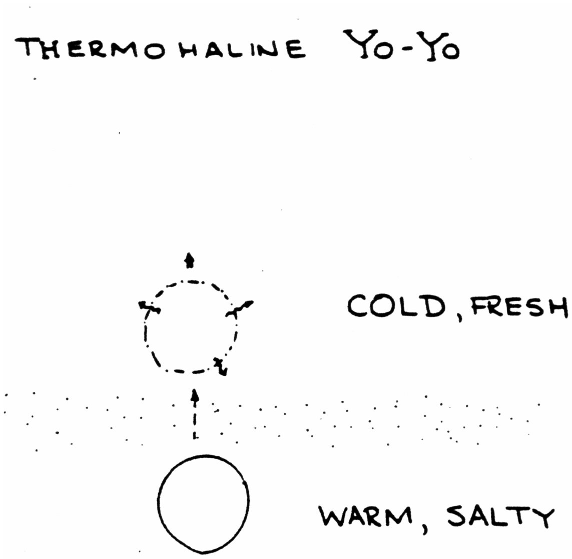

Figure 4.8. A neutrally buoyant conducting shell isolates a parcel of water from its stratified surroundings.

Real Ocean Thermohaline Convection: Salt Fingers

These conceptual models are relevant to the real ocean because the molecular diffusion of heat is so much greater than the molecular diffusion of salt in sea water the rather artificial pipes and shells used in the conceptual models are not necessary. In fact, long narrow convecting cells called "salt fingers" have been predicted and observed*. (While the existence of oscillatory motions have not been verified.) There is evidence that salt fingering is important over large oceanic stales. Because it is the disparity in salt and heat molecular diffusion rates which lead to this process it is sometimes called double diffusion convection. The Mediterranean outflow appears to generate the conditions for salt fingering (Figure 4.9).

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*Read Williams A.J. 1974, "Salt Fingers in the Mediterranean Outflow", Science, 13 Sept. 1974.

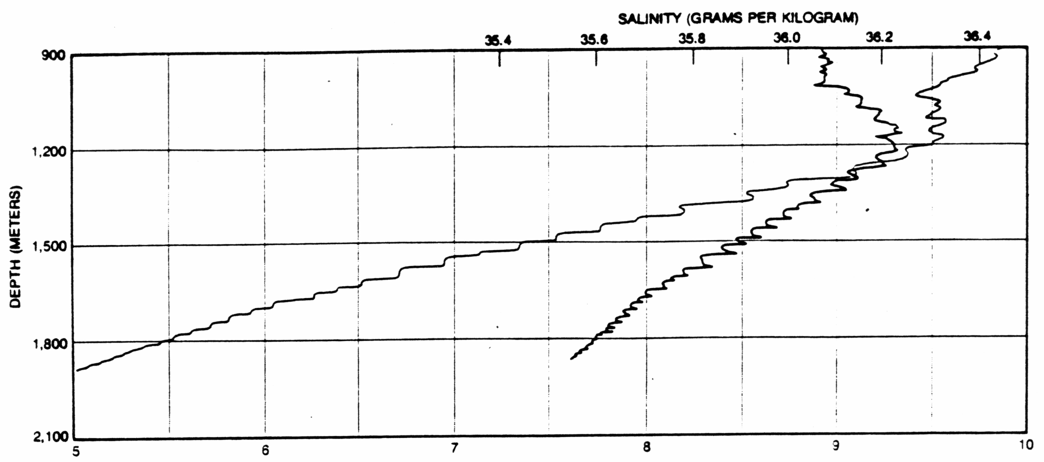

Figure 4.9. Probable example of salt-fingering is represented by the series of temperature steps (color) and salinity steps (black) recorded in the Atlantic Ocean below an intrusion of warm saline water that has flowed westward through the Strait of Gibraltar. Horizontal layers 10s of meters thick may extend laterally for 30 miles. Recordings were made by R.I. Tait and M.R. Howe of the University of Liverpool.

The instability associated with salt fingers can be discussed with the assistance of a T/S Diagram. Assume an initial two layer state in which a warmer, saltier water layer, A, overlies a cooler, fresher water layer, B, of the same density (neutral stability) as in Figure 4.10. As time proceeds, heat diffuses on the molecular scale more rapidly than salt and the profiles and T/S curve change. An unstable density profile develops near the interface of the original layers. Rather than the entire layer sinking uniformly, salt fingers with widths of about 1 cm and lengths of 20-30 cm develop. Figure 4.10 show how temperature and salinity microstructure might develop under these conditions.

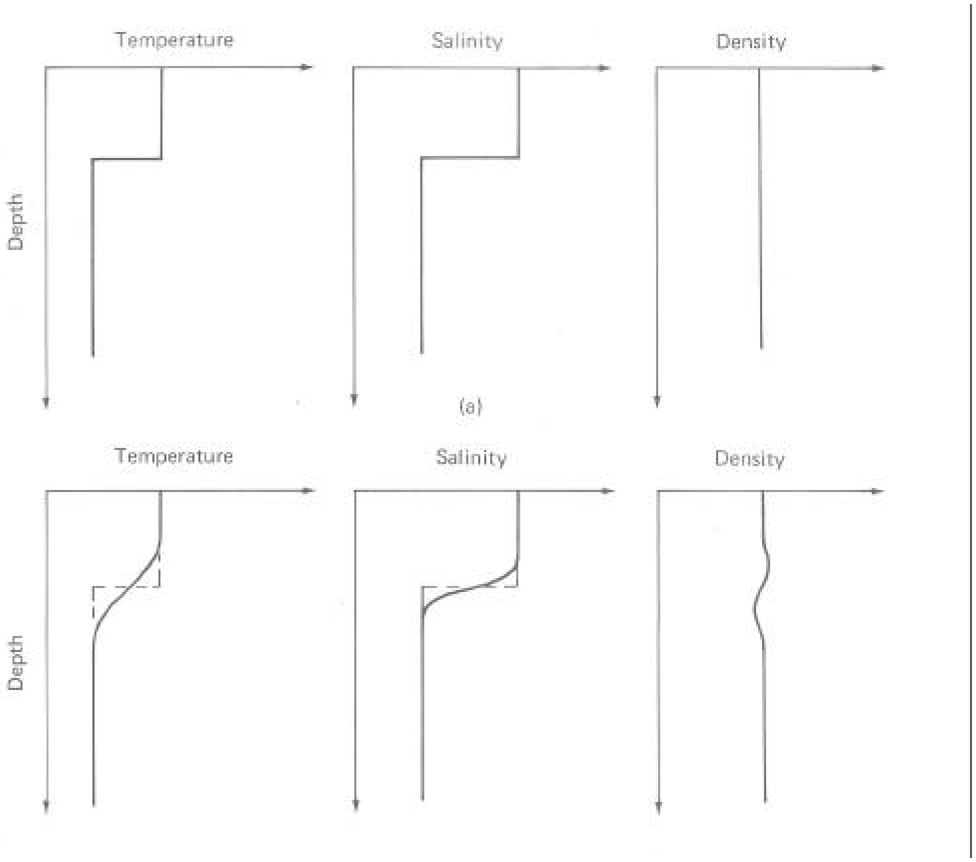

Figure 4.10. Salt fingering thermohaline convection results in some situations where salinity is destabilizing. (Knauss)

In the situation depicted in Figure 4.11 colder, fresher water layer A (less dense) overlies warmer, saltier water layer B (more dense). With time the layer A water near the interface becomes warmer and saltier through the thermohaline processes described above and conversely, the water in layer B becomes colder and fresher. Because of the relatively rapid molecular diffusion of heat the water immediately above (below) interface becomes relatively less dense (more dense) leading to rising (sinking). A sharpened interface results from this process.

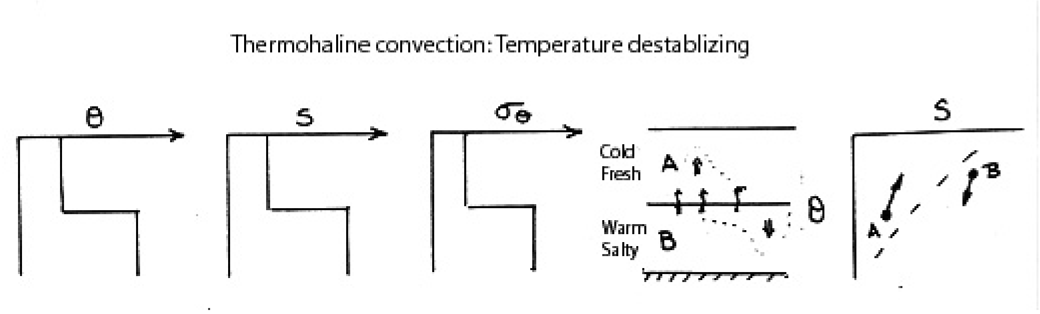

Figure 4.11. Thermohaline convection in a temperature destabilizing ocean environment.

E. Thermohaline Circulation: Antarctica

The two most important features indicated in Figure 4.12 are the Antarctic and Subtropical Convergences zones near 52^{N}S and 35^{N}S respectively. These zones are defined by large horizontal gradients of temperature, namely

(i) 2-3^{N}C per 50 km for the Antarctica Convergence

(ii) 4^{N}C per 100 km for the Subtropical Convergence

These features are due to the thermohaline circulation in the region of the southern ocean, which controls important meridional flow in the deep water. The deep thermohaline driven meridional and the wind driven zonal flow in this region are depicted in Figure 4.12. The thermohaline flow is described in terms of the different Antarctic water masses and has characteristic velocities of only a few *cm/sec*.

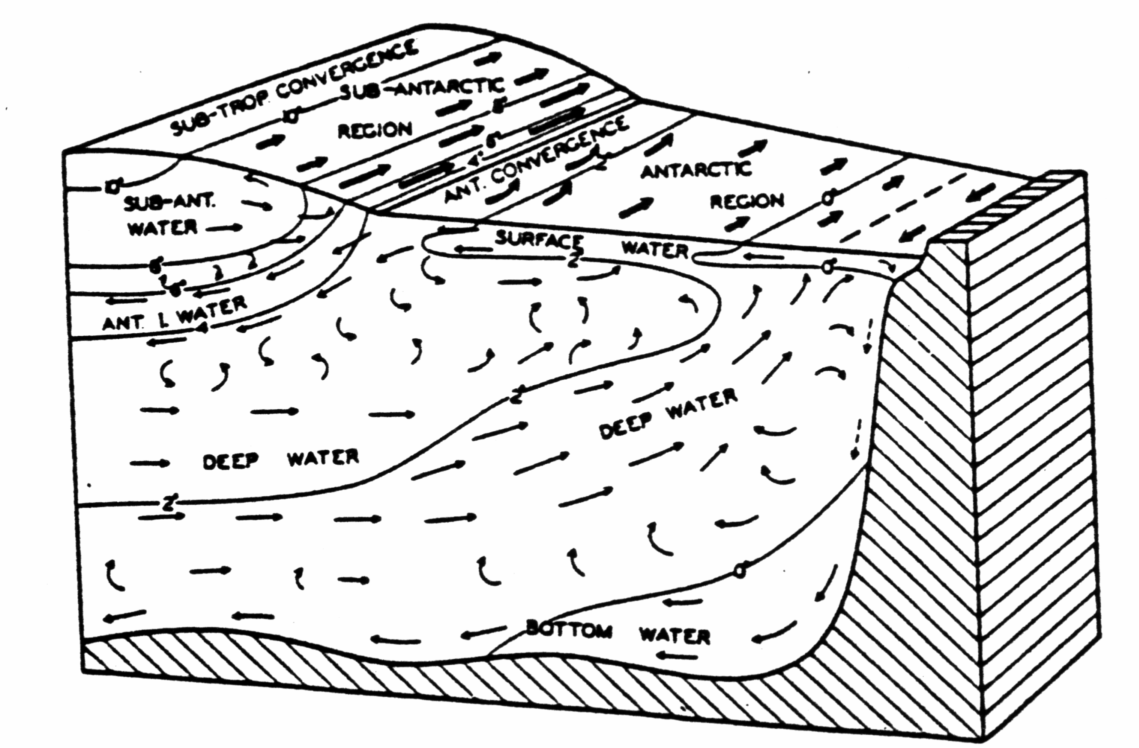

Figure 4.12. Schematic representation of currents and water masses near Antarctica.

Two sub-regions are distinguished by their water characteristics; namely the Antarctic region from the continent to the Antarctic convergence (~52^{N}S) and subantarctic region between the Antarctic Convergence and the Subtropical Convergence. See Figure 4.13 for typical T/S curves for these regions. Figure 4.13 is a simplified diagram derived from the measurement-derived fields in Figure 4.14 and the more complete T/S diagram in Figure 4.15.

Principal Water Masses: Antarctic

ANTARCTIC SURFACE WATER; AASW

The T/S characteristics of AASW is controlled by melting and cooling rates in the summer and winter respectively.

ANTARCTIC CIRCUMPOLAR WATER; AACP

AACP is an extremely uniform water mass, which rings the Antarctic continent. Its principal source is from the northern Atlantic.

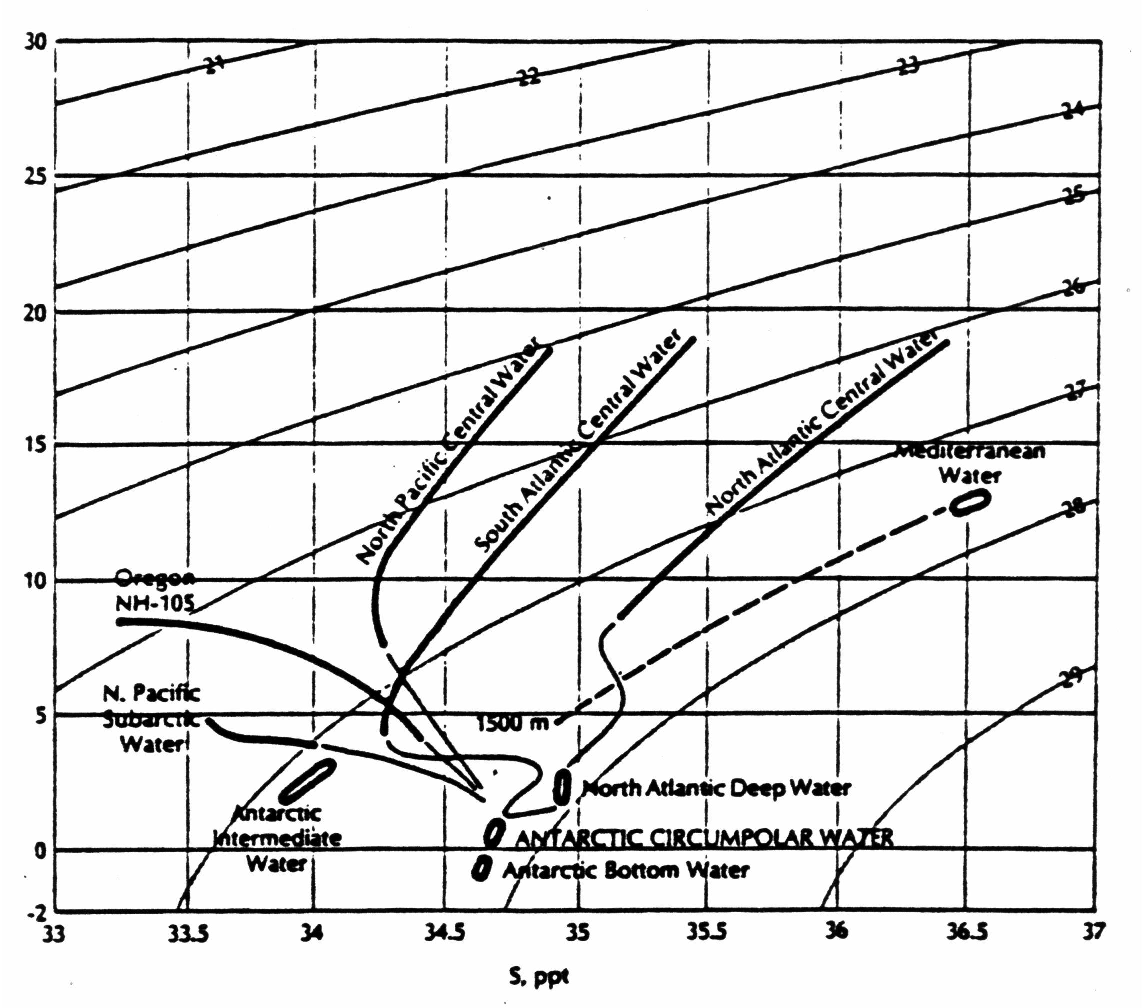

Figure 4.13. T-S graphs showing the different types of water mass structures found in different ocean basins. (Neshyba, 1987)

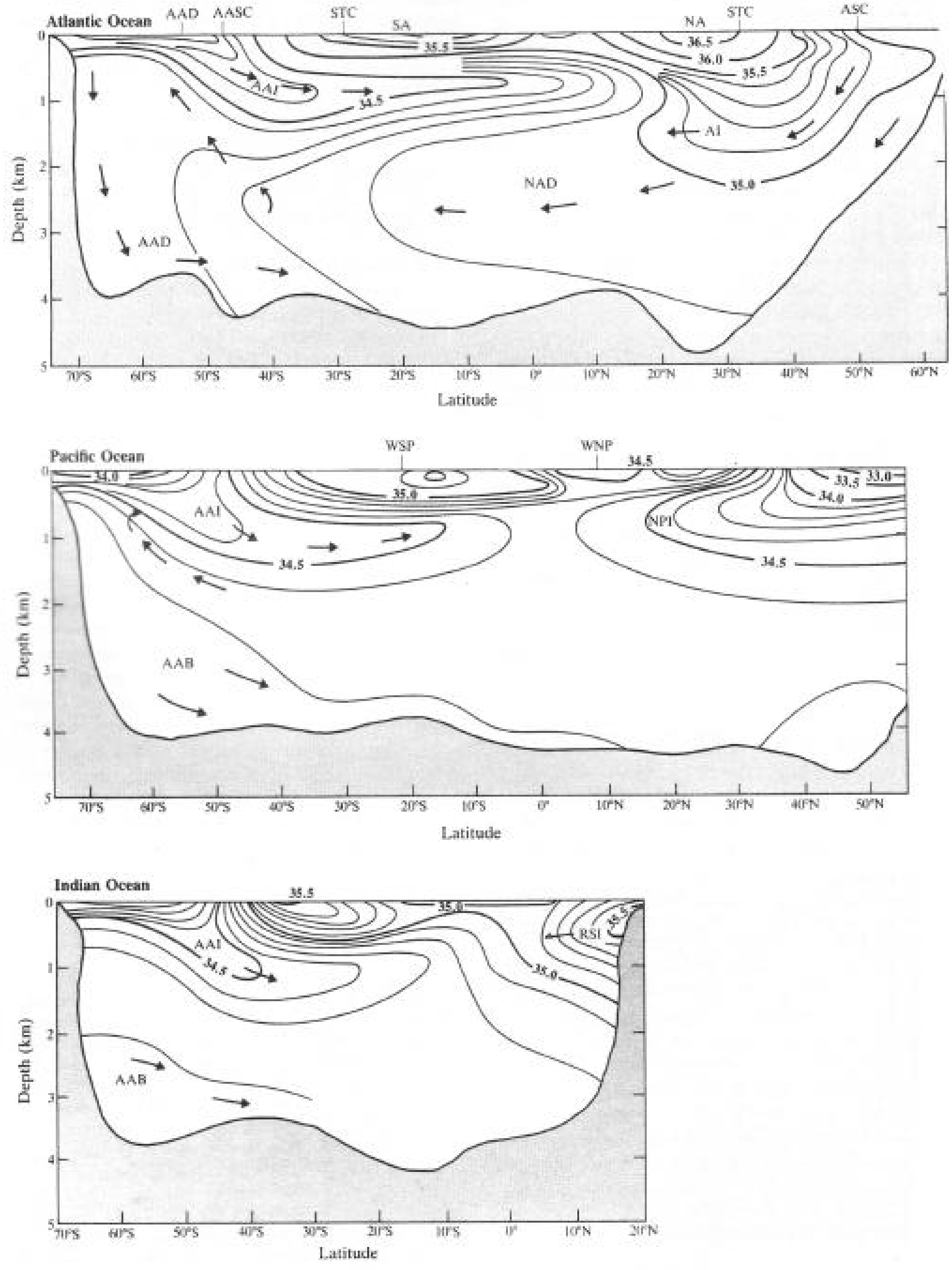

Figure 4.14. Meridional section of salinity indicating location of principal water masses in each of the major ocean basins. (Tolmazin, 1985)

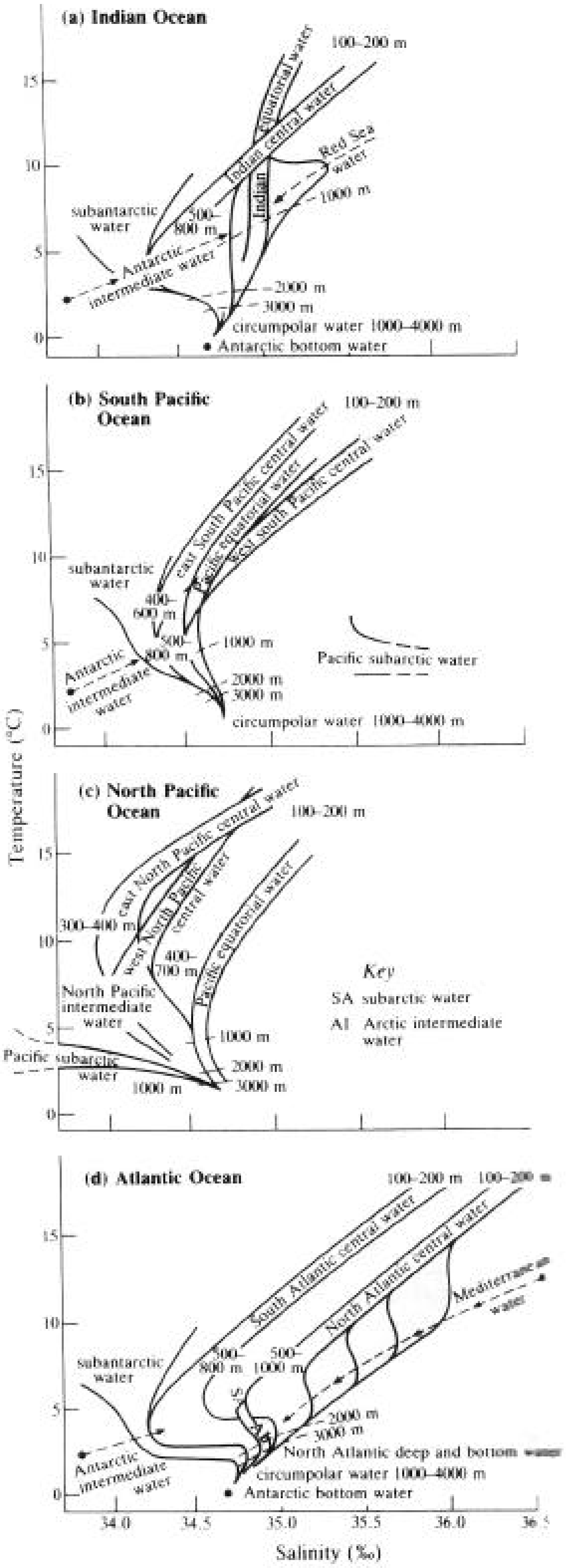

Figure 4.15. T/S diagrams for the principal ocean basins indicating water masses. (Tolmazin, 1985)

ANTARCTIC BOTTOM WATER: AAB

AAB is an extremely important water type formed in the Weddell Sea by a complicated mixing process which includes continental runoff (-1.9NC, 34.62psu) and Antarctic Circumpolar Water (0.5^{N}C, 34.68psu). Mixtures of these water types (masses) eventually form Antarctic Bottom Water (-.4NC, 34.66psu) whose density s_t = 27.86 is dense enough to sink below the circumpolar water. The ?-S properties of this water have been used to trace it as far north as 40^{N}N.

Principal Water Masses: Subantarctic

SUBANTARCTIC UPPER WATER: SAU

SAU is formed from surface water from the north and the sinking of local surface water.

ANTARCTIC INTERMEDIATE WATER: AAI

AAI forms near the Antarctic Convergence from the convergence of Antarctic Surface Water with Subantarctic Upper Water to form AAI (2.2^{N}C, 33.80psu), with a density s_t = 27.02 is such that it sinks (mixing as it does so) to mid-depth and spreads towards the north. At its depth between the Subantarctic Upper Water and Upper Atlantic Deep Water it is traceable through its q , S properties as far north as 20^{N}N.

UPPER AND LOWER ATLANTIC DEEP WATER: UDW AND LDW

UDW AND LDW are formed by cooling and sinking processes in different sub areas of the North Atlantic and flow southward to fill a major proportion of the Atlantic Ocean. There is strong evidence to support the notion that these deep water meridional flows are concentrated in deep western boundary currents (see Warren).

These and the Antarctic Water Masses represent the primary water mass elements of the deep thermohaline circulation in the Atlantic.

By contrast, the Pacific Ocean has no regions where large amounts of deep water can form. Thus most of the Pacific deep water is supplied by the Antarctic region in the form of modified circumpolar and bottom water. Based on observed $q\ / S / O_2$ distributions and core techniques, Wüst and others have defined these other water masses with sources and characteristics indicated:

Principal Water Masses: South Atlantic

South Atlantic Central Water (SACW) has the same T/S as in subtropical convergence (in winter) at 30-40 ^{o}S (see surface T/S graph). SACW formed in the region of the subtropical convergence and spread northward along s_t surfaces.

Antarctic Intermediate Water (AAIW): 2.2^{o}C/33.80 psu is the salinity minimum water which is clearest at the most southern stations.

North Atlantic Deep Water and Antarctic Bottom Water are discussed above.

Principal Water Masses: Equatorial Atlantic

Central Water is a mixture of North and South Atlantic Central Water

Principal Water Masses: North Atlantic

North Atlantic Central Water (NAC) forms by the sinking of surface waters in winter along d_t surfaces. Notice the resemblance of this T/S relation to the surface T/S relation above (which was drawn for northern water) from 30-50^{o}N.

Antarctic Intermediate Water (AAIW) has a slight influence on the mid-depth properties southern regions.

Mediterranean Water (MED), a high salinity and temperature water, which forms when the surface waters of the Mediterranean Sea evaporate. This flows onto the straits of Gibraltar at 11.9^{N}C, 36.50psu s_t = 27.78 and depths of ~1000 m after settling in between s_t = 27.6 and 27.8. Can be traced to South Atlantic, but fades out as the distance from the Straits increases.

North Atlantic Deep Water (NADW): Forms in the Arctic and spreads all the way south to the Antarctic. Several possible ways of formation:

(1) water of high salinity carried north by Gulf Stream mixed with some cold Labrador Sea water and cooled.

(2) Mixing of whole water column (c.f. N. At. figure Discovery II 35l7 - notice remarkable uniformity of water) - rapid sinking and spreading.

(3) intermittent formation during periods of exceptionally cold climate (during 1800s) in large quantities.

<u>Arctic Intermediate Water</u>(AIW) is analogous to AAIW but not as much formed - only influences northern stations.

<u>18^{N} Water</u> forms in the Saragasso in winter to give a thick layer of water at 17.9 ± 0.3^{N}C - 36.5psu/300 m.

<u>Mediterranean Outflow</u> - Warm 6-10NC
Saline 35.3-36.4psu

- Spills over side at Gibraltar and spreads laterally at mid-depths in Atlantic
- Distinctive properties are diluted by mixing estimates of the amount of mixing can be made from measurement at distance from the source.

Summary: The properties of the principal water types and masses in the world's oceans are presented in Table 4.1. The distributions of the principal water masses in the world's oceans in presented in Figure 4.16.

Table 4.1. Temperature and salinity properties of the major water masses of the world's oceans.

TYPE	S (psu)	q (NC)	0_2 (ml/l)
AACP	34.7	0	5
AAB	34.6	<0	>5
NAD&B	34.9	2-4	>6
AAIW	34.0	2	>6
NAC	36.5	18	
	35.1	8	
SAC	35.9	18	
	34.6	8	
SAA	34.6		
	34.0		
MED	36.5	12	

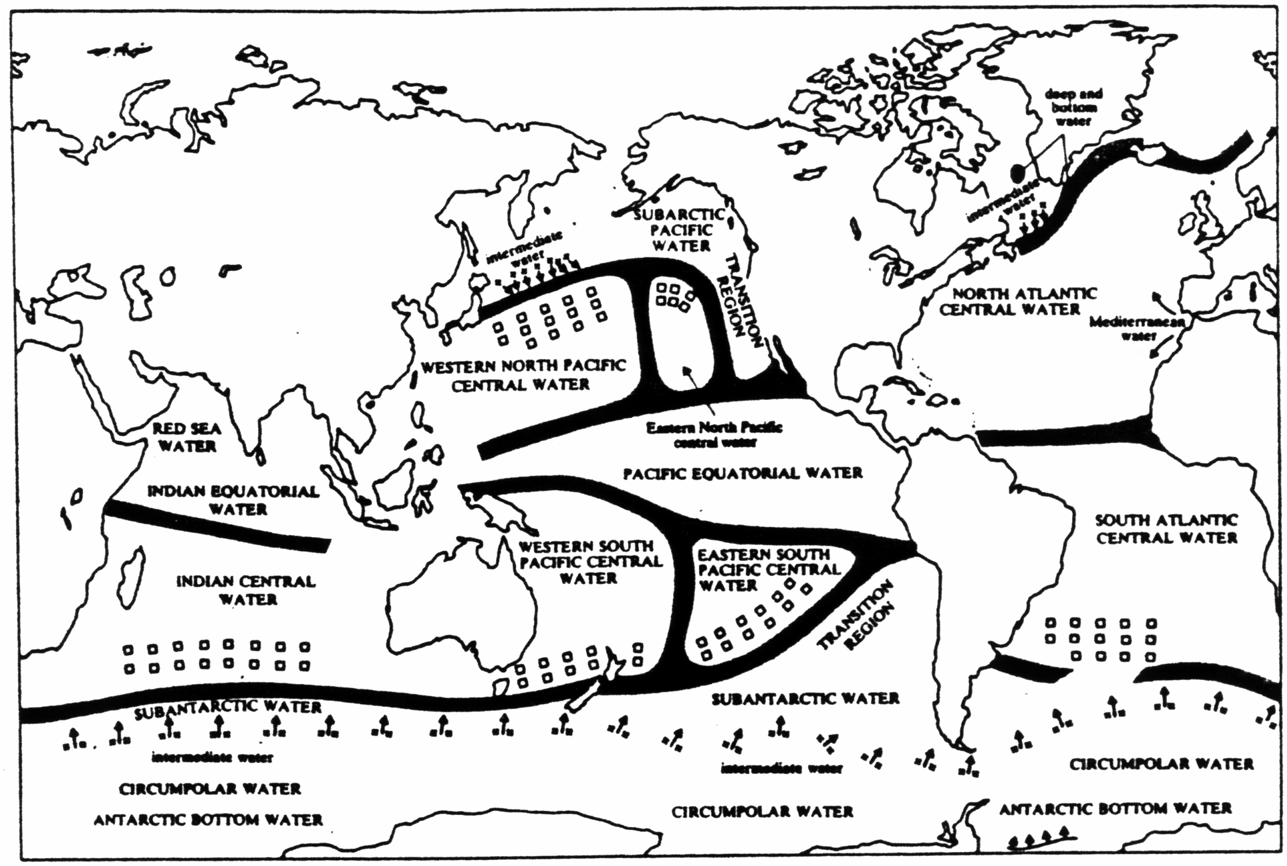

Figure 4.16. Surface water mass distributions for the world's oceans. Squares mark regions where central water masses are formed; crosses indicate where Antarctic and Arctic intermediate water sinks (from Sverdrup et al. 1942). (Tolmazin, 1985)

Deep Thermohaline Flow

The deep flow suggested by water mass distributions is clearly meridional. In addition there is considerable property distribution evidence that these meridional flows are concentrated along the western boundary of the ocean basins. Deep salinities (Figure 4.17) show a concentrated flow of deep water out over the sill in Denmark Strait. Other evidence indicates that another branch of deep water from the Norwegian Sea joints the Denmark Strait overflow water southwest of Greenland at the base of the continental slope. The flow follows bathymetric contours around the Southeast Newfoundland Ridge (Figure 4.18).

Hydrographic evidence is consistent with the Figure 4.19 depiction of an equatorward deep western boundary flow of North Atlantic Deep Water along the base of the North American continental slope. There is further evidence (Figure 4.20) that the flow crosses the equator and continues southward as a deep western boundary current as far as Brazil in the South Atlantic. The Brazil salinity section (Figure 4.20) also indicates the presence of Antarctic Intermediate and Bottom Water which appear to both flow northward from their origins near Antarctica (Figure 4.21).

Stommel summarizes (Figure 4.22) the principal elements of the deep thermohaline circulations as derived from the water property distributions.

Figure 4.17. Careful analysis of small salinity differences in the deep Atlantic reveals the Antarctic Bottom Water moving up from the south and the Norwegian Sea Water moving through the Denmark Strait. (After Worthington, L.V. and W.R. Wright, 1970: "North Atlantic Ocean Atlas," Woods Hole Oceanographic Institution Atlas Series, Vol. II, Woods Hole, Mass.). (Knauss, 1978)

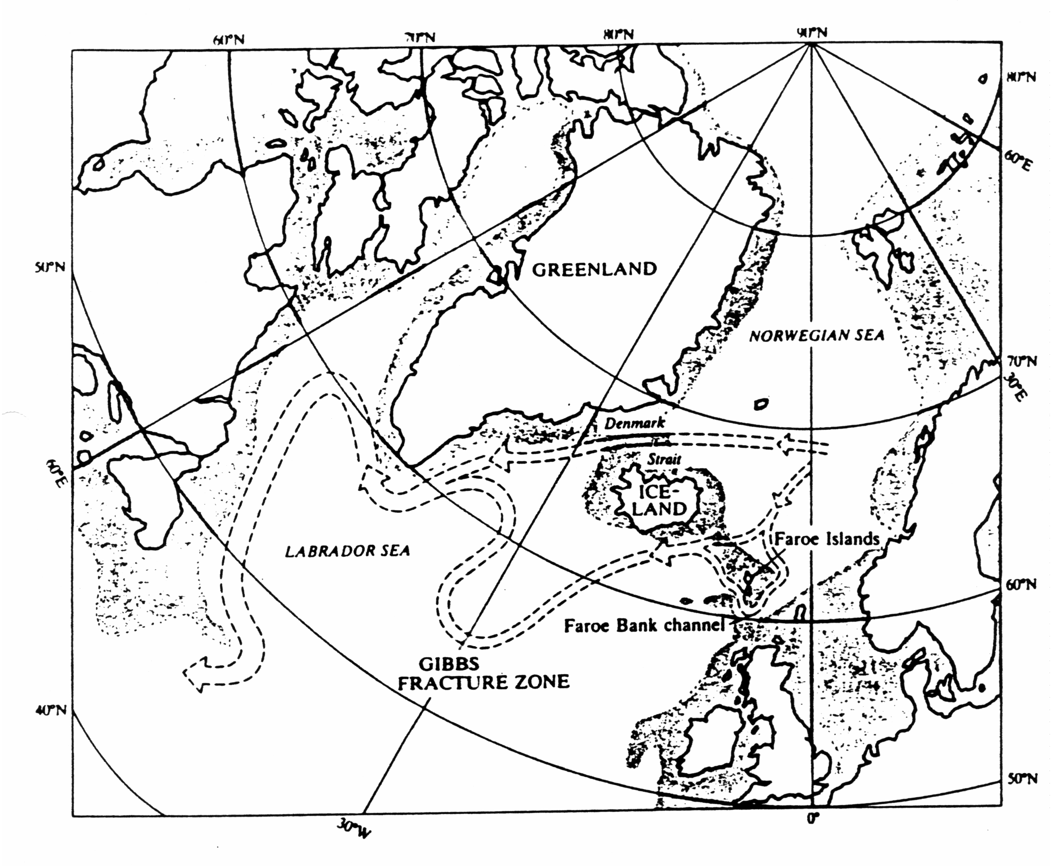

Figure 4.18. Schematic of deep flow resulting from sinking in the Norwegian Sea.

Figure 4.19. Schematic of the major flow of North Atlantic deep water along the continental slope of North America.

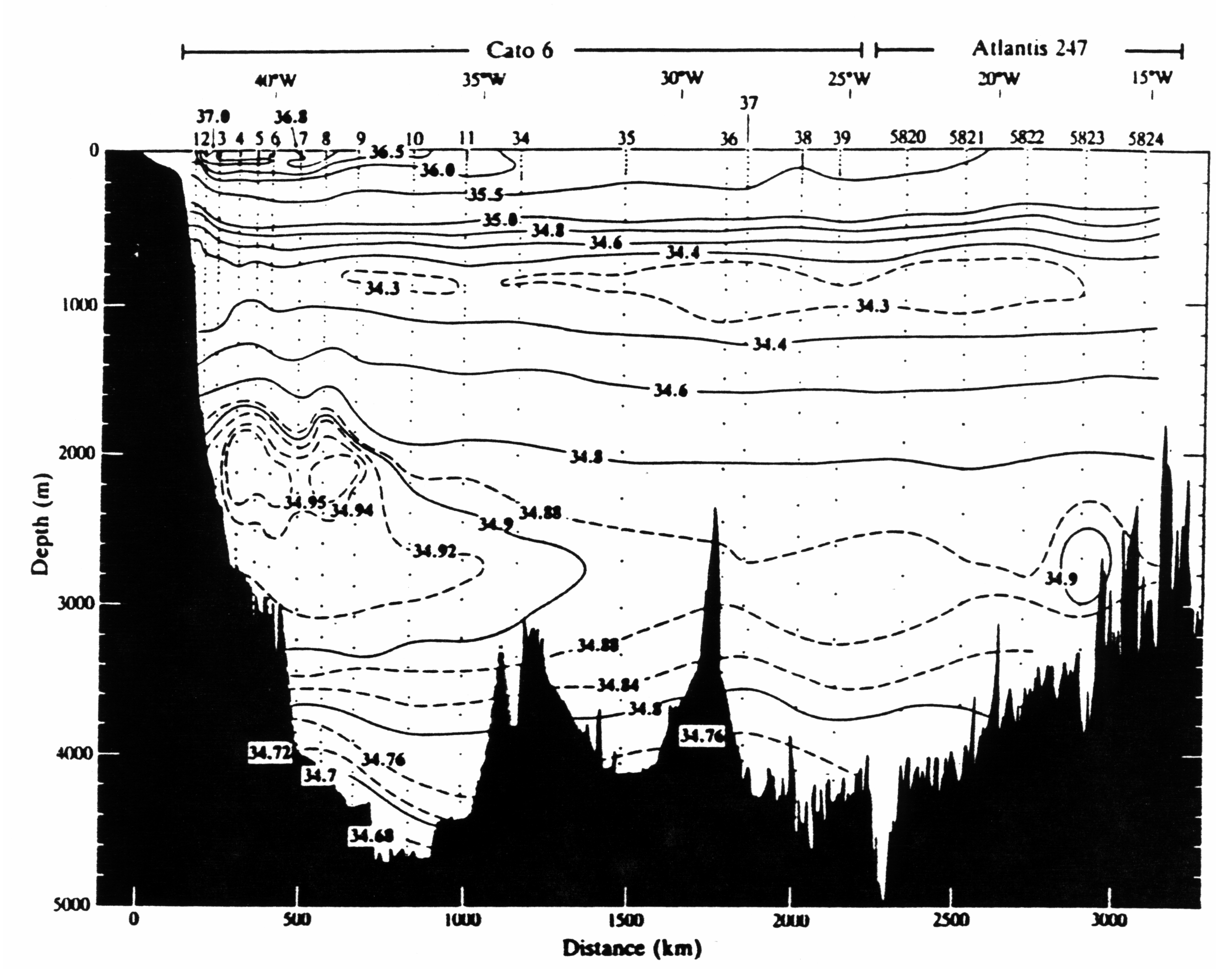

Figure 4.20. Section of salinity (psu) along roughly latitude 30 ^{o}S from South America (left) to the Mid-Atlantic Range, illustrating the two western boundary currents of the South Atlantic, namely the northward-flowing Antarctic bottom water and southward-flowing North Atlantic deep water above. Cato 6 (RV 'Melville') stations 1-11, November 8-12, 1972 and stations 34-39, November 25-9, 1972; RV 'Atlantic' stations 5820-5824, May 5-9, 1959.

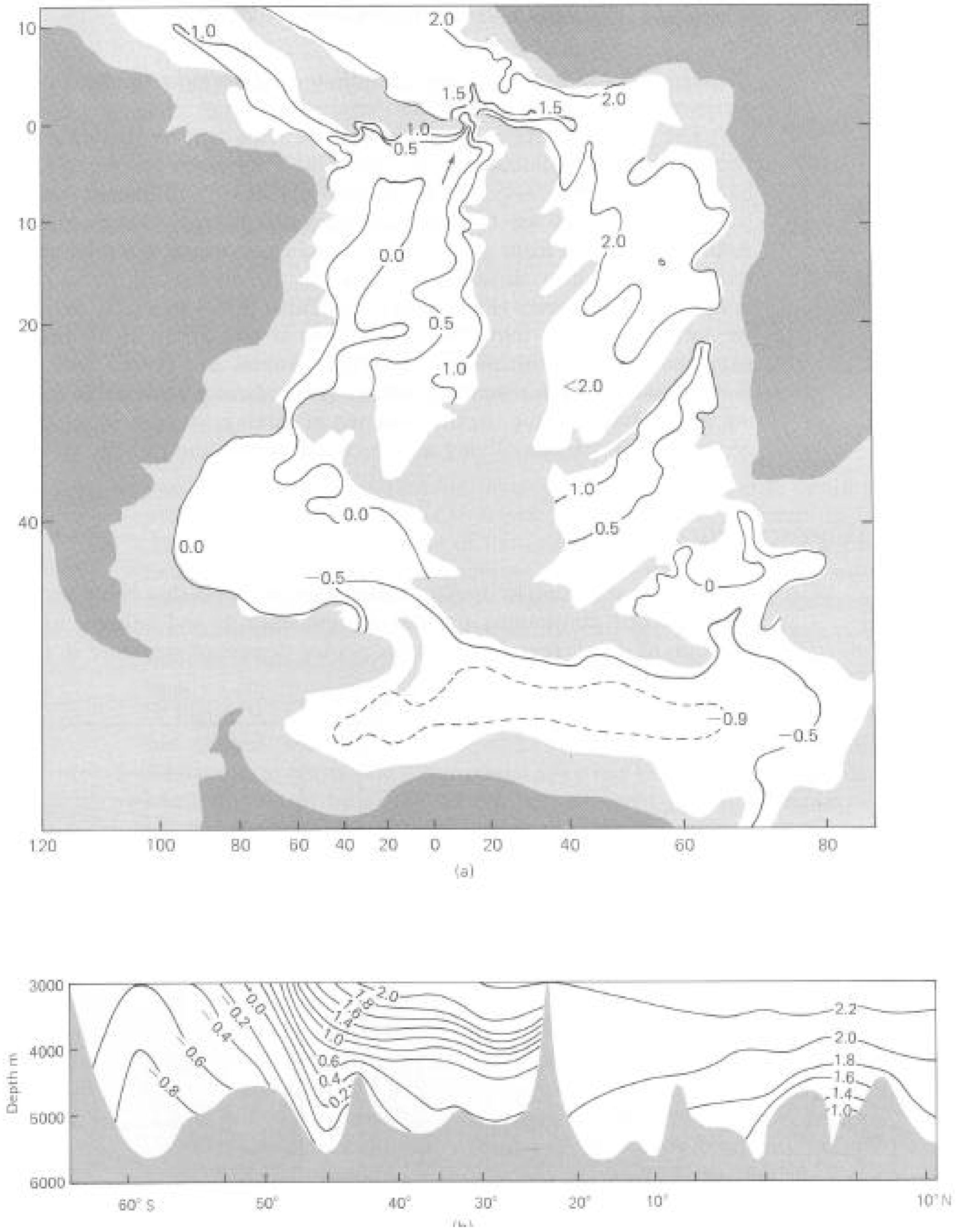

Figure 4.21. The potential temperature sections indicate pathways of Antarctic Bottom Water. (Knauss, 1978)

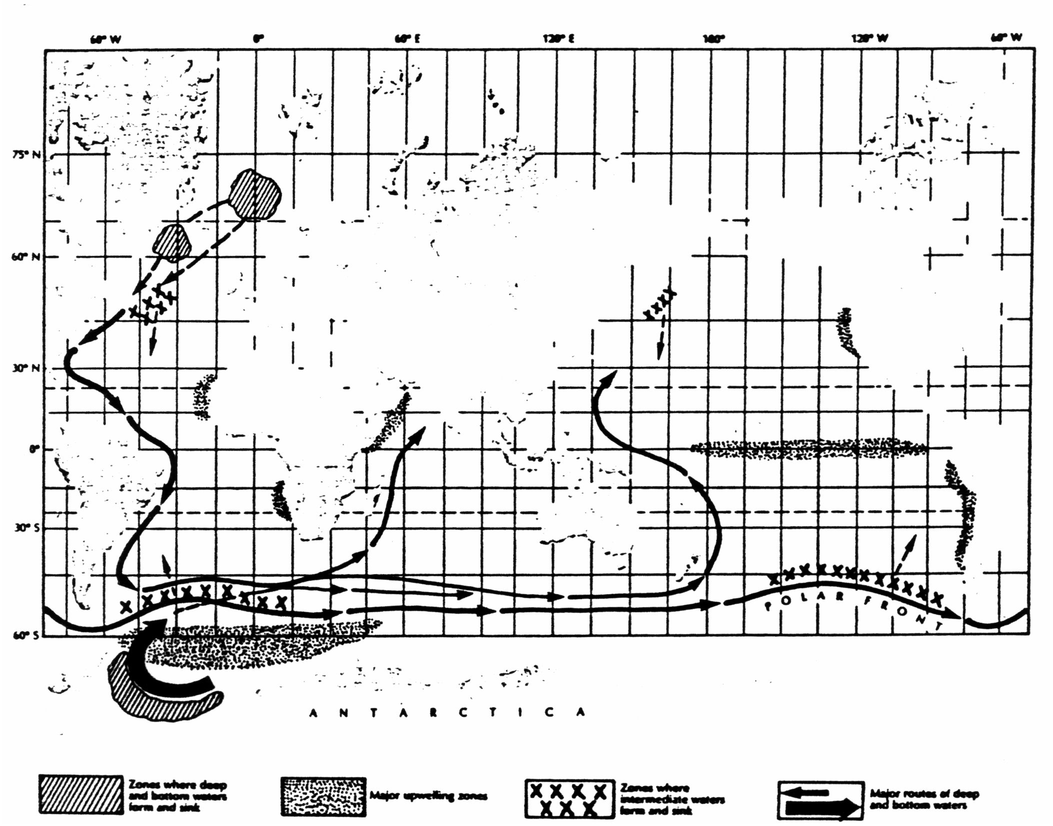

Figure 4.22. Circulation within the deep ocean layers (after Stommel, 1958). (Tolmazin. 1985)

CHAPTER 4 PROBLEMS

PROBLEM 4.1. Interpretation of q -S Diagrams

Plot the stations below on a q -S diagram. Indicate mixed layer, seasonal pycnocline, main pycnocline, instabilities, and the approximate depths and q -S properties of the probable water types associated with each of the core layers where appropriate. Now using the core layers you have postulated, calculate the percentage of each water type found at 150m, 600m, 1250m, and 2500m depths respectively.

Depth (m)	Pot. Temp(°C)	Salinity (psu)
0	14.97	34.953
50	15.11	34.951
100	11.91	35.079
150	11.21	34.995
200	10.82	34.942
250	10.27	34.872
300	10.89	34.867
400	8.98	34.675
500	8.41	34.599
600	7.89	34.549
700	7.14	34.493
800	6.36	34.457
1000	5.01	34.479
1250	3.71	34.477
1500	2.93	34.554
2000	2.33	34.672
2500	1.94	34.729
3000	1.53	34.733
4000	1.16	34.719
Bottom		

Give a guess as to the latitude and time of year of this station.

PROBLEM 4.2. Water Mass Volumes

Estimate the mixing ratio of continental shelf water q = -1.9°C, S = 34.62 psu and Antarctic circumpolar water q = 0.5°C and S = 34.68 psu necessary to produce Antarctic bottom water q = -0.4°C and S =34.66 psu. Mixing ratio here is defined as the percent of shelf water to the percent of circumpolar water mixed. What are the

σ_θ values of these three water types? What would tend to sink to the bottom, the middle, or rise to the surface? Does your answer make sense?

What happens oceanographically if we mix 20% subantarctic surface water at θ =12°C, 35 psu, and 80% surface water at 33.60 psu, θ = 4.4°C? What are the values of the θ, S, σ_θ of the original types and the mixture? Discuss your result.

PROBLEM 4.3. Salt Fingers

Using the formula in Knauss as modified in the handout, determine if it is possible for salt fingers could occur in North Atlantic Central water based on the data in Figure 8.8 of Knauss.