Some XBT-observations* on the thermal structure of the *Warmwassersphäre* in equatorial and lower latitudes of the eastern Atlantic

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Summary

Two megameter long XBT sections passing through the Atlantic between the Iberian Peninsula and the equatorial Brazilian shelf, and between the Peninsula and the Cape region of South Africa were obtained during supply cruises to the Antarctic in November 1980 and March 1981. Most of the individual probes reached an observation depth of nearly 800 m allowing statements on the thermal stratification and zonation of the *Warmwassersphäre* in the open ocean. Our new data are compared with a number of earlier long sections. As a general result we identify five zones dividing different hydrographic regions. Zone 1 is characterized by the clear influence of the Mediterranean Undercurrent on the lower boundary of the *Warmwassersphäre* creating nearly thermostatic conditions below 300 m off Portugal. The adjacent zone 2 is identical with the Subtropical Convergence, where the *Warmwassersphäre* reaches its maximum depth (15 °C isotherm at about 300 m). We call the equatorial region zone 3 and present an improved scheme of its current system and its thermal stratification. Zone 4 is marked by the Benguela Current and its northern extension. In a final zone 5 we show the influence of the Agulhas Current extension on the stratification.

XBT-Beobachtungen zur thermischen Struktur der Warmwassersphäre in äquatorialen und niederen Breiten des östlichen Atlantiks (Zusammenfassung)

Im November 1980 und März 1981 wurden auf Versorgungsfahrten zur Antarktis zwei lange XBT-Schnitte gewonnen. Sie verlaufen zwischen der Iberischen Halbinsel und dem äquatorialen brasilianischen Schelf beziehungsweise der Kapregion von Südafrika. Die meisten Sonden reichten bis zu einer Meßtiefe von 800 m, so daß Aussagen zur thermischen Schichtung und horizontalen Gliederung der Warmwassersphäre im offenen Ozean möglich wurden. Wir vergleichen unsere neuen Daten mit einer Reihe von früher gewonnenen Schnitten. Als Ergebnis erhalten wir fünf unterschiedliche hydrographische Regionen. Zone 1 ist gekennzeichnet durch den klaren Einfluß des Mittelmeerausstromes, der an der Unterseite der Warmwassersphäre westlich Portugals unterhalb von 300 m nahezu thermostatische Bedingungen schafft. Die anschließende Zone 2 ist identisch mit der Subtropenkonvergenz, innerhalb derer die Warmwassersphäre ihre Maximaltiefe (15-°C-Isotherme bei etwa 300 m) erreicht. Die äquatoriale Region nennen wir Zone 3. Es wird eine überarbeitete

* XBT Expendable Bathythermograph

Darstellung der Strömungs- und Temperaturschichtungsverhältnisse dieser Region gegeben. Die Zone 4 ist durch den Benguela Strom und seine nördlichen Ausläufer geprägt. In der letzten Zone 5 wird der Einfluß des Agulhas-Strom-Ausläufers auf die Schichtung vorgestellt.

Des observations XBT sur la structure thermique de la *Warmwassersphäre* dans les latitudes équatoriales et basses de l'Atlantique oriental (Résumé)

En novembre 1980 et mars 1981 on a obtenu deux longues sections XBT pendant des voyages d'approvisionnement à l'Antarctique. Les sections passent entre la péninsule Ibérique et le plateau équatorial brasilien et entre la péninsule Ibérique et la région du Cap de l'Afrique du Sud respectivement. La plupart des sondes descendaient jusqu' à 800 m, ce qui a permis d'obtenir des renseignements sur la stratification thermique et la structure horizontale de la *Warmwassersphäre* en haute mer. Nous avons comparé nos nouvelles données avec une série de sections obtenues plus tôt. Nous en avons obtenu comme résultat cinq zones hydrographiques. La zone 1 est caractérisée par l'influence évidente du courant profond de la Méditerranée sur la côté inférieure de la *Warmwassersphäre,* ce qui crée des conditions presque thermostatiques aux profondeurs excédant 300 m à l'ouest du Portugal. La zone 2 adjacente est identique à la convergence subtropicale, où la *Warmwassersphäre* atteint sa profondeur maximale (isotherme de 15 °C à environ 300 m). Nous désignons la région équatoriale la zone 3, et nous présentons un schéma révisé des systèmes des courants et des stratifications thermiques de cette zone. La zone 4 est marquée par le courant Benguela et son extension vers le nord. Dans la zone 5 nous présentons l'influence de l'extension du courant Agulhas sur la stratification.

1 Introduction

On the occasion of the German Filchner Ice Shelf Expedition 1980/81 we had an opportunity to map large parts of the *Warmwassersphäre* in both hemispheres of the eastern Atlantic Ocean. The *Warmwassersphäre* is defined as the upper part of the ocean bounded towards the poles by the polar fronts and below by the 10 °C isotherm. The special importance of this relatively thin warm water layer comes from the meridional heat transport which takes place within this stratum and which feeds the atmosphere in the moderate and higher latitudes. In continuation of an earlier series of megameter long temperature sections (Henke [1978]; Henke and Zenk [1980]), we compiled two new sections of expendable bathythermograph (XBT) observations. In contrast to our earlier observations, most of our new profiles cover the whole *Warmwassersphäre,* since 760 m probes could be used. While our activity on the southbound leg (section K) on the RV "Polarsirkel" in December 1980 had to be limited to the direct course of its destination port in South America, the return leg (section W) in March 1981 deviated from the shortest course and led through the eastern deep basins of the Atlantic (Fig. 1). Thus, shelf effects on the thermal stratification of the *Warmwassersphäre* could be avoided. As a nominal distance between XBT stations, 56 km was chosen. In areas of special interest the station distance was reduced to 28 km. In total, 312 XBT observations were obtained, 133 on section K and 179 on section W. The reader is referred to Georgi, Dean and Chase [1979] for information about temperature and depth accuracy of the XBT probes.

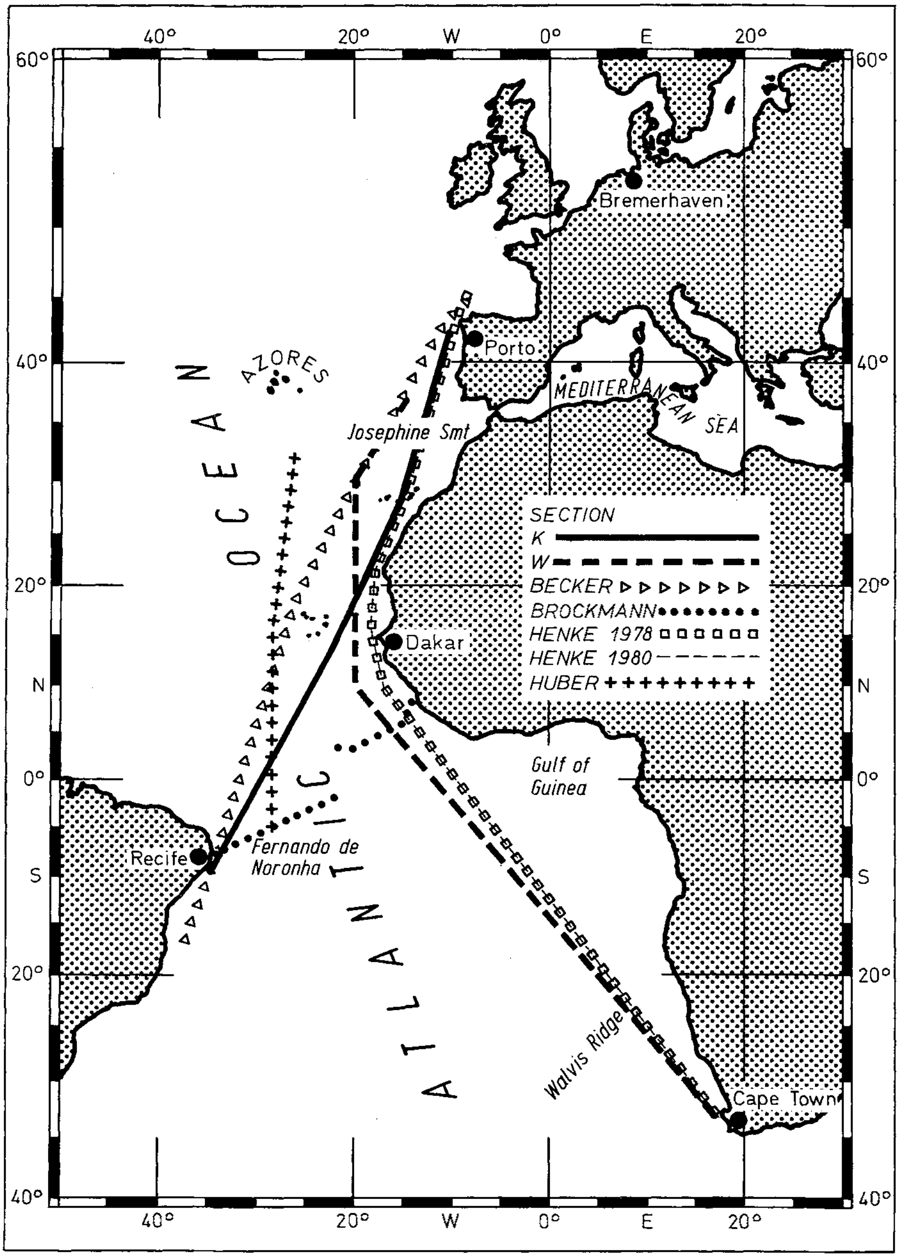

Fig. 1. Track lines of selected XBT sections across the Atlantic Ocean (Sections K and W are shown in Fig. 2 and 3)

2 Temperature distribution along section K

This section (Fig. 2) was obtained during north winter and intersects the area between the eastern Iberian Basin (42° N) and tropical latitudes (10° S) of the Brasilian shelf. The observations took 13 days. Hydrographically the section can be divided into three zones.

From north to south, the first zone follows roughly the Iberian Shelf off Portugal to a chain of sea mounts southwest of Portugal. A mixed layer depth down to 80 m is present. In the horizontal, the temperature increases gradually by 5 °C/1000 km. Also characteristic of this region is the weak thermal stratification in mid depth range, that mainly originates from heat diffusion from the underlying Mediterranean Outflow (Zenk [1971]).

The adjacent second zone of section K covers the Subtropical Convergence Zone. It begins with a significant drop of the 15 °C isotherm (stations 15 to 20) southwest of the Josephine/Gettysburg Bank region at about 37° N. This drop probably caused by topography can be observed in several XBT sections (Tab. 1). Typical of this division which reaches its southern boundary near 16° N is the well marked deep thermocline. Concurrently with the nearly horizontal orientation of the deep thermocline, we observe a decrease of the vertical extent of the *Warmwassersphäre* from greater than 800 m to approximately 400 m within 1600 km. It is represented by the continous slope of the 10 °C isotherm.

Although the XBT section is not totally free of a zonal component (Katz [1977]), the horizontal temperature gradient shows the predominently meridional isothermal slopes of the equatorial region. In the third zone, the *Warmwassersphäre* represented by the 10 °C stratum rises in steps from 400 m near the Cape Verdes to 280 m north of Fernando de Noronha. Further south towards the Brasilian Shelf, it slopes down to 380 m again. The typical doming of the 11 °C water near 9° N, the Guinea Dome, is found repeatedly in this area as an expression of a cyclonic gyre in conjunction with the North Equatorial Counter Current. The area of highest surface temperatures, the thermal equator, observed at 4.5° N coincides with comparable observations by Becker, Hennings and Metzner [1981] and Huber, Miller, Weisberg et al. [1976]. The temperature differences between those sections correspond to the seasonal variations of the surface temperature in that region as shown by Merle, Fieux and Hisard [1980]. Other characteristic features are the equatorial thermostad extending from 4° S to 4° N and the spreading of the thermocline at the equator. Both features are part of the South (SEUC), the North (NEUC) and the Equatorial Undercurrent (EUC) flowing eastward at about 240 m (SEUC, NEUC) and 90 m (EUC) depth. Due to the locations of the undercurrents and the equatorial divergence, a minimum of the thermostad occurs at the equator. While the SEUC extends from Brazil to the Golf of Guinea (Molinari, Voituriez and Duncan [1981]), the NEUC breaks up east of 28° W (Cochrane, Kelley and Olling [1979]). Therefore, only a week indication of the NEUC is found in this section. The sharpest thermocline occurs above the SEUC and NEUC with a vertical temperature gradient of 12 °C/25 m at 3° S and 12 °C/30 m at 4° N. The location of the equatorial current system of several selected XBT sections is summarized in Tab. 1.

3 Temperature distribution along section W

A second, long XBT section connecting the Agulhas Current extension area (31° S) with the southern Iberian Basin (36° N) was obtained during 18 days in northern spring (Fig. 3). Again, from the temperature distributions, the area can be divided into hydrographic zones. In addition to the three divisions already seen in section K, we have to add more for the southern Atlantic.

Compared to the first zone of section K, temperatures at the surface near the Ibe-

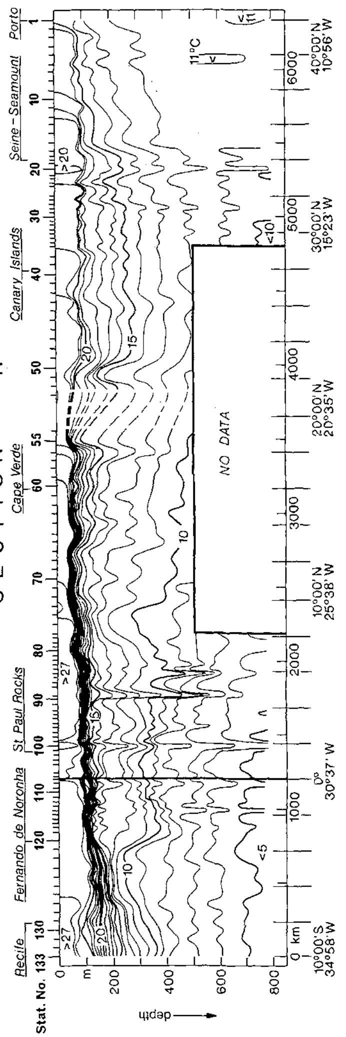

Fig. 2. XBT section K (dashed isotherms mean interpolated values) taken in December 1980. Temperature in °C

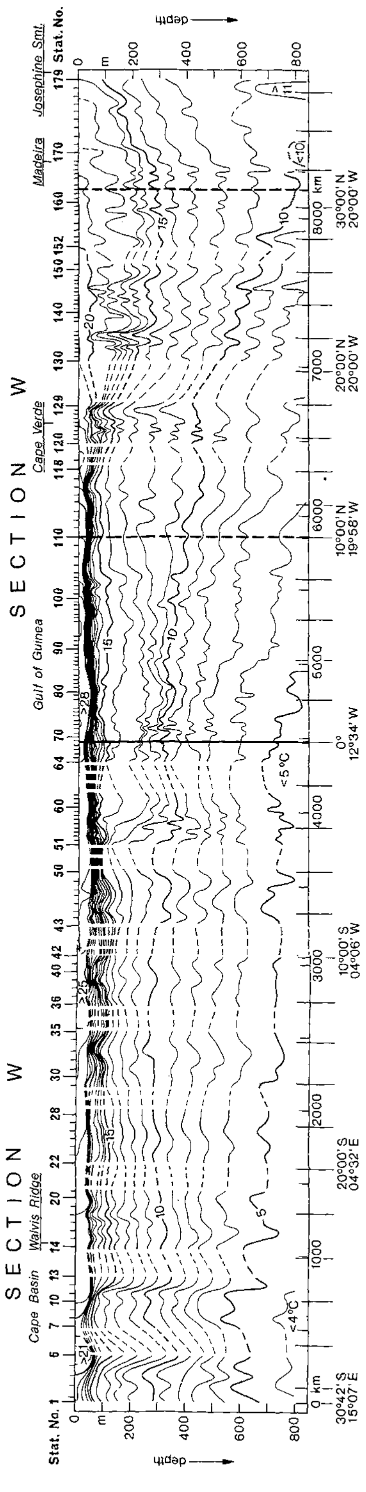

Fig. 3. XBT section W taken in March/April 1981. Temperature in °C

rian Peninsula are 1 or 2 degrees lower. Associated with the observed surface cooling is the maximum of the deep winter convection. It clearly can be seen from the weaker thermal stratification and a pronounced deepening of the 15 °C isotherm. Of course, the influence of the Mediterranean outflow water is present in the Upper Deep Water of the first zone below 650 m. South of the sea mount chain Josephine/Gettysburg Bank, which represents the transition to the second zone, near Madeira, we observe the characteristic drop of the 15 °C isotherm already seen in section K from 180 m down to 290 m within 150 km. The systematic southbound decrease of the *Warmwassersphäre,* represented by the 10 °C isotherm, coincides with section K. Towards the Cape Verde Island, an upper thermocline is forming, which gradually sharpens.

In the equatorial region, the third zone, the thermocline continues sharpening and the depth of the 10 °C isotherm shoals towards the equator up to 300 m. Due to the different location of section W (Fig. 1), the Guinea Dome cannot be observed. The mixed layer depth at the equator diminishes from 80 m in section K to 20 m in section W in accordance with the east-west slope of the isotherms shown by Merle [1980]. Also, the minimal mixed layer depth at the north equatorial divergence zone is getting deeper towards the west (cf. Tab. 1). At the thermal equator, 5.5° N, the surface temperature exceeds 29 °C coinciding with the seasonal variations in the equatorial Atlantic described by Merle [1978]. The equatorial thermostad, presented by a spreading of the 13 °C and 15 °C isotherms is found between 4° S and 3° N in a depth of 80 to 260 m with the sharpest thermocline at 2° N (12 °C/20 m) and 3° S (12 °C/28 m).

In the fourth zone, south of 10° S, the section encounters the northwestward extensions of the Benguela Current. This part is characterized by a smooth temperature distribution within the *Warmwassersphäre.* Its vertical extent, limited by the 10 °C isotherm, expands from 280 to 320 m depth. The upper part of the main thermocline weakens gradually. Within the mixed layer, we find a horizontal temperature gradient of approximately 3 °C/1000 km.

The adjacent fifth zone covers the area of the Walvis-Ridge at 23° S and the Cape Basin towards the South African Shelf. This part is governed by an eddy-like feature caused by the extension of the Agulhas Current. Harris, Legeckis and Forest [1978] showed that due to the southeasterly winds, appearing especially in the southern summer, a branch of the Agulhas Current sometimes passes into the South Atlantic. Even at 19° S, Darbyshire [1966] observed a T/S-relationship corresponding to Agulhas water. In two earlier sections made in July/August 1978 and March 1980 (Henke [1978]; Henke and Zenk [1980]), an eddy-like feature was also found at exactly the same location. At the end of this zone, there is an indication of the shelf edge divergence belt separating the weather dominated Benguela Current, flowing along the coast, from the climate forced Trade Wind Drift (Defant [1936 a]; Hart and Currie [1960]; Bang [1971]).

4 Summary

We have presented two new quasi-meridional and quasi-synoptic XBT sections from the eastern North and South Atlantic. Due to natural variations in time and space, one needs synoptic data sets to describe the mean properties of the *Warmwassersphäre.* While a number of permanent features can already be extracted from available data collections, others of a more transient nature, such as the vertical scales, the horizontal zonation and variability of eddy size and frequency, need a statistical treatment of data homogeneous in time and space. In Table 1, we present a number of characteristic properties of the *Warmwassersphäre* in equatorial and lower latitudes as derived from sections K and W and from other XBT sections in the literature. The track lines of the discussed cross sections are depicted in Fig. 1. In addition to Table 1, we present an updated picture (Defant [1936 b]) of the temperature and current systems at the equator (Fig. 4), where our data coverage was best. Recent findings on various equato-

Table 1 — **The locations of observed features during different sections across the Atlantic**

Zone	feature	W March 81	K Dec. 80	Henke and Zenk March 80	Henke Juli/Aug. 78	Becker et al. Begin of Oct. 80	Becker et al. End of Oct. 80	Brockmann et al. Feb.–Juni 79	Huber et al. Juli/Aug. 74
1	location and depth of Mediterranean outflow water	northward 35° N >650 m	northward 34° N >650 m	northward 37° N >650 m	*)	*)	*)	*)	*)
2	location of the 15 °C isotherm drop (1)	33.5° N, 18° W (Madeira) 36.5° N, 15.5° W (Josephine-seam.)	34.5° N, 13.5° W (Seine-seamount)	34.5° N, 13.5° W (Seine-seam.) 36.5° N, 12° W Gettysburg-seam.)	36.5° N, 12.5° W (Gettysburg-seamount)		34° N, 15° W (Seine-seamount)	*)	*)
2	max. depth of 15 °C isotherm (Center of the subtropical convergence)	29° N 310 m	26° N 300 m	31° N 280 m	30° N 280 m	25° N 280 m	25° N 330 m	*)	24° N 360 m
2–4	region and depth of the max. vertical temperature gradient	15° S to 15° N 20 to 60 m	6° S to 18° N 50 to 110 m	28° S to 10° N 15 to 70 m	20° S to 20° N 20 to 100 m	7° S to 14° N 40 to 100 m	7° S to 14° N 40 to 100 m	6° S to *) 30 to 100 m	*) to 12° N 30 to 100 m
3	minimal mixed layer depth (north equatorial divergence zone)	8.5° N 10 m	12.5° N 40 m	8° N 5 m	10° N 10 m	11° N 30 m	13° N 30 m	8° N 20 m (2)	6.5° N 20 m
3	mixed layer depth at the equator	20 m	80 m	20 m	20 m	90 m	60 m	(7) 50 m	40 m
3	thermal equator (maximal sea surface temperature)	5.5° N >29 °C	4.5° N >27.5 °C	3° N >28.5 °C	13° to 15° N >28 °C	8° N >28 °C	5° N >28 °C	*) >28 °C	4.5° N >26 °C
3	thermostad	4° S to 3° N 13 to 15 °C	4° S to 4° N 11 to 13 °C	4° S to 4° N 13 to 15 °C	4° S to 3° N 13 to 15 °C	4° S to 8° N 11 to 13 °C	5° S to 7° N 11 to 14 °C	4° S to 6° N 12 to 14 °C	(3) 5° S to 4° N 12 to 14 °C
3	NEC (north equatorial current)	9° to 12° N	12.5° to 18° N	8° N to *)	10° to 16° N	12° to 22° N	12° to 22° N	*)	7° to 12° N
3	NECC (6) (north equatorial countercurrent)	3° to 8° N	5° to 10.5° N	4° to 8° N	5° to 10° N	3° to 12° N	3° to 12° N	5° to 9° N	4° to 7° N
3	NEUC (north equatorial undercurrent)		4° N ~250 m			7° N ~250 m	6° N ~250 m		2° to 4° N ~300 m (4)
3	EUC (equatorial undercurrent)	0.5° S to 0.5° N 80 m	1° S to 1° N 130 m	0.5° S to 0.5° N 90 m	~km south of the equator 50 m	1° S to 0° 150 m	0° to 1° N 130 m	0.5° S to 0.5° N (7) 100 m	1° S to 0° 100 m
3	SEUC (south equatorial undercurrent)	4° to 3° S ~200 m	4° to 3° S ~280 m	4° to 2° S ~230 m	4° to 2° S ~200 m	4° to 3° S ~280 m	4° to 3° S ~280 m	4° to 3° S ~250 m	(3) 5° to 2° S (5) ~300 m
3	SEC (south equatorial current)	7° S to 2° N	6° S to 2° S	6° S to 1° N	8° S to 2° N	14° S to 6° S	14° S to 3° N	6° S to *)	(3) 5° S to 4° N

notes: *) no measurements in that depth or region

☐ this feature was not observed

(1) The 15 °C isotherm drop is next to the following seamount
(2) This section ends at 8° N
(3) This section ends at 5° S
(4) Called by Huber et al. subthermocline North Equatorial Counter Current
(5) Called by Huber et al. northern edge of the South Equatorial Counter Current
(6) Also called Equatorial Counter Current in older literature
(7) This depth measured with a CTD instrument was given by E. Fahrbach in a personal communication

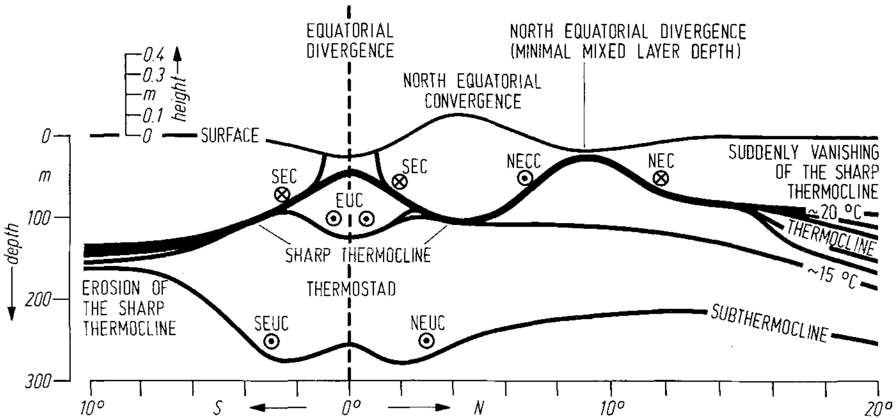

Fig. 4. Generalized graph of the equatorial temperature stratification and current system in the *Warmwassersphäre* according to Defant [1936 b]. Several XBT sections across the Atlantic Ocean (Becker, Hennings and Metzner [1981]; Brockmann, Fahrbach and Meincke [1980]; Henke and Zenk [1980]; Henke [1978]; Huber, Miller, Weisberg et al. [1976] and current measurements (Molinari, Voiturez and Duncan [1981]; Düing, Ostapoff and Merle [1980]; Cochrane, Kelley and Olling [1979] are included. Due to the variations of depth and latitude of the illustrated features with season and longitude, their positions can only be given approximately

rial current branches by Düing, Ostapoff and Merle [1980]; Cochrane, Kelley and Olling [1979] and Molinari, Voituriez and Duncan [1981], are included in Fig. 4. This note is a presentation of some preliminary results of our ongoing work.

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