Meandering of the subtropical front south-east of the Azores

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A subtropical front was observed in the area south and south-east of the Azores during cruises of FS *Meteor* and FS *Poseidon* in early 1982. The front has a basically west–east extension, with considerable meandering observed. Meso-scale eddies are found on both sides. The overall flow pattern corresponds to earlier results on geopotential differences in the upper north-east Atlantic, but the baroclinic transport of the order of 10^7 m^3 s^{-1} is found to be concentrated in a 60-km wide jet. We suggest here that the current band is part of the gyre circulation, resulting from a branching of the North Atlantic Current.

Such subtropical fronts can be expected where strong Ekman transport convergence occurs in a region of large horizontal thermohaline or haline gradients. They are temperature and salinity fronts in winter and spring and salinity fronts only in summer and autumn in the North Pacific[1], with a density front existing simultaneously at both times of the year. Jet-like baroclinic surface currents have been found at a 1,000-km long front in the central subtropical North Atlantic, with current speeds as high as 50 cm s^{-1} (ref. 2). The subtropical front is more pronounced in the Southern Hemisphere, and a complicated mesoscale structure connected to the front has been found in the southern Indian Ocean[3].

The subtropical front also marks the transition between the eastward and westward flow in the oceanwide anticyclonic gyre circulation. Early studies of the North Atlantic circulation in the area north of the Azores[4,6] led to the conclusion that the North Atlantic Current splits into two branches at approximately 45° N, 25° W, with a southern branch heading towards the Azores and continuing south-east towards Madeira. The upper ocean flow field can most easily be seen in the potential density field in Fig. 77 of ref. 6, indicating a splitting-up into two more branches west of the Azores. An eastern branch in this historical map flows southward to the Azores, then veers left towards the south-east. A second branch reaches the Azores west of the Mid-Atlantic Ridge, oriented west at first at 37° N and turns back to the east at 35° N. Note that Hansen's[5] numerical model of Atlantic Ocean surface currents including a variable wind field produced a dynamic topography that is consistent with a flow from the Azores to the Madeira region. A similar basic pattern can be found in more recent maps of upper ocean geopotential differences[7–9].

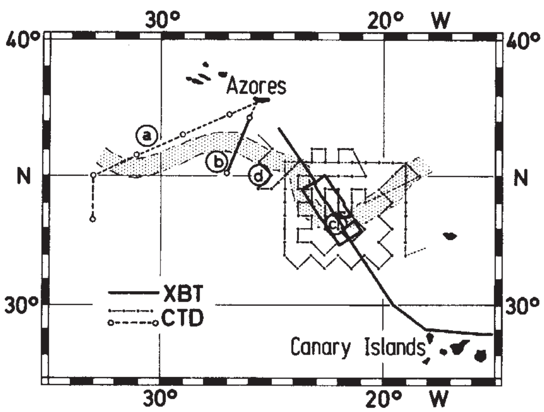

Fig. 1 Pattern of hydrographic survey performed by FS *Meteor* and FS *Poseidon* during March–April 1982. Sections *a*–*d* are referred to in Fig. 3. The dotted area indicates the estimated location of the subtropical front.

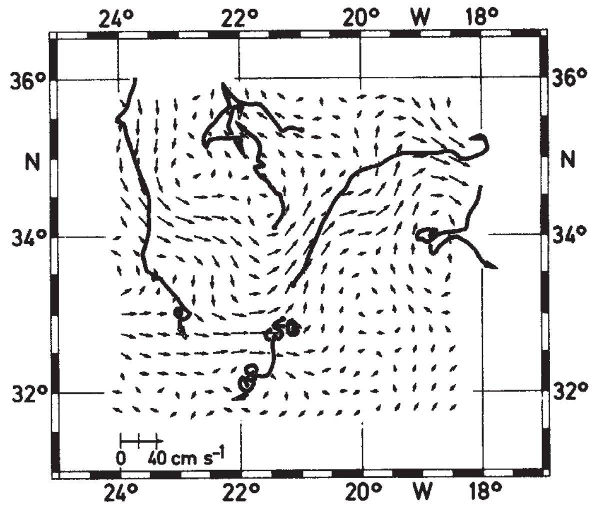

Fig. 2 Estimated geostrophic surface velocity relative to 1,500 dbar and paths of satellite-tracked drift buoys with drogue at 100 m depth. Map determined from objective analysis of geostrophic surface velocity relative to 1,500 dbar using a non-isotropic gaussian covariance function with zonal and meridional correlation scale of 100 and 65 km. Trajectories of satellite drift buoys obtained from daily fixes during FS *Poseidon* hydrographic observations.

These early data led to an easterly flow in the region where Ekman transports calculated from Bunker's[10] wind data (H.-J. Isemer, personal communication) result in an Ekman convergence zone approximately along 35° N, with a seasonal meridional shift of ±3° latitude. These results on the gyre circulation and the Ekman convergence suggest a connection between the current branching from the North Atlantic Current system towards the Azores and the current related to the subtropical front in the eastern North Atlantic.

Within the framework of the Warmwassersphäre research programme at Kiel University several cruises were performed in the tropical, subtropical and moderate latitude basins of the eastern North Atlantic. Indications of frontal variability were found to exist persistently in the region between 30 and 38° N, and subsequently observational programmes were designed for 1982 cruises with the aim of resolving mesoscale features of the frontal region south and east of the Azores (Fig. 1). FS *Meteor* in March/April occupied several XBT and CTD sections including a XBT box pattern between the Canary Islands and the Azores in the northern Canaries Basin and also south-west of the Azores close to Mid-Atlantic Ridge. FS *Poseidon* in April covered 82 CTD stations 30 nautical miles apart in a box pattern between the Azores and the Canary Islands. Also four satellite buoys deployed by FS *Meteor* previously were drifting in the area of the FS *Poseidon* box.

The geostrophic flow field obtained from the CTD box data is presented in Fig. 2. It reveals a current band with ~60 km width and 25 cm s^{-1} speed in its core, entering the box in the northwestern corner, turning east in the centre and leaving the area from the northeastern corner. This current band corresponds to large horizontal temperature gradients and also to salinity gradients in the upper ocean that specify a front. The related geostrophic shear reaches levels as deep as 650 m, more than is usually reported for surface fronts. The satellite drifters' tracks also shown in Fig. 2 conform with the general pattern of geostrophic currents obtained from the CTD data. Note that closed streamline patterns on both sides of the jet suggest the presence of mesoscale eddies with typical scales of 200 km.

The larger-scale spatial distribution of the front can be determined from further surface temperature data and temperature sections to the west of the CTD box (see Fig. 1). The surface temperatures displayed in Fig. 3 include the position of the front marked by the maximum horizontal gradient at the surface. The corresponding temperature sections are also shown

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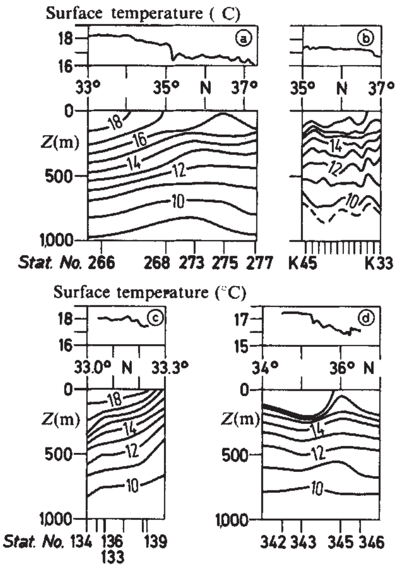

Fig. 3 Temperature obtained from sections *a–d* indicated in Fig. 1. Note the different scale in section *c*.

in Fig. 3. The front stretches zonally south of the Azores, turns to a southerly direction south-east of the Azores and in the box veers round to northerly directions. IR radiation satellite photographs confirm the existence of a continuous temperature gradient band in this general pattern (G. Hardtke, personal communication). Time variability of the front on time scales of the order of 1 month can be deduced from current meter moorings in the area. This will be discussed elsewhere.

The long-term persistence of the front can be tested by inspecting data from three different cruises: RRS *Discovery*, January 1981[11,12], FS *Meteor*, April 1981, and FS *Poseidon*, April 1982. The density at 250 m depth obtained in sections crossing the area under discussion is presented in Fig. 4. The horizontal density gradient related to the front is found at similar positions in all three sections. The observed surface front obviously separates regions with a permanent thermohaline mixed layer and subtropical thermocline from regions with seasonal thermocline formation, winter convection and advection of North Atlantic Current water masses. We suggest that the subtropical front found here corresponds to a branch of the North Atlantic Current that is already indicated as a broad band in Wüst's[6] map of potential density at 200 m. This is supported by the fact that downstream volume transports in the observed baroclinic current band related to the front are of the same order of magnitude ($10^7\ m^3\ s^{-1}$) as mean meridional Sverdrup transports across this area between the Mid-Atlantic Ridge and the African coast estimated from zonal hydrographic

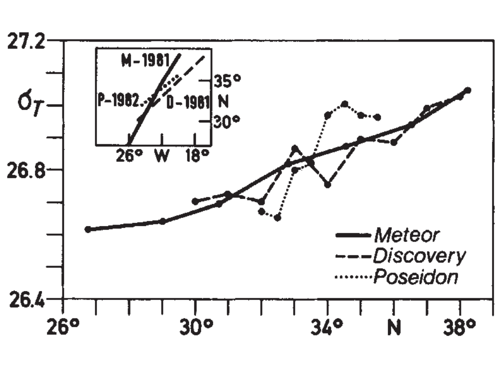

Fig. 4 Density (σ_T) at 250 m depth as function of latitude from three different cruises in the area south-east of the Azores.

sections[11,12]. Transports in the narrow band at the front may thus constitute the major portion of the total long-term transport. It is also possible that the front observed here is a continuation of the frontal zone found[13] to the west of this area.

The observed meandering of the front, with an even more complicated smaller-scale structure seen in IR satellite photographs, may be due to several processes. The most obvious candidates are quasi-stationary Rossby waves, which were earlier suggested[14] as the cause of wave-like patterns observed in the polar boundary of the subtropical convergence in the South Atlantic, or baroclinic instability of the jet.

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Oxygen utilization rates in North Atlantic subtropical gyre and primary production in oligotrophic systems

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If the observed distribution of dissolved oxygen in deep oceans below the euphotic zone is in stationary and steady state, then it can be assumed that the *in situ* consumption of oxygen is balanced by 'ventilation', or, in other words, physical transport of oxygen from regions of higher dissolved oxygen and ultimately the sea surface. It follows, therefore, that measurement or determination of those physical transport processes, coupled with observation of the oxygen distribution will lead to an estimate of the net oxygen utilization rate (OUR). The character of such an estimate is that it is a space and time average over scales governed by the nature (space and time scales) of the transport processes, the scale of the oxygen distribution, and the climatologic nature of the system. As such, one obtains an average which is characteristically of the order of 10^8 s, 10^8 cm or more, that is large compared with scales of biological variability. I report here some new determinations of oxygen utilization rates determined by tritium dating in the North Atlantic subtropical gyre, compare them with other and previous estimates, and discuss their implications regarding primary production and nutrient cycling in an oligotrophic system.

The Beta Triangle is a triangular study area in the eastern subtropical North Atlantic whose apices are at 26.5° N × 38.5° W, 32.5° N × 30.0° W, and 22.5° N × 28.5° W. The area

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