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# An Atlantic meridional transect of surface water dimethyl sulfide concentrations with 10–15 km horizontal resolution and close examination of ocean circulation

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**Abstract.** Underway measurements of dimethyl sulfide (DMS) in the Atlantic surface waters have been made during the ALBATROSS campaign from 65°N to 45°S along about 30°W. The main patterns of DMS variability in subtropical waters of both hemispheres were the existence of (1) a poleward negative gradient of DMS (0.04 nM/°latitude) paralleling the temperature and salinity meridional trends and opposite to that of chlorophyll *a* (chl *a*) and particulate DMSP (pDMSP), and (2) sharp DMS enhancements, up to twenty fold the background levels, coinciding almost systematically with thermohaline frontal zones. We observed that DMS concentrations and TOPEX/Poseidon sea level anomalies (SLAs) were clearly in opposition of phase in the subtropical and tropical waters of the Atlantic. Neither meridional changes in pDMSP nor in chl *a* concentrations account for these large-scale (15°–20° latitude) DMS variations. It is suggested that the spatial distribution of DMS is highly sensitive to the upper ocean dynamics. The tropical Atlantic is a zone of contrasted DMS levels with two broad maxima associated (1) with the cyclonic circulations generated by the North Equatorial currents and (2) with the South Equatorial Current, a situation very much resembling the autumnal meridional distribution of surface pCO<sub>2</sub>. A close examination of the South Atlantic subtropical front (38°–43°S) show that DMS and in situ validated satellite chl *a* have a distinct spatial distribution suggesting important spatial segregation of biogeochemical processes in the frontal zones. These observations at different spatial scales provide indications for the existence of a DMS-climate link through frontogenesis and surface ocean circulation in the Atlantic.

## 1. Introduction

Oceanic emissions of dimethyl sulfide (DMS) are the major natural source of gaseous sulfur to the atmosphere. DMS oxidation provides the starting material for the nucleation of new particles in the free troposphere and supports the growth of smaller particles into cloud condensation nuclei in the marine boundary layer [Andreae and Crutzen, 1997; Bates *et al.*, 1998]. Atmospheric DMS is believed to play a significant role in regulating the Earth's temperature on geological timescales [Watson and Liss, 1998]. However, its role on shorter human timescales is still uncertain. Because surface ocean circulation in general and especially in the Atlantic is very important in the context of climate change studies [Wood *et al.*, 1999], the aim of our investigation is to provide an estimate of the role played by open Atlantic Ocean frontal systems and currents on the spatial distribution of DMS.

The Pacific and Atlantic Oceans have been studied extensively for their surface water DMS concentrations [Bates and Quinn, 1997; Groene, 1995]. The Max-Planck DMS database [Kettle *et al.*, 1999], which includes over 15,000 measurements from tens of research cruises spanning more than 10 years, provides the opportunity to assess the spatiotemporal variations in seawater DMS concentrations on a global scale. The present work provides an up-dated picture of the DMS meridional variability in the Atlantic Ocean at the sea surface. The specificities of this survey are (1) the fine resolution of 10–15 km from 65°N to 45°S never previously attained by others, (2) the cruise track which followed an offshore route as far as possible from European, African, and South American coasts, and (3) the period where the cruise took place providing an estimate of the early winter DMS levels in the center of the North Atlantic Ocean where severe weather conditions were experienced. Moreover, to help interpret the large-scale DMS variability along this meridional section, we have made use of TOPEX/Poseidon products available over the same time period along with more standard physical measurements such as salinity and temperature. TOPEX/Poseidon sea level anomalies were combined with a climatological mean steric height

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from 0/2000 dbars to provide 10 day maps of dynamic topography in the Atlantic Ocean. These dynamic topography maps reflect the upper ocean's density variations, and we will examine the relation between DMS and strong density fronts, which are evident from the sharp slopes in dynamic topography. Maps of the associated surface geostrophic currents are a useful independent tool for interpreting the major currents systems and frontal zones encountered along the meridional section. Second, in order to assess for the role of phytoplankton production of DMS in seawater, samples were also collected to determine concentrations of the particulate and dissolved phases of dimethylsulfoniopropionate (DMSP), the major precursor of DMS. These samples were taken when necessary according to the changes in DMS along the cruise track. Finally, concurrent POLDER satellite chlorophyll observations were analyzed and in some cases compared with in situ pigment measurements. This research was carried out as part of the marine atmosphere oxidation capacity experiment (MARATHON), which was an essential part to the comprehensive atmospheric chemistry campaign ALBATROSS onboard the RV *Polarstern*.

## 2. Methods

### 2.1. Sampling

During ALBATROSS, underway seawater samples were collected 11 m below the ocean surface by means of the ship's bow membrane pump following the techniques of *Meyerdierks et al.* [1997]. The seawater flow rate in the circuit was 8 L min<sup>-1</sup>. Prior to sampling, the circuit was flushed for 5 days during the transect from Germany to Iceland. Since there was no conductivity-temperature-depth on board we were unable to check for pump effects. However, a comparison with CTD samples carried out during a previous expedition of the RV *Polarstern* showed that neither chlorophyll *a* (chl *a*) nor particulate DMSP (pDMSP) estimates were biased by the pump system [*Meyerdierks et al.*, 1997]. In oligotrophic waters at 35°N we compared DMS/DMSP, pigment, and adenosyltriphosphate (ATP) concentrations from the seawater circuit and a handheld bucket underway sampling. Differences in DMS (1.1 nM in both cases) and total pDMSP (surface/11 m: 12.5/13.2 nM) were not significant, the experimental precision being 10% (n=3) for DMS and 7% (n=3) for pDMSP. On the contrary, most pigments were 15-60% lower at 11 m than at the surface as was total ATP and size-fractionated ATP (F. Sunverrick, personal communication, 1996). Dissolved DMSP (dDMSP) and pDMSP in the size fraction <10 μm were 30% lower at 11 m than at the surface. The case of pDMSP in the size fraction >10 μm resembled the situation at the EUMELI site 18°30'N-21°W, showing no pDMSP >10 μm at the surface and a subsurface maximum at 30 m depth [*Belviso et al.*, 1993, Figure 3]. Hence this test shows that there is indeed a pump effect on the dissolved and particulate material sometime. Samples for salinity and temperature measurements were obtained from the same inlet as the DMS samples. Meteorological parameters (air pressure, temperature, relative humidity, dew point, global radiation, wind speed, and direction) were provided by the ship's "POLDAT" data-logging system.

### 2.2. Analysis of DMS

Samples were filtered through 47-mm glass fiber filters (Whatman GFF) by gravity. Intercalibration of filtration

methods using glass fiber filters of different types had previously been performed using diluted phytoplankton cultures of *Phaeocystis* sp. and *Emiliana huxleyi* in the framework of an European Union (EU) project on marine DMS involving four European laboratories [*Kwint and Kramer*, 1995]. DMS predominated (85%) in cultures of *Phaeocystis* sp., while it accounted for about 20% of the DMS+dDMSP pool in cultures of *Emiliana huxleyi*. DMS+dDMSP and pDMSP levels were in the range 2-15 nM and 50-1000 nM, respectively. There were only minor variations of DMS+dDMSP concentrations between the gentle filtration methods, using gravity filtration or gentle pressure only. During ALBATROSS the filtrate was collected in a 100-mL flask and allowed to overflow about three fold before subsampling. The potential loss of DMS by adsorption onto the glass fiber filter was not tested. However, the filtration of about 300 mL of seawater before subsampling most probably lessens this. A syringe with a long needle was used to collect the filtered sample (2-30 mL) from the bottom of the flask so that degassing was avoided. The aliquot was injected into a nonsilanated but seawater-conditioned purging vessel through a Teflon-faced septum replaced frequently to avoid leaks, and degassed for 15 min with high-purity helium. The gas stream passed through a Nafion dryer (Permapure MD050-72F) to remove the water vapor and was cryotrapped in liquid nitrogen with a 1/8 inch diameter fluoro-ethylene-propylene (FEP)-Teflon loop containing Teflon wool. The trap was heated to 95°C, and its contents were transferred for 5 min to a 1/16 inch FEP-Teflon loop immersed in liquid nitrogen. Cryofocusing was a necessary step to allow a rapid injection onto the wide bore PorapLOT Q capillary column (Chrompack). Samples were analyzed using a Varian 3400 gas chromatograph equipped with a Pulsed Flame Photometric Detector (PFPD) optimized as by *Christaki et al.* [1996]. DMS was calibrated from DMSP standards [*Christaki et al.*, 1996]. Precision from seawater replicates (n=3) was 10%.

### 2.3. Analysis of DMSP Dissolved and Particulate

Samples were filtered through 47-mm glass fiber filters (Whatman GFF) by gravity for the analysis of DMS+dDMSP concentrations. An unfiltered sample was also collected systematically. Both types of samples were treated with cold alkali and stored at room temperature in 64 mL biochemical oxygen demand (BOD) bottles (Wheaton) with no headspace, with glass stoppers and plastic caps (Wheaton), and some distilled water was allowed to sit at the top of the bottle during storage time. Back at the laboratory, samples were analyzed by gas chromatography with flame photometric detection (FPD) within 3 months of their collection. Percentage recovery over 3 months was investigated using DMSP standards treated on board with cold alkali and analyzed back at the laboratory with the method described by *Belviso et al.* [1993]. The recovery for samples containing 18.3, 9.1, and 4.6 ng DMS(S) was 93, 99, and 94%, respectively. When alkali-treated DMSP standards were stored without plastic caps, a headspace formed, and recoveries were in the range 50-88%. It is thus clear that samples can be properly stored over months under alkaline conditions in BOD glass bottles with extra protection against headspace formation.

### 2.4. HPLC Determination of Chlorophyll *a* and Ocean Color from POLDER

Pigment analyses were performed at the Laboratoire de Physique et Chimie Marines in Villefranche/mer, France, from

in situ filtered samples (2 L filtered through 47 mm GF/F glass fiber filters with gentle vacuum) stored in liquid nitrogen. The general procedure for high-performance liquid chromatography (HPLC) pigment analysis, identification, and quantification has been described [Claustre *et al.*, 1994a, b]. Total chl *a* is the sum of mono- and divinyl-chl *a*. Its horizontal resolution was about 10 times lower than the DMS one (82/930). Ocean Color from the POLDER instrument flown on ADEOS was provided courtesy of F.-M. Bréon and C. Moulin (LSCE) for the period november 1-10, 1996 when R/V *Polarstern* was in the South Atlantic south of 30°S. We made no use of the whole POLDER results north of 30°S because they differed markedly from our sea surface measurements. This is supposed to arise from the absence of temporal overlap of the two sets of measurements and from biases in the chl *a* estimates from space due to heavy aerosol loading in the Northern Hemisphere atmosphere (C. Moulin, personal communication, 1999).

### 2.5. Dynamic Topography From TOPEX/Poseidon Altimetry

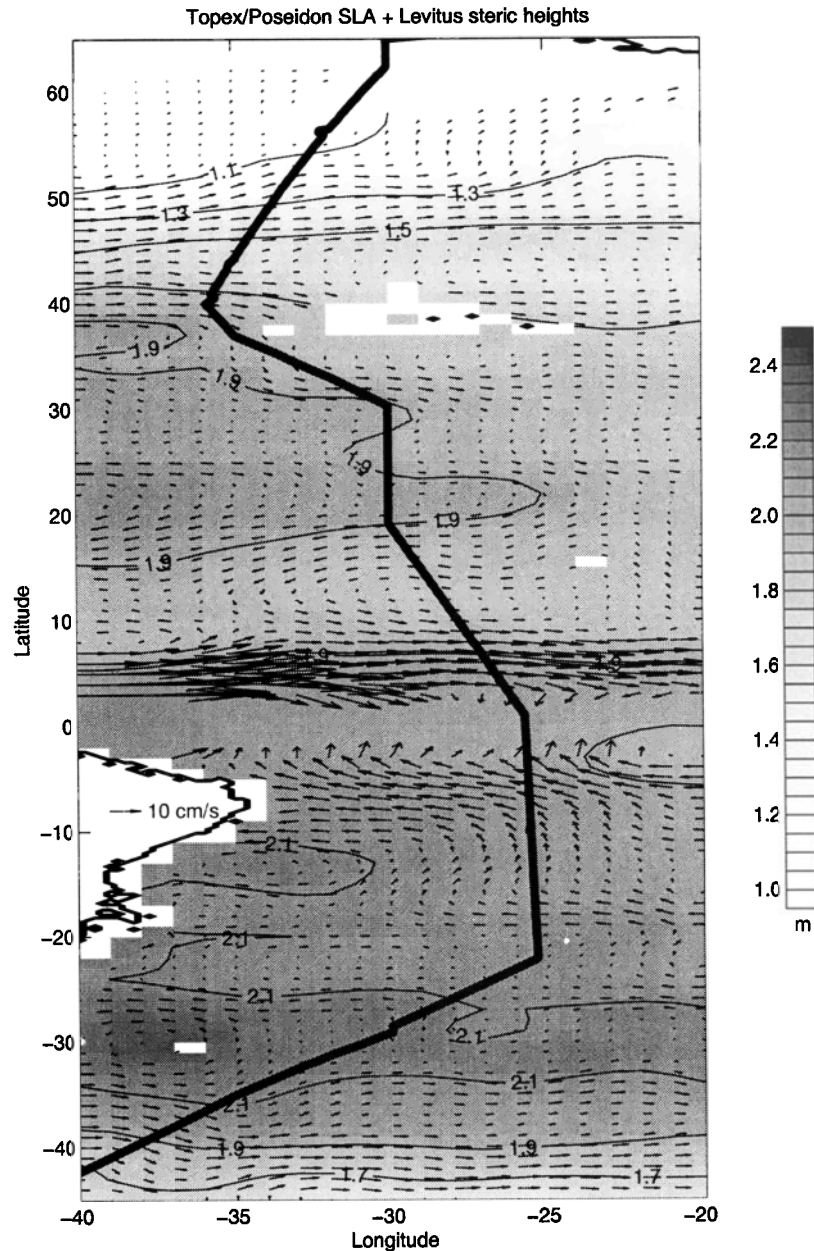
The satellite radar altimeter, TOPEX/Poseidon (T/P), launched in October 1992, measures the large-scale global sea level variations at very high precision. The T/P sea surface heights used here have been processed using standard corrections, explained in detail by *Le Traon and Ogor* [1998]. Sea level anomalies (SLAs) were calculated relative to a mean sea surface (OSUMSS95) which removes an estimate of the unknown but stationary marine geoid, as well as the mean circulation. The SLAs were then mapped every 10 days onto a regular 1°x1° grid, using a decorrelation radius of 2.5°. This large spatial smoothing is necessary to obtain smooth fields on a regular grid, given T/P's large intertrack separation (300 km at the equator decreasing to 160 km at 60° latitude). To calculate the dynamic topography, we need to add on an estimate of the mean ocean circulation. Our estimate is based on the mean steric height relative to a depth of no motion of 2000 dbar, calculated using the *Levitus et al.* [1994] climatology. Note that both the mapped SLAs and the climatological mean are interpolated fields, which smooth out the mesoscale features less than 250 km wavelength. So we can only interpret DMS concentrations with regard to the large-scale ocean dynamical features, such as the main frontal positions and the large-scale current systems. Sharp density fronts, and small scale eddies and meanders, will appear smoothed or not be measured at all.

## 3. Results

The cruise track for the R/V *Polarstern* in the Atlantic is shown in Figure 1 superimposed on a map of dynamic topography (altimetry plus climatology), with arrows denoting the associated surface geostrophic currents. The main features of the dynamic topography are the large positive maxima around 20°-30° latitude with a western intensification, associated with the wind-forced subtropical gyres. Lower dynamic topography occurs in the denser waters at higher latitudes. The DMS sampling started northwest of Iceland, and the ship took a route to the southwest to contour the Azores Islands. It passed the North-Atlantic Current at 52°-40°N. Then the ship turned southeast, crossed the Azores Current at 33°-31°N, roughly followed longitude 30°W from 30°N down to 20°N crossing an area of weak slope currents directed westward between 30° and 25°N, and finally passed between two anticyclonic circulations centered 22°N-40°W and 21°N-28°W.

The ship entered the North Equatorial Current at about 20°N and the North Equatorial Countercurrent at about 10°N. A recognizable feature of interest is the local minimum in dynamic topography centered at 12°N-26°W corresponding to a cyclonic circulation generated by the westward flowing North Equatorial Current and eastward flowing North Equatorial Countercurrent. It is certainly an external boundary of the Guinea Dome usually centered around 12°N-22°W [Oudot, 1989] where nutrients are supplied to the near-surface waters due to upwelling of the thermocline. A fairly intense eastward North Equatorial Countercurrent is the normal situation for this time of year. The North Equatorial Countercurrent extends to a few degrees north. From the equator to 22°S the ship followed a route along 25°W, crossed the westward flowing South Equatorial Current, passed on the edge of an anticyclonic circulation centered 13°S-25°W, and crossed a southern branch of the South Equatorial Current at 18°S. From 22°S the ship went southwest and crossed a westward flowing current at 26°S, most probably a recirculation of the South Atlantic Current [Peterson and Stramma, 1991], and entered the the South Atlantic Current south of 32°S. The sampling ended at 45°S-42°W.

The surface dynamic topography (climatology plus SLAs) has been extracted along the cruise track and compared to the climatological mean steric height in Figure 2a. The location of the major currents is shown with horizontal bars along the x axis. Figure 2 also shows the salinity, DMS, pDMSP, and chl *a* levels along the cruise track. Steric heights associated with the subtropical gyre (SG, Figure 2a) in the Northern Hemisphere are lower than in the Southern Hemisphere since NH waters are more saline and denser (Figure 2b). The large-scale trends of steric height, salinity, and DMS in the subtropical waters of the North Atlantic (Figures 2a, 2b, and 2c) were both negative poleward and opposite to that of chl *a* and pDMSP (Figure 2d). The large-scale DMS gradient in the North Atlantic between 65°N and 28°N (subtropical and subpolar waters) was 0.04 nM/degree latitude (0.036 nM/100 km). The DMS gradient between 18°S (1.4 nM) and 45°S (0.3 nM) was similar. However, the South Atlantic waters show a series of DMS maxima, each several degrees of latitude wide, centered at 27°S, 33°S, and 40°S whereas in the Northern Hemisphere the DMS variations occur at smaller scales of the order of 2° of latitude as in the North Atlantic Current. Four of the five mesoscale peaks of DMS in the North Atlantic Current area (Figure 2c) coincide with thermohaline fronts and drops of salinity. Similar features were observed in the South Atlantic at 23°S, 26°S and in the South Atlantic Current. More quantitatively, in the South Atlantic front between 38° and 39°S, the gradients of salinity and DMS were 0.35 practical salinity unit (psu) /100 km and 1.1 nM /100 km, respectively. There was a broad DMS maximum coinciding with the salinity maximum of the South Atlantic (15°-20°S). In contrast, in the Northern Hemisphere, the salinity maximum was associated with a broad minimum of DMS. However, enhanced levels of DMS were found slightly to the north between the Azores Current and the NH salinity maximum. Two well-resolved broad maxima of DMS were observed in the tropical-equatorial zone. They were centered at 12°-14°N and 2°-4°S. The northern one is coinciding with the local minimum in dynamic topography corresponding to an extension of the Guinea Dome (Figure 2a). The adjacent slope currents (North Equatorial Current and North Equatorial Countercurrent) show decreasing DMS levels which are roughly in opposition

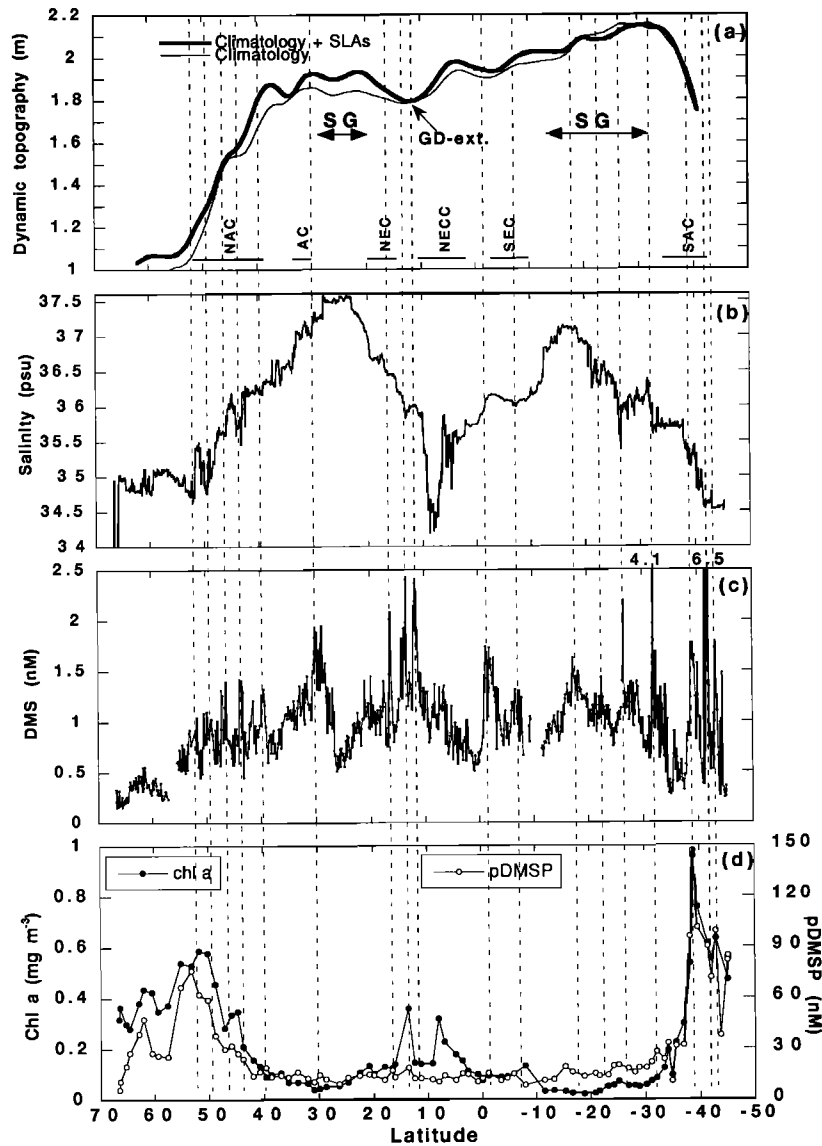


**Figure 1.** Cruise track of R/V *Polarstern* superimposed on a map of climatological steric heights with added T/P SLAs, which also includes geostrophic surface circulation (current direction and speed) between 40°W and 20°W.

of phase with the dynamic topography and roughly proportional to the chl *a* content of surface waters but not to the pDMSP one. The DMS maximum lying south of the equator is clearly associated with the presence of the South Equatorial Current and a thermohaline front on the northern edge of South Equatorial Current (Figure 2b) with chl *a* levels similar to that of the Northern Equatorial Current. Between the equator and 2°S the gradients of salinity and DMS were 0.2 psu /100 km and 0.5 nM /100 km, respectively.

The latitudinal variability of the surface DMS concentration is compared in Figure 3 to the sea level anomalies obtained from altimetric measurements along the track of R/V *Polarstern*. SLAs represent variations from the mean sea surface that are caused by variations in the ocean circulation, due

to seasonal heating, shifts in the wind regime, eddies and meanders. The anomalies are positive in the Northern Hemisphere reflecting the heat content still present from the end of summer, with more negative anomalies in the southern subtropical gyre indicating the effects of the winter cooling. A series of positive SLAs was observed (Figure 3a). They were centered at 60°-50°N, 40°N, 25°N, 5°N, 12°S, and 35°S. Negative SLAs were observed in the SH at 25°S, 32°S, and 40°S. To visualize and quantify the relationships between DMS and the SLAs, the data sets were evenly sampled from 40°N to 45°S with a step of 0.02° using the integration method and a linear function (using AnalySeries 1.1 software). The linear trends were then removed. Least squares smoothing with 300 points (6° latitude) was then applied to generate the delta-DMS signal of



**Figure 2.** Distribution of (a) T/P SLAs plus Levitus steric heights, (b) sea surface salinity, (c) sea surface DMS, and (d) pDMSP and chl *a* concentrations measured by HPLC, along the R/V *Polarstern* transect in October-November 1996. SG, subtropical gyre; GD-ext, Guinea Dome extension. In Figure 2a the lower horizontal bars indicate the positions of the equatorial and subtropical slope currents (NAC, North Atlantic Current; AC, Azores Current; NEC, North Equatorial Current; NECC, North Equatorial Countercurrent; SEC, South Equatorial Current; SAC: South Atlantic Current). The dotted lines mark the positions of the major peaks of DMS.

Figure 3b. The large-scale DMS signal and the SLAs appear to be significantly anticorrelated ( $r^2=0.40$ ,  $p<0.001$ ).

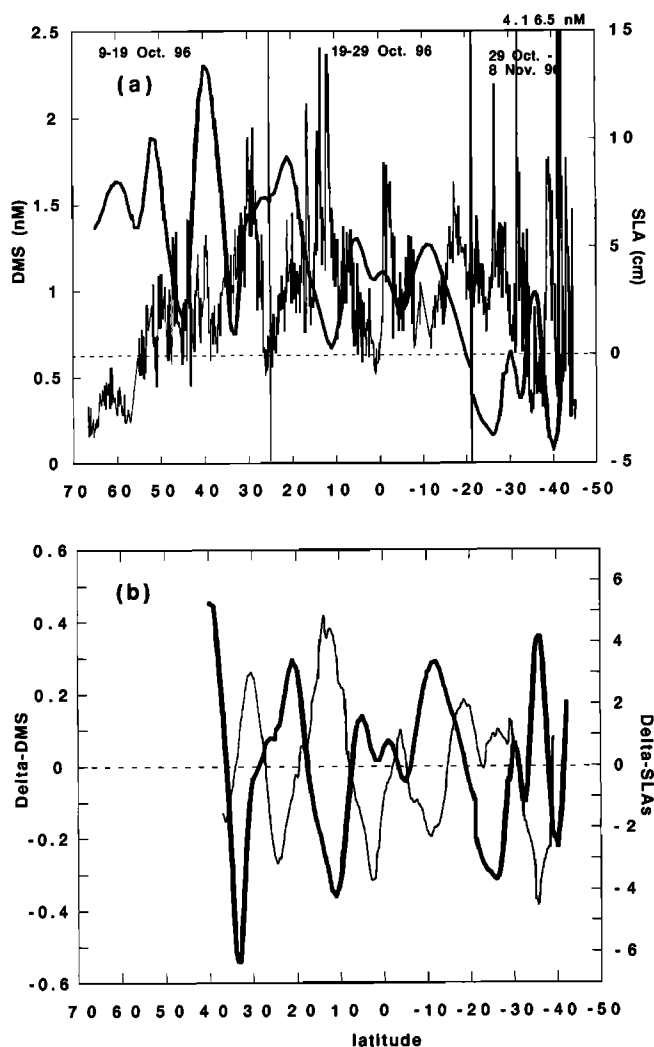
The distribution of DMS and satellite chl *a* in the South Atlantic Subtropical Front is shown in Figure 4a. South of 40°S, DMS highs are associated with chl *a* lows and reciprocally. North of 40°S, DMS and chl *a* show better covariation although in the latitudinal band 35.5°-37.5°S their trends are clearly opposite. Evidence that the spatial distributions of both parameters are generally different and do not result from a shift of the chl *a* field is given from the in situ chl *a* measurements which are in remarkable agreement with the satellite mean chl *a* levels for the period November 1-10, 1996. DMS increased markedly when the cruise track cut across the areas of strongest thermohaline gradients (Figure 4b, areas A, C, and

D but not in B). Chl *a* on the contrary was enhanced in areas of less abrupt changes in salinity or temperature between B and C, and between C and D.

## 4. Discussion

### 4.1. Large-Scale Changes in DMS Related to Dynamic Topography

This first Atlantic meridional transect of surface water DMS concentrations with 10-15 km horizontal resolution is the first attempt to relate the spatial variations in DMS with ocean dynamic topography and sea level anomalies. The interpolated dynamic topography is fairly smooth, resolving only features larger than 250 km. We observed that DMS concentrations



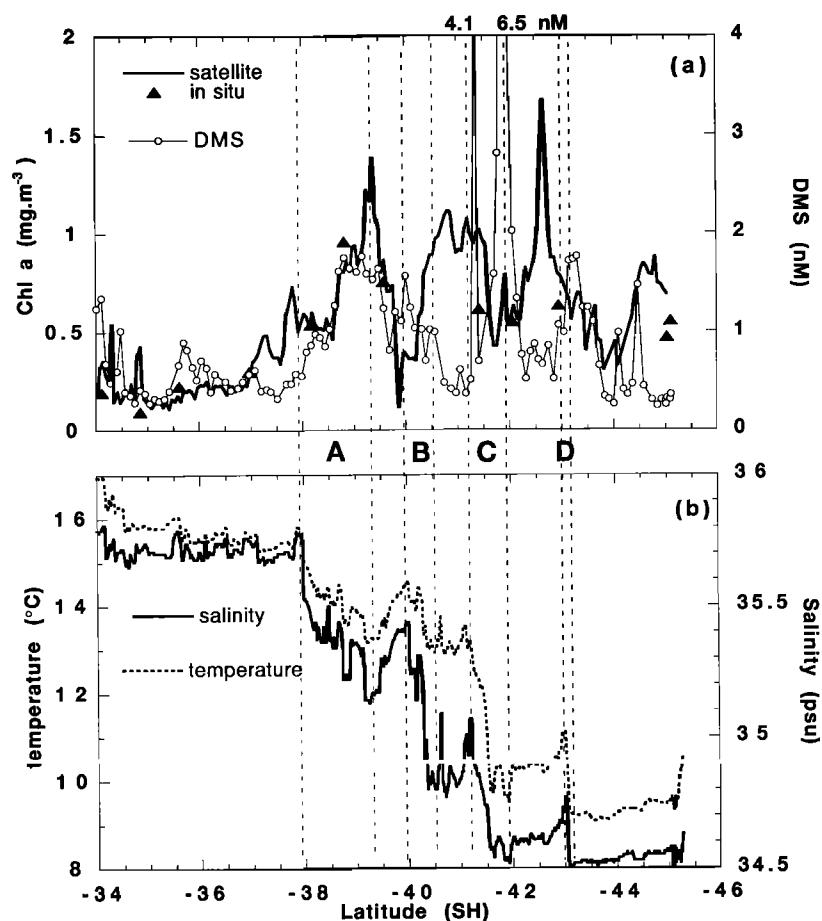
**Figure 3.** (a) Composite of T/P SLAs for 3 decades according to the dates of the cruise (thick line), and DMS concentrations along the R/V *Polarstern* transect. (b) Large-scale variations in DMS concentrations and SLAs (thick line) between 40°N and 45°S after removal of the linear trends and least squares smoothing with 300 points (6° of latitude) of the DMS signal.

and SLAs were clearly in opposition of phase in the subtropical and tropical waters of the Atlantic (Figure 3b). Neither meridional changes in pDMSP concentrations nor in chl *a* appear to account for these large-scale DMS variations. Indeed, pDMSP only slightly fluctuated from 40°N to 30°S ( $14.2 \pm 2.9$  nM,  $n=47$ ). Moreover, highs in DMS were associated indifferently with highs or lows in chl *a* (Figure 2d). It suggests that the spatial distribution of DMS responds at the first order to the dynamics of the ocean circulation. We believe that the investigation of SLAs would be potentially important to better understand the large-scale distribution of DMS and would provide a way to document the effects of a climatic change of the surface ocean circulation on the spatial distribution of DMS at least in tropical and subtropical waters.

North of 20°S the areas with relatively low DMS levels had strong positive SLAs (Figure 3a). The area between 25°N and the equator is characterized by a climatological minimum in dynamic topography centered at 12°N (Figure 2a). The SLAs in October 1996 were very small in the center of this oceanic

trough. This suggests that the ocean circulation in October 1996 was representative of the mean circulation. It is suggested that the elevated DMS levels measured during this period may also be representative of the mean situation. This hypothesis is sustained by the fact that *Barnard et al.* [1982] and *Tanzer and Heumann* [1992] reported DMS levels in the range 1-3 nM, hence comparable to ours, in the area 12°-15°N in mid October 1980 and late March 1989, respectively. On the contrary, the sea surface on the edges of the oceanic trough had raised markedly as shown from the strong positive SLAs observed around 25°N and 5°N (Figure 3 and Figure 2a). Since DMS accumulation in the tropical waters of the NH appears to be influenced by surface divergence, increasing convergence of surface water should decrease the abundance of DMS. This may explain why DMS decreased markedly away from the oceanic trough. The second large-scale DMS maximum located south of the equator is also associated with an oceanic trough. In the North Atlantic between 30° and 40°N a third oceanic trough was observed centered at 34°N and associated with the eastward flowing Azores Current (Figure 2a). DMS was about 1.7 times lower at 38°N than at 34°N. However, between 34° and 30°N, whereas the SLAs were positive (Figure 3a), the DMS concentration increased another 50% and remained high down to 28°N. In this latter case the SLA-DMS relationship is rather misleading. South of 20°S the series of negative SLAs, the magnitude of which was less than -5 cm (Figure 3a), clearly coincides with the thermohaline fronts (Figure 2b) and the recirculations of the South Atlantic Current richer in DMS than the adjacent waters (Figure 3a). In the North Atlantic Current area, DMS showed a series of peaks generally smaller than 250 km, a scale which is not appropriate for comparison with steric heights and SLAs.

The distribution of DMS in the intertropical region very much resembles the autumnal distribution of pCO<sub>2</sub> [*Schneider and Morlang*, 1995; *Lefevre et al.*, 1998]. The high pCO<sub>2</sub> between 15° and 10°N is explained by advection of coastal upwelled water in the North Equatorial Current [*Lefevre et al.*, 1998]. In our case, since the measurements were carried out more to the west, the DMS enhancement originates from the cyclonic circulations creating divergence at the latitude of the Guinea Dome (Figure 1). In the region of the North Equatorial Countercurrent where DMS is less abundant, an undersaturation of CO<sub>2</sub> has been observed partly due to biological activity. At the South Equatorial Current, pCO<sub>2</sub> is supersaturated because upwelled waters at the equator are then advected westward in the South Equatorial Current. Hence advection of upwelled waters and mesoscale processes at equatorial currents strongly influence the pCO<sub>2</sub> and DMS fields. *Bates and Quinn* [1997] provided indications of small interannual variations of DMS fields in the equatorial Pacific Ocean. During the SAGA 3 experiment (February-March 1990) the latitudinal distributions of DMS and pCO<sub>2</sub> in surface seawater were quite different [*Bates et al.*, 1993; cf. Figures 3a and 6a] and contrast with the rather uniform distribution of DMS and pCO<sub>2</sub> in the equatorial Atlantic during autumn. Indeed, in the center of the equatorial Pacific, where pCO<sub>2</sub> values were maximum, DMS concentrations were about two times lower than in areas southward which showed only slight water CO<sub>2</sub> supersaturation [*Bates et al.*, 1993]. Similar situations for different years and seasons are given by *Bates and Quinn* [1997] where nitrates are indicative of recently upwelled waters. The survey in autumn 1995 shows no DMS enhancement in recently upwelled waters. Thus the biogeochemical processes taking



**Figure 4.** Distribution of (a) satellite chl *a* and DMS concentrations, and of (b) sea surface temperature and salinity when the track of R/V *Polarstern* cut across the South Atlantic Subtropical Front. The dotted lines mark the boundaries of areas with strongest thermohaline gradients.

place in the equatorial Pacific (a high-nutrient low-chlorophyll (HNLC) area) and the equatorial Atlantic upwelled waters may be quite different. These observations suggest that future investigation of DMS sensitivity to climate change in equatorial waters of the Atlantic Ocean should be undertaken.

#### 4.2. Mesoscale Changes in DMS Related to Frontal Systems

Salinity appears to be a powerful parameter to document the mesoscale changes in DMS concentration. In the North Atlantic Current for example, DMS highs and lows were alternating with an amplitude of about a factor of 2. The DMS lows were associated with salinity highs and vice versa. This resembles the situation described by *Matrai et al.* [1996], who investigated DMS concentrations across a Gulf Stream meander and found low DMS levels in the stream (salinity 36.43 psu) and highest levels coinciding with slope waters of lower mean salinity 35.53 psu. Low DMS levels appear to be a characteristic of the Gulf Stream and its extension in the North Atlantic, the North Atlantic Current [*Krauss*, 1986]. Clearly, in areas of steep thermohaline gradients of the South Atlantic Subtropical Front (SA-STF), there are strong enhancements in DMS concentration up to twenty fold the background DMS levels (Figure 4a). It is worth noting that in the SA-STF the high-resolution signals of DMS and chl *a* are in opposition of

phase. We estimate that this does not simply result from a higher abundance of DMS producing algae in areas with low phytoplankton abundance since the in situ distributions of chl *a* and pDMSP were similar (Figure 2d). The DMS spatial distribution, however, could be indicative of spatial heterogeneities in phytoplankton turnover due to zooplankton grazing since grazing is an important pathway for DMS production [*Christaki et al.*, 1996, and references therein]. The case of the oligotrophic waters of the subtropical gyres is also illustrative of the complexity of the DMS production pathways. Between 15°S and 20°S, DMS levels reached up to 1.5 nM in good agreement with the extensive observations carried in the area by R/V *Meteor* during February-March 1991 [*Andreae et al.*, 1994]. In October 1996 the highest salinities (37.1 psu) and the lowest chl *a* levels (0.02 mg m<sup>-3</sup>) coincided with the highest DMS levels in waters of South Atlantic subtropical gyre. However, in the Northern Hemisphere subtropical gyre where highest salinities were 37.5 psu and lowest chl *a* levels were 0.04 mg m<sup>-3</sup>, DMS levels fluctuated in the range 0.5 to 1.9 nM. The DMS maximum coincided with the minimum of chl *a* (Figure 2) as in the work of *Andreae* [1990]. Indeed, during a southbound transect between 40°N and 30°N for the period April-May 1986, DMS concentrations increased from about 1 nM to about 4 nM, respectively, in Sargasso Sea's oligotrophic waters with chl *a*

levels lower than  $0.1 \text{ mg m}^{-3}$  [Andreae 1990]. Although the absolute numbers are different, the trends are consistent. During ALBATROSS, however, a few degrees toward the south where salinity was maximum (37.5 psu), pDMSP was unchanged and chl a levels were only 25% higher than the minimum chl a level, the DMS dropped to 0.5 nM (Figure 2c). In March-April 1989, Tanzer and Heumann [1992] observed a feature resembling this study with DMS levels down to about 0.7 nM but located about  $5^\circ$  to the south. Hence oligotrophic waters of the Atlantic subtropical gyres are potentially important production areas of DMS. Nevertheless, important changes in DMS levels can also occur in these areas on relatively short distances for reasons that do not appear to be linked to changes in water masses or in phytoplanktonic biomass.

The intertropical Atlantic Ocean is also a zone of contrasted DMS levels with two broad maxima associated with the divergence zones between the North Equatorial Current and the North Equatorial Countercurrent, and between the North Equatorial Counter Current and the South Equatorial Current (Figure 2a). Although the DMS richness of the intertropical Atlantic has been observed from previous surveys [Barnard et al., 1982; Tanzer and Heumann, 1992; Staubes and Georgii, 1993] it has never been characterized with high spatial resolution. We were able to identify a series of DMS peaks about 100-200 km wide between  $20^\circ$  and  $10^\circ\text{N}$ , a length scale typical of eddies. However the northern peak ( $17^\circ\text{N}$ ) does not appear to be generated at the northern boundary of the North Equatorial Current but in the core of this current. Chl a and DMS surveys in the equatorial region demonstrate that although their meridional distributions are roughly similar, the fine structures do not coincide (Figures 2c and 2d). Moreover, at  $17^\circ\text{N}$ , DMS is high where satellite chl a (nonvalidated POLDER products, data not shown) is low. Dadou et al. [1996] have shown from a modeling approach that plankton production due to eddies and fronts could significantly increase phytoplankton biomass up to 26% at the edge of the NEC eddies. It seems that the DMS response is opposite to that of chl a. Another illustration of this is obtained when the DMS and satellite chl a measurements are compared in the area of the equator. Figure 2c shows a DMS low at the Equator and a peak of DMS at  $1^\circ$ - $2^\circ\text{S}$ , whereas the nonvalidated POLDER products for the period November 1-10, 1996, show a green band lying at the equator. Hence the high-resolution profiles of chl a and DMS obtained in subtropical waters suggest that DMS production is more related to the turnover or mortality of phytoplankton than to its production [Nguyen et al., 1988; Malin and Kirst, 1997]. In the intertropical area both processes can take place and alternate over short distances.

## 5. Conclusion

The ALBATROSS-MARATHON cruise has offered a first opportunity to investigate with high spatial resolution the latitudinal distribution of DMS in the center of the Atlantic Ocean far away from coastal areas. The autumnal large-scale DMS gradient in subpolar and subtropical waters of the North Atlantic Ocean is negative poleward. A similar situation takes place in the subtropical waters of the South Atlantic during springtime. However, the recirculations of the South Atlantic Current and the South Atlantic Current itself generate fronts

richer in DMS than the adjacent waters, which reduce the negative poleward gradient in the South Atlantic. The surface dynamic topography (steric heights plus sea level anomalies) was shown to be a powerful tool to localize the subtropical and tropical sources of DMS from space. The large-scale gradients of DMS and chl a were opposite except between  $25^\circ\text{N}$  and  $10^\circ\text{S}$  where advection of upwelled waters by equatorial currents and raise of the thermocline appear to influence chl a, DMS, and  $\text{pCO}_2$  similarly. The mesoscale variability of DMS and chl a (validated POLDER products for the period November 1-10, 1996) was investigated in detail in the area of the South Atlantic Current. Both signals were clearly in opposition of phase suggesting that DMS mainly resulted from the turnover of phytoplankton.

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## References

- Andreae, M. O., Ocean-atmosphere interactions in the global biogeochemical sulfur cycle, *Mar. Chem.*, **30**, 1-29, 1990.
- Andreae, M. O., and P. J. Crutzen, Atmospheric aerosols: Biogeochemical sources and role in atmospheric chemistry, *Science*, **276**, 1052-1058, 1997.
- Andreae, T. W., M. O. Andreae, and G. Schebeske, Biogenic sulfur emissions and aerosols over the tropical South Atlantic, 1, Dimethylsulfide in seawater and in the atmospheric boundary layer, *J. Geophys. Res.*, **99**, 22,819-22,829, 1994.
- Barnard, W. R., M. O. Andreae, and W. E. Watkins, The flux of dimethylsulfide from the oceans to the atmosphere, *J. Geophys. Res.*, **87**, 8787-8793, 1982.
- Bates, T. S., and P. K. Quinn, Dimethylsulfide (DMS) in the equatorial Pacific Ocean (1982 to 1996): Evidence of a climatic feedback?, *Geophys. Res. Lett.*, **24**, 861-864, 1997.
- Bates, T. S., K. C. Kelly, and J. E. Johnson, Concentrations and fluxes of dissolved biogenic gases ( $\text{DMS}$ ,  $\text{CH}_4$ ,  $\text{CO}$ ,  $\text{CO}_2$ ) in the equatorial Pacific during the SAGA 3 experiment, *J. Geophys. Res.*, **98**, 16,969-16,977, 1993.
- Bates, T. S., V. N. Kapustin, P. K. Quinn, D. S. Covert, D. J. Coffman, C. Mari, P. A. Durkee, W. J. De Bruyn, and E. S. Saltzman, Processes controlling the distribution of aerosol particles in the lower marine boundary layer during the First Aerosol Characterization Experiment (ACE 1), *J. Geophys. Res.*, **103**, 16,369-16,383, 1998.
- Belviso, S., P. Buat-Ménard, J.-P. Putaud, B. C. Nguyen, H. Claustre, and J. Neveux, Size distribution of dimethylsulfoniopropionate (DMSP) in areas of the tropical northeastern Atlantic Ocean and the Mediterranean Sea, *Mar. Chem.*, **44**, 55-71, 1993.
- Christaki, U., S. Belviso, J. R. Dolan, and M. Corn, Assessment of the role of copepods and ciliates in the release to solution of particulate DMSP, *Mar. Ecol. Prog. Ser.*, **141**, 119-127, 1996.
- Claustre, H., P. Kerhervé, J.-C. Marty, and L. Prieur, Phytoplankton photoadaptation in relation to some frontal physical processes, *J. Mar. Syst.*, **5**, 251-265, 1994a.
- Claustre, H., P. Kerhervé, J.-C. Marty, L. Prieur, C. Videau, and J. H. Heccq, Phytoplankton distribution associated with a geostrophic front: Ecological and biogeochemical implications, *J. Mar. Res.*, **52**, 711-742, 1994b.
- Dadou, I., V. Garçon, V. Andersen, G. R. Flierl, and C. S. Davis, Impact of the North Equatorial Current meandering on a pelagic ecosystem: A modeling approach, *J. Mar. Res.*, **54**, 311-342, 1996.
- Groene, T., Biogenic production and consumption of dimethylsulfide (DMS) and dimethylsulfoniopropionate (DMSP) in the marine epipelagic zone: A review, *J. Mar. Syst.*, **6**, 191-209, 1995.
- Kettle, A. J., et al., A global database of sea surface dimethylsulfide

- (DMS) measurements and a procedure to predict sea surface DMS as a function of latitude, longitude, and month, *Global Biogeochem. Cycles*, *13*, 399-444, 1999.
- Krauss, W., The North Atlantic current, *J. Geophys. Res.*, *91*, 5061-5074, 1986.
- Kwint, R. L. J., and K. J. M. Kramer, Intercalibration of DMSP analysis and filtration methods, *Rep. EV5V-CT93-0326*, 222 pp., Dep. of Mar. Biol., Univ. of Groningen, Groningen, Netherlands, 1995.
- Lefevre, N., G. Moore, J. Aiken, A. Watson, D. Cooper, and R. Ling, Variability of  $p\text{CO}_2$  in the tropical Atlantic in 1995, *J. Geophys. Res.*, *103*, 5623-5634, 1998.
- Le Traon, P.-Y., and F. Ogor, ERS-1/2 orbit improvement using Topex/Poseidon: the 2 cm challenge, *J. Geophys. Res.*, *103*, 8045-8057, 1998.
- Levitus, S., T. P. Boyer, and R. Burgett, World ocean atlas 1994, NOAA atlas NESDIS 3 and 4, Natl. Oceanic and Atmos. Admin., Washington, D. C., 1994.
- Malin, G., and G. O. Kirst, Algal production of dimethyl sulfide and its atmospheric role, *J. Phycol.*, *33*, 889-896, 1997.
- Matrai, P. A., D. J. Cooper, and E. S. Saltzman, Frontal enhancement of dimethylsulfide concentrations across a Gulf Stream meander, *J. Mar. Syst.*, *7*, 1-8, 1996.
- Meyerdierks, D., B. Bolt, and G. O. Kirst, Spatial and vertical distribution of particulate dimethylsulfoniopropionate (DMSP) during spring in the Atlantic sector of the Southern Ocean, *Deep Sea Res.*, *44*, 283-297, 1997.
- Nguyen, B. C., S. Belviso, N. Mihalopoulos, J. Gostan, and P. Nival, Dimethyl sulfide production during natural phytoplanktonic blooms, *Mar. Chem.*, *24*, 133-141, 1988.
- Oudot, C.,  $\text{O}_2$  and  $\text{CO}_2$  balances approach for estimating biological production in the mixed layer of the tropical Atlantic Ocean (Guinea Dome area), *J. Mar. Res.*, *47*, 385-409, 1989.
- Peterson, R. G., and L. Stramma, Upper-level circulation in the South Atlantic Ocean, *Prog. Oceanogr.*, *26*, 1-73, 1991.
- Schneider, B., and J. Morlang, Distribution of the  $\text{CO}_2$  partial pressure in the Atlantic Ocean between Iceland and the Antarctic peninsula, *Tellus, Ser. B*, *47*, 93-102, 1995.
- Staubes, R., and H.-W. Georgii, Measurements of atmospheric and seawater DMS concentrations in the Atlantic, the Arctic and Antarctic region, in *Dimethylsulphide: Oceans, Atmosphere, and Climate*, edited by G. Restelli and G. Angeletti, pp. 95-102, Kluwer Acad., Norwell, Mass., 1993.
- Tanzer, D., and K. G. Heumann, Gas chromatographic trace-level determination of volatile organic sulfides and selenides and of methyl iodide in the Atlantic surface water, *Int. J. Environ. Anal. Chem.*, *48*, 17-31, 1992.
- Watson, A. J., and P. S. Liss, Marine biological controls on climate via the carbon and sulphur geochemical cycles, *Philos. Trans. R. Soc. London, Ser. B*, *353*, 41-51, 1998.
- Wood, R. A., A. B. Keen, J. F. B. Mitchell, and J. M. Gregory, Changing spatial structure of the thermohaline circulation in response to atmospheric  $\text{CO}_2$  forcing in a climate model, *Nature*, *399*, 572-575, 1999.
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