SHORT COMMUNICATION

Greenhouse Gases in Cold Water Filaments in the Arabian Sea During the Southwest Monsoon

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Abstract The distribution of partial pressure of carbon dioxide and the concentrations of nitrous oxide and methane were investigated in a cold water filament near the coastal upwelling region off Oman at the beginning of the southwest monsoon in 1997. The results suggest that such filaments are regions of intense biogeochemical activity which may affect the marine cycling of climatically relevant trace gases.

Filaments of cold water with maximum widths of 150 km and offshore extensions of 400 km (Arnone et al. 1998) appear as a characteristic feature of monsoon-forced coastal upwelling in the northwestern Arabian Sea. These arise where interaction between the surface current system, the topography of protruding capes, and the Ekman transport causes offshore deflection of upwelled water (Haidvogel et al. 1991; Summerhayes et al. 1995). Consequently the relative age of the filament water which moves in a southeasterly direction to the open Arabian Sea increases with distance from the coast. Filaments are easily detectable by satellite-derived data of sea surface temperature (SST) and are known to be areas of nutrient enrichment and enhanced biological productivity (Brink et al. 1998). Processes associated with these structures might be also of importance in the cycling of climatically relevant trace gases.

We carried out a systematic survey of several trace gases in a cold water filament which appeared off the coast of Oman at the beginning of the southwest monsoon period in June 1997. CO_2 partial pressure (pCO_2), dissolved nitrous oxide (N_2O), and methane (CH_4) were measured continuously on board the research vessel *Sonne* (cruise SO119) during German JGOFS research activities in the area (Figs. 1, 2). For these purposes a bubble-free stream of seawater was supplied by a submersible pump which was installed at 6.5 m depth in the ship's "moon pool." pCO_2 was logged at 1-min intervals and is presented here in microatmosphere units. To account for temperature effects the pCO_2 data are normalized to a SST of 28° C using the empirical relationship of Takahashi et al. (1993). Due to analytical limitation N_2O and CH_4 were measured alternately every 40 min. The saturation values (percentages) were calculated by applying the solubility equation of Weiss and Price (1980) and Wiesenburg and Guinasso (1979) according to the measured atmospheric dry mole fractions of 312 ± 2 ppb N_2O and 1.69 ± 3 ppm CH_4 (100% = equilibrium with respect to the atmosphere).

The core of the filament was marked by a SST of approximately 27° C (Fig. 2a). The observed SST gradient inside the filament core indicated contin-

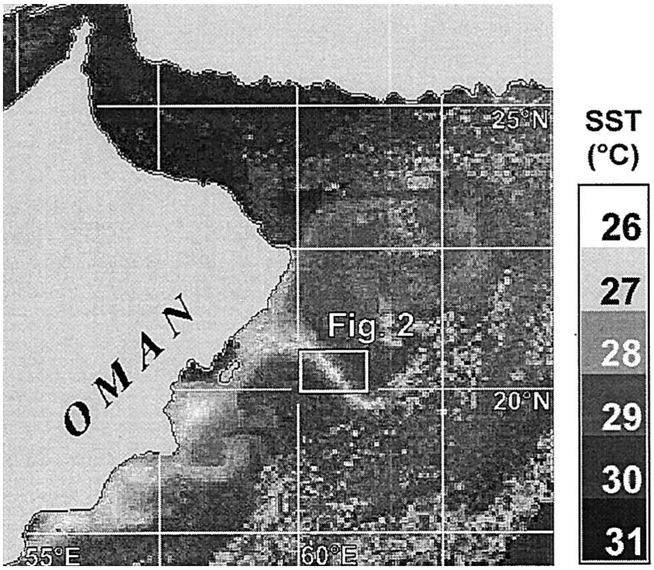

Fig. 1. SST satellite image of the Arabian Sea (03.06.1997) including the area of the filament survey (20.3–20.85°N and 60–61°E) during the German JGOFS cruise SO119. *Lighter gray* cooler water. (Image provided by Rosenstiel School of Marine and Atmospheric Sciences, University of Miami; http://www.rsmas.miami. edu/images.html)

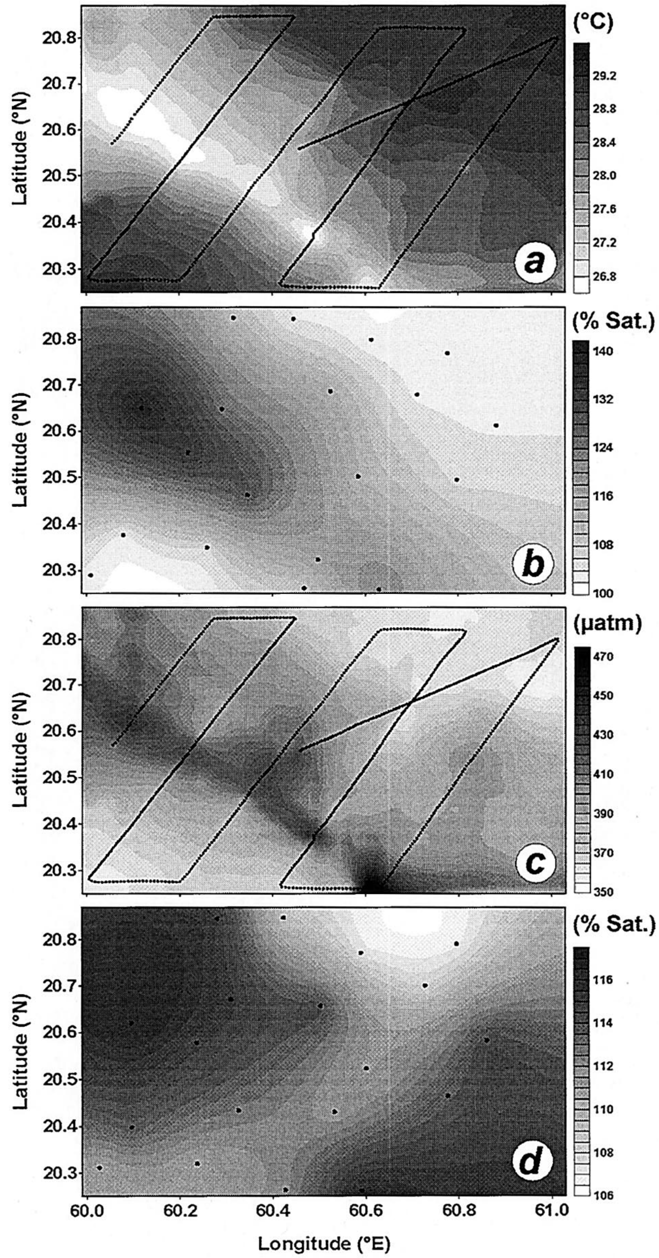

Fig. 2. Distribution patterns of SST (a), N_2O saturation (b), partial pressure of CO_2 (c), and CH_4 saturation (d). *Dots* individual measurements. The pCO_2 data were normalized to a SST of 28° C (Takahashi et al. 1993). N_2O and CH_4 are given as saturation values in percentages (Wiesenburg and Guinasso 1979)

uous warming during the transport offshore and showed a younger stage (26.5° C) in the northwestern part and an older one (27.2° C) in the south. N_2O, pCO_2 and CH_4 (Fig. 2b–d) were generally correlated with SST, but pCO_2 and CH_4 also exhibited distinct differences in their distributions. The SST distribution was reflected in the N_2O pattern, which showed a decreasing saturation state from 150% in the northwest to 115% in the south. N_2O was not likely to be affected by biological processes since the time the upwelled water came into contact with the atmosphere. Thus we conclude that the observed N_2O gradient is the result of progressive degassing and mixing with surrounding waters while the filament moved offshore. A similar pattern was observed for dissolved CH_4, but an unexpected, slight CH_4 enrichment was seen in the filament's southern part. pCO_2 is also clearly associated with SST; however, it exhibited extremely high spatial variability. Values of pCO_2 up to 510 µatm were detected in the (older) southern part of the filament while lower values of approximately 420 µatm appeared in the (younger) northwestern segment. The pCO_2 distribution within the filament appeared to be strongly affected by biological activity. Although our measurements represent a snapshot of ongoing dynamic biological processes, it appears that the observed pCO_2 pattern reflects a system in transition from predominantly autotrophic to enhanced heterotrophic. Thus, the relatively low pCO_2 in the younger part of the filament can be attributed to enhanced primary production fueled by nutrients from upwelling waters, while remineralization of organic matter by developing zooplankton and bacteria leads to high pCO_2 (and also CH_4 concentration) in the older part (de Angelis and Lee 1994; Brink et al. 1998).

Compared with SST and pCO_2 (Fig. 2a, c) N_2O and CH_4 (Fig. 2b, d) exhibited much broader anomalies. This differed from that which was expected from the rate of gas transfer between ocean surface and the overlying atmosphere, which is much slower for CO_2 than for nitrous oxide and methane. Broecker and Peng (1982) observed that the lateral extension of CO_2 anomalies in the equatorial upwelling of the Pacific is two to three times larger than that of N_2O since, because of its slower exchange rate, CO_2 has more time to spread out than other nonreactive gases. Therefore the lateral extension of the N_2O and CH_4 maxima shown in Fig. 2 may be due to the poor spatial resolution of the measurements.

N_2O and CH_4 saturation and pCO_2 in the investigated filament were remarkably higher than those usually expected for noncoastal areas (Bange et al. 1996; Takahashi et al. 1997) and indicate that the filaments might represent significant sources for atmospheric trace gases. From satellite images the area of the filaments off Oman appears about one-third of the coastal upwelling area, which is 0.2×106^6 km^2 (Körtzinger et al. 1997). The mean CO_2 flux from the filament to the atmosphere (using the relationship of Wanninkhof 1992; in situ wind speed data and an atmospheric pCO_2 of 350 μatm as measured during the investigation time) was 14.5 mmol/m^2 per day, which leads to CO_2 emissions of 1.5 TgC from these filaments for a 4-month southwest monsoon season. This is about 10% of the estimated CO_2 emissions for the coastal upwelling off Oman (14 TgC in 4 months, from cruises SO119 and SO120) and 6% of the estimates of Körtzinger et al. (1997).

Our results suggest that filaments must be considered for basin-wide trace gas flux estimations in the Arabian Sea. The quantification of trace gas emissions from filaments is rather difficult and requires more knowledge of their spatial and temporal extension on a global scale, and here long-term remote sensing records of SST might yield appropriate information. Additionally, investigations should focus on the relationships between the production and remineralization of organic matter and the trace gas budget of filaments.

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