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Methane Production in the Waters off Walvis Bay

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Nine stations were occupied in the vicinity of Walvis Bay, Namibia, during a detailed study of the distribution of methane in this highly productive coastal environment. The principal features of the observed coastal methane distribution included (1) excess methane in the mixed layer of from 2 times to greater than 300 times solubility equilibrium with the atmosphere, (2) a subsurface maximum, located in the top of the pycnocline, at which concentrations ranged from 2.6 to 440 times solubility equilibrium, (3) an intermediate depth minimum, where concentrations were comparable to those offshore at similar depths and which we attribute to the influence of onshore movement of subsurface offshore water, and (4) a bottom maximum, which we attribute to input of methane to the water column from the anoxic sediments in the Walvis Bay area. An attempt was made to identify the relative importance for methane supply to the coastal mixed layer of in situ biological production and of eddy diffusive and advective transport of methane-rich water which has been in contact with the bottom at the coast. Calculations suggest that both in situ production and physical processes are major sources of excess methane for the highly productive coastal surface waters. However, the complicated circulation patterns make quantification extremely difficult.

Upwelling areas, such as the one near Walvis Bay, Namibia (formerly South-West Africa), are known to be regions of extremely high biological productivity. In Walvis Bay the high surface productivity is accompanied by rapid accumulation of organic matter in the sediments [Boon *et al.*, 1975; Bremner, 1974], which thus become anoxic.

Methane is produced in anoxic environments as a final step in the anaerobic degradation of organic matter [Wolfe, 1971]. It may also be produced in oxygenated ocean waters, probably as a by-product of algal metabolism and/or anaerobic activity in the guts of zooplankton or higher marine animals [Scranton and Brewer, 1977]. The occurrence of both reducing sediments and high primary productivity near Walvis Bay suggested that a study of this area might allow us to determine the relative importance of methane input from coastal sediments and of in situ methane production in controlling the methane distribution in the water column of a productive coastal area.

The data which will be discussed in this paper were collected on cruise 93 of the R/V *Atlantis II* (AII 93) to the Walvis Bay region during late December 1975 and early January 1976. Relevant station locations are shown in Figure 1.

METHODS

Temperature, salinity, oxygen, phosphate, and methane measurements were made at all stations discussed. (See Figures 2-7. Tabulated data from water samples taken on AII 93-3 can be obtained from J. W. Farrington, Woods Hole Oceanographic Institution.) Temperatures were obtained from reversing thermometers and from expendable bathythermographs (XBT's) at the start of each station. It was surmised that observed differences between XBT and thermometer temperatures were due to ship drift in areas of strong horizontal temperature gradients and that the reversing thermometer measurements, taken at the time at which the water samples were being collected, were more appropriate for comparison with nutrient and methane measurements. XBT's were calibrated by shifting the traces to agree with the thermometer values. Salinity was determined with a conductive salinometer at Woods Hole about 6 weeks after sample collection.

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Oxygen concentrations were determined by a modification of the Winkler method [Carpenter, 1965]. Phosphate concentrations were determined by the molybdenum blue method of Murphy and Riley [1962]. Temperature, oxygen, phosphate, and methane were measured within 24 hours of collection on unfiltered samples.

Methane measurements were made by a modification of the technique developed by Swinnerton *et al.* [1962a, b] and Swinnerton and Linnenbom [1967] as described by Scranton and Brewer [1977]. Briefly, this method involves transfer of a sample under methane-free helium from a ground-glass stoppered bottle into a glass stripper. Purified helium gas is bubbled through the water in the stripper for 20 min, and the dissolved gases are thus extracted. The helium containing the extracted gases is dried by passage through a magnesium perchlorate drying tube, and the methane is then removed by passage of the gas through an activated charcoal trap maintained at dry ice-acetone temperatures. Once the methane from the sample has been completely trapped, the trap is heated for 1 min by using a hand-held hair dryer. The methane is injected into a ¼-in. OD silica gel (60-80 mesh) column in the oven of an HP 5410 gas chromatograph equipped with dual-flame ionization detectors.

Measurements of atmospheric methane concentrations were obtained while the ship was steaming between stations. Samples were collected by sucking air (using a vacuum pump in the main lab) through about 150 ft (45.72 m) of copper tubing and then through a calibrated air sample loop (115 ml) attached to a six-way gas sample valve. The air inlet was positioned on the top deck of the ship forward of the smokestack. Air samples were only taken while the ship was under way. For each sample, air was sucked through the tubing for about 10 min at 250 ml/min. Then the pump was shut off, and the gas sample valve was quickly switched, allowing carrier gas to flush the air sample from the sample loop into a charcoal trap cooled to dry ice-acetone temperatures. The trapping and all following steps are exactly those used in water sample analysis.

DISCUSSION

Circulation in Walvis Bay Area

The Walvis Bay region has been studied by a number of workers [Stander, 1964; Visser, 1969; Calvert and Price, 1971;

Fig. 1. Stations occupied during AII 93-3 in the vicinity of Walvis Bay. Station 2244, not shown on this chart, was located at 22°16'S, 09°00'E.

Hobson, 1971]. On the basis of these studies and others it is known that upwelling is vigorous near Walvis Bay in the late winter and early spring but is largely absent by midsummer (January-February). The occurrence of upwelling is usually identified by the presence at the surface near the coast of cool water with temperatures less than 15°C and with weak vertical

Fig. 2. Temperature section across the slope and shelf near Walvis Bay. Note the variability in the depth of the isotherms between stations 2245 and 2248.

Fig. 3. Salinity section from near Walvis Bay. The pool of low-salinity water at the surface in stations 2246, 2252, and 2248 indicates the presence of remnant upwelled water.

temperature gradients, although not all upwelled water reaches the sea surface. The salinity of the upwelled water tends to be low, usually less than 35.00‰.

During December 1975 to January 1976 it appeared that upwelling was either absent or very weak. The sloping isotherms which appear in the temperature section (Figure 2) suggest that some residual upwelling may have been taking place. However, this upwelling could not have been strong, as strong vertical temperature gradients were found at 10–20 m in all stations occupied in this area. Some of the variability in the depth of the isotherms might be due to the presence of eddies or meanders in the Benguela Current rather than to upwelling.

The salinity distribution (Figure 3) also supports the idea

Fig. 4. Phosphate section from near Walvis Bay. Isoconcentration lines shoal abruptly between stations 2245 and 2246.

Fig. 5. Oxygen section from near Walvis Bay. Note the formation of the oxygen minimum on the continental shelf.

Fig. 6. Methane section from near Walvis Bay.

that upwelling was weak or absent. The presence of a pool of low-salinity surface water at stations 2246, 2252, and 2248 suggests that former upwelled water was present but had been isolated from its source. These interpretations agree with those of *Stander* [1964], who has noted that moderate upwelling may occur in December but that as summer progresses, greater vertical stability is achieved in surface water and upwelling is greatly reduced or ceases.

Phosphate concentrations (Figure 4) over the shelf were very high except above the thermocline, in comparison to offshore values at comparable depths. A sharp depth change in phosphate isolines was seen between stations 2245 and 2246. Oxygen concentrations on the shelf (Figure 5) ranged from very low values at the bottom (0.0 ml/l at station 2247) to very high values at the surface (>6.0 ml/l as compared to a solubility equilibrium value of 5.4 ml/l at stations 2246, 2247, 2248, 2253, and 2254). Between stations 2245 and 2246 the oxygen isolines deepened abruptly, and offshore the oxygen minimum was about 400–500 m.

The most dramatic feature found in the oxygen and phosphate sections was the sharp concentration gradient observed at shallow depths between stations 2245 and 2246. *Stander* [1964] has found that a strong correlation exists between the presence of well-aerated (high oxygen) water and the presence of the Benguela Current and, conversely, between poorly aerated water and a subsurface southward setting current. However, the low-oxygen water need not be an entirely advective feature. Instead, the opposing currents may trap the coastal water in a region where sediments are highly reducing and where oxygen is rapidly removed from and phosphate added to the water.

Calvert and Price [1971] and others have noted that upwelled water on the shelf of an upwelling region commonly has nutrient concentrations much higher than water of similar TS character off the shelf. The increased nutrient levels can best be attributed to regeneration of organic matter by bacterial action in the water column and sediments. Below the surface layer, phosphate concentrations are high and increase to the bottom, while oxygen concentrations are low and decrease

with depth. Concentrations also increase shoreward for phosphate and decrease shoreward for oxygen. The best explanation for the phosphate and oxygen distributions in the bottom water includes regeneration of nutrients either in or above the highly anoxic sediments.

In summary, the distribution of properties indicates that upwelling was weak or absent at the time of this study. Remnant upwelled water was present at the surface in some stations but was probably not being renewed. The coastal waters

Fig. 7. Vertical profile of methane and phosphate at station 2252. The predicted methane values are based on solubility data, an atmospheric methane concentration of 1.44 ppm by volume, and measured temperatures and salinities.

appeared to be trapped on the shelf, perhaps by the combined actions of the Benguela Current and the southward flowing countercurrent. Because the waters were retained over the reducing sediments off Walvis Bay, bottom phosphate concentrations had become very high, and oxygen concentrations very low.

Observed Methane Distribution

With this picture of the circulation of the area in mind we can now attempt to identify processes important in controlling the methane distribution in a coastal upwelling region. As far as we know, ours are the first detailed methane data from such an environment.

As is shown in Figures 6 and 7, there were a number of prominent features in the methane distribution. Mixed layer concentrations were high in the stations over the shelf and slope. Values ranged from 2 times to greater than 300 times the concentrations predicted from solubility equilibrium with the atmosphere as calculated from the solubility data of Yamamoto *et al.* [1976] and an average atmospheric methane concentration measured on this cruise of 1.44 ± 0.04 ppm by volume. Methane maxima were present at most stations in the top of the thermocline, generally at about 10–20 m. In and below the thermocline on the shelf, concentrations decreased again and were approximately equal to concentrations at similar depths in the offshore stations. Near the bottom in shelf stations, concentrations increased again. At stations 2244 and 2245, in more oceanic environments, deep concentrations were quite low (decreasing to only 19% of solubility equilibrium with the atmosphere at 3000 m at station 2244). This has been observed in other oceans [Lamontagne *et al.*, 1973; Scranton, 1977].

The methane distribution below the mixed layer on the shelf is consistent with some transport of offshore water with low methane concentrations onto the shelf. The high bottom water concentrations indicate that methane diffuses rapidly into the water from the sediments. The presence of a middepth min-

imum suggests that methane generation within this portion of the water column was not extensive.

The region in which sediment supply of methane was undoubtedly the highest was in Walvis Bay itself. At station 2247 (see Figure 8) we observed sulfide in the bottom water and methane concentrations as high as 879 nmol methane/l. In comparison, the deep waters of the Cariaco Trench have a methane concentration of $9.06 \mu\text{mol}$ methane/l, and the Black Sea deep waters have a methane concentration of $11.1 \mu\text{mol/l}$ [Scranton, 1977]. Since no physical barriers to circulation such as are present in the Cariaco Trench and Black Sea are present in Walvis Bay, the high methane concentrations suggest extremely rapid methane supply from the sediments.

Sediments seem to be a principal source of methane to the bottom water on the shelf in the vicinity of Walvis Bay. However, the source of methane for the high concentrations in the mixed layer and upper thermocline cannot be the sediments directly beneath, since there is an intermediate methane minimum in most stations.

Discussion of Methane Data

We would like to determine if the primary source of methane for the surface waters near Walvis Bay is the water and sediments at very shallow depths. The surface water in the Walvis Bay region is isolated from the deeper water below about 10 m by a sharp pycnocline. Some of the most methane-rich water is found in contact with the sediment. When sediment and bottom water are both above the thermocline, as occurs in very shallow water, the methane-rich bottom water is able to exchange freely with waters further offshore and may provide a source of methane to the mixed layer and upper thermocline. For example, station 2247 (Figure 8) has a maximum methane concentration at 5 m, even though the bottom water at this station is anoxic below 30 m. The high methane concentrations seem to be supplied laterally rather than vertically.

Brewer and Spencer [1975] have presented a model which attempts to describe the distribution of a species with a coastal source in terms of the relative contributions of horizontal mixing, first-order loss, and in situ production or consumption. As we are trying to determine the importance of a coastal source for the methane distribution in the surface waters off Walvis Bay, it seems appropriate that we attempt to use this model.

We hope to determine whether horizontal mixing processes alone can supply sufficient methane to the offshore waters to explain the observed surface distribution. If the model is applicable and if horizontal physical processes alone cannot describe the distribution, an in situ production term is probably important.

This discussion makes a number of assumptions about the physical situation. First, offshore advection is neglected. The predominant currents in the Walvis Bay area flow to the north (the Benguela Current) and to the south (the coastal return flow). Upwelling was not active, so this source for offshore advective transport can be ignored. However, the possibility of advective transport in eddies or by nonsteady currents cannot be eliminated by the data that we have available. Second, north-south gradients in methane concentrations are ignored. Undoubtedly, there are geographical variations. However, our data suggest that both to the north and to the south of the immediate Walvis Bay region, surface water concentrations are roughly comparable for similar distances from shore. Unfortunately, our geographic coverage is not adequate to define

Fig. 8. Vertical profile of methane and phosphate at station 2247. The waters below 30 m at this station were anoxic. Note that methane concentrations are in micromoles of CH₄ per liter.

the situation further. *Bremner* [1974] has noted that the only region in which high organic carbon is present in the sediments in very shallow water is Walvis Bay. Thus we can at least ignore the potential problem that high offshore concentrations are due to rapid southward advection of unusually methane-rich coastal waters further to the north. The only region which could potentially supply methane to coastal surface waters appears to be Walvis Bay itself.

A third basic assumption within the model is that mixing is taking place only between a nearshore end-member and an open ocean end-member. Because solar heating of the surface waters is important in the area near Walvis Bay [*Calvert and Price*, 1971; *Stander*, 1964], the TS diagram for the surface waters in this area is not linear. However, since there are no rivers in this area, the sole source of low-salinity surface water is probably upwelling at the coast. Evaporation can probably be considered negligible. The one case in which the assumption of two-end-member mixing would be invalid would be if north-south currents were supplying waters of different properties to the region at different distances from shore. Our data are not adequate to resolve the question, but from *Stander* [1964] it appears that some such water mass input may occur during periods of minimum upwelling. This makes the assumption of two-end-member mixing more tenuous; however, as a first attempt we will try to use this model in the hope of clarifying the most important features of the methane distribution. Mathematically, the model can be expressed by

$$K_h \frac{\partial^2 C}{\partial x^2} - \lambda(C - C_{eq}) + \alpha_0 e^{-\mu x} = 0 \quad (1)$$

where

- C methane concentration in surface seawater;
- C_{eq} methane concentration in a water sample at equilibrium with the atmosphere;
- K_h horizontal eddy diffusion coefficient;
- λ first-order loss coefficient;
- α_0 production rate at $x = 0$;
- μ exponent determining rate of decrease of production rate with distance from shore.

The solution to this equation is

$$C = C_0 \exp[-(\lambda/K_h)^{1/2} x] + \frac{\alpha_0}{\lambda - \mu^2 K_h} \{ \exp(-\mu x) - \exp[-(\lambda/K_h)^{1/2} x] \} + C_{eq} \{ 1 - \exp[-(\lambda/K_h)^{1/2} x] \} \quad (2)$$

where C_0 is the concentration at the coast.

K_h can be estimated from the empirical results of *Okubo* [1971], who found that $K_h = 0.0103 l^{1.15}$. The scale length in which we are interested is $l = 200$ km, indicating that K_h is about 2×10^6 cm²/s. Parameter λ can be estimated by assuming that it represents loss to the atmosphere of excess methane in surface water. From the thin film model for gas exchange [*Danckwerts*, 1970; *Broecker and Peng*, 1974; *Liss and Slater*, 1974] the rate of loss of gas across the air-sea interface is directly proportional to the 'piston velocity' D/z , where D is the molecular diffusion coefficient of methane in water at the temperature and salinity of interest and z is the thickness of the laminar diffusion layer assumed to control gas exchange across the interface. If the thickness of the mixed layer underlying the laminar diffusion layer is M , the first-order rate constant for gas loss from the mixed layer is

$$\lambda = (D/zM) \quad (3)$$

At 17°C, the surface water temperature in Walvis Bay, D is approximately 1.5×10^{-5} cm²/s [*Witherspoon and Bonoli*, 1969]. Wind speed during the cruise was variable, but force 3 winds (3.5–5 m/s) were most common. At an average wind speed of about 4.5 m/s and when a mixed layer thickness of 10 m is assumed, the thin film thickness can be estimated from *Emerson* [1975] to be about 100 μ m. Thus $\lambda = 45$ yr⁻¹.

Parameter μ defines the rate of decrease of the production term with increasing distance from the coast. We have chosen $\mu = 0.014$ km⁻¹, which would suggest that production at 70 km from shore is $1/e$ times that at the coast. The phytoplankton biomass (determined from chlorophyll *a* data by S. Watson and co-workers (personal communication, 1976)) also gives this same exponential plot with distance from the coast.

The average value for C_{eq} (the concentration of methane in surface water which would be present if the seawater and atmosphere were in equilibrium) for the stations under consideration here is 1.85 nmol/l.

The methane data to be modeled are plotted in Figure 9 as a function of distance from the coast. All values used were from the mixed layer, and most were from samples taken at 0 m. If in situ production is neglected ($\alpha_0 = 0$), the model can be fit to the data only if high K_h (5×10^7 cm²/s) and high coastal methane values (67 nmol/l) are assumed. This fit is represented in Figure 9 by triangles. On the basis of *Okubo's* [1971] data a K_h of 5×10^7 cm²/s appears to be more than a factor of

Fig. 9. Surface methane concentrations plotted versus distance from the coast compared with curves calculated from the models discussed in the text. In situ production model: solid circles, $\alpha_0 = 2.23$ μ mol/l/yr; open circles, $\alpha_0 = 1.12$ μ mol/l/yr for $K_h = 2 \times 10^6$ cm²/s and $C_0 = 22$ nmol/l; triangles, $\alpha_0 = 0$ for $K_h = 5 \times 10^7$ cm²/s and $C_0 = 67$ nmol/l. Advection diffusion model: crosses, $K_h = 2 \times 10^6$ cm²/s, $C_0 = 60$ nmol/l, and $u = 10$ cm/s.

10 too large for the oceanographic region under consideration. In addition, coastal values of 67 nmol/l or greater were observed at the surface only in the anomalous Walvis Bay station and not in any other coastal station that we occupied. Our best choice for C_0 was 22 nmol/l. This estimate agrees well with data from station 2250, our most shoreward station except for 2247, but can be in error by a factor of 2 either way without making a significant difference in the following argument once K_h is chosen.

Since the parametric fit which ignores in situ production requires unreasonably high values of K_h and C_0 , it appears that an in situ production term must be considered. The curves in Figure 9 identified by open and solid circles represent model calculations using two values for α_0 , the in situ production rate at the coast. These curves (for $\alpha_0 = 1.12$ and $2.24 \mu\text{mol/l/yr}$) bracket all of the data except for the sample from station 2247, which appears to be anomalous in many ways.

If the production occurs uniformly throughout a 10-m-thick mixed layer, it represents a methane supply of $1.1\text{--}2.2 \mu\text{mol/cm}^2/\text{yr}$ at the coast. At 100 km from shore the production rate would be $0.4\text{--}0.8 \mu\text{mol/cm}^2/\text{yr}$.

We have treated in situ production rates as if they were representative of the absolute production of methane in the mixed layer and upper thermocline. In fact, it is probable that these rates are net production estimates. It is well known [Lamontagne *et al.*, 1973; Brooks and Sackett, 1973; Scranton, 1977] that below about 500 m in the open ocean, methane concentrations are less than those predicted from solubility equilibrium with the atmosphere. There are no known abiotic chemical processes which could consume methane at depth in the ocean at a significant rate, so the consumption is attributed to biological processes.

If methane-oxidizing bacteria are present in the deep ocean, as deep methane data would indicate, it seems probable that similar organisms are also present in surface waters, where methane concentrations are much higher. Indeed, T. Weaver (personal communication, 1974) has isolated methane-oxidizing bacteria from seawater. Thus any production estimates made are measures of the net production only and actually underestimate the apparent ability of organisms to produce methane in a highly oxygenated macroenvironment.

Our production estimate was derived from a model neglecting offshore advection. Because the circulation pattern in Walvis Bay is extremely complex [Stander, 1964], we cannot be certain that this assumption is correct. Therefore we will also describe the methane data with a model which assumes that there is no in situ production and that loss of methane across the air-sea interface is balanced by eddy diffusion and horizontal advection of coastal water offshore. Mathematically, this can be expressed as follows:

$$K_h \frac{\partial^2 C}{\partial x^2} - u \frac{\partial C}{\partial x} - \lambda C = 0 \quad (4)$$

where K_h and λ have the same values as were substituted into (2). The model can be fit to the methane data if $u = 10 \text{ cm/s}$ and C_0 (the coastal concentration) is 60 nmol/l. This curve is represented in Figure 9 by crosses. While it is conceivable that C_0 could be as large as 60 nmol/l, an east-west current of 10 cm/s in this region of strong northward flow seems unlikely. However, if the Benguela Current meanders significantly, it is possible that rapid advective transport could carry coastal methane far offshore.

If advection is the sole source of the methane excess in offshore waters, it is of interest to estimate the amount of

methane which must be supplied by diffusion from coastal sediments. One way to do this is to calculate the amount of methane required to balance the air-sea loss in the preliminary model (equation (1)). Advective transport may provide methane to offshore surface waters, and in the most extreme case, all the methane initially ascribed to in situ production could actually be supplied by advection.

We wish to estimate the magnitude of this contribution and to determine if sufficient methane could realistically be supplied by the sediments. The in situ production term of the model (which represents the amount of methane not attributable to eddy diffusion) can be integrated over the 200-km section. If the area under consideration is that between 22° and 23°S , the north-south distance is about 100 km. If we use $\alpha_0 = 1700 \text{ nmol/l/yr}$ as an average coastal in situ production and take a 10-m-thick mixed layer, the total amount of methane to be accounted for is $1.14 \times 10^{14} \mu\text{mol/yr}$.

If all the excess methane is supplied advectively, $1.14 \times 10^{14} \mu\text{mol}$ of methane must be being produced in the coastal region in waters less than 10 m deep each year. If we take a coastline of 150 km (allowing for inlets and coastline irregularities) and assume that the 10-m contour is about 5 km offshore, the maximum area of sediments which could supply methane to the mixed layer is $7.5 \times 10^{12} \text{ cm}^2$. The flux out of the sediments that would be required is $15.2 \mu\text{mol/cm}^2/\text{yr}$.

Reeburgh [1976] has published sediment data for the Cariaco Trench which suggest that the sediment-water flux of methane there is $0.4\text{--}4 \mu\text{mol/cm}^2/\text{yr}$. Thus if the supply of methane to offshore waters is completely advective, the sediments in the vicinity of Walvis Bay must supply 4–40 times as much methane to overlying waters as do the Cariaco Trench sediments.

A number of workers [Barnes and Goldberg, 1976; Reeburgh, 1976; Martens and Berner, 1977] have shown that a considerable percentage of the methane produced in anoxic marine sediments is consumed either at the sediment-water interface by oxygen-utilizing methane-oxidizing bacteria or deeper within the sediment by sulfate-reducing bacteria which oxidize methane while reducing sulfate. In a marine system such as Walvis Bay, the presence of both high sulfate and significant oxygen concentrations in bottom waters would act to diminish the amounts of methane which could be supplied by the sediments, especially in comparison to the Cariaco Trench, where bottom waters are highly reducing. In Walvis Bay itself (station 2247, see Figure 8) it is quite possible that very high rates of methane supply are present. However, for the coast as a whole this is probably not true. An additional factor to be considered is that shallow sediments of very high organic carbon content (and thus high methane production potential) are restricted in extent to the immediate vicinity of Walvis Bay [Bremner, 1974]. Thus the area of sediments used in the calculation of possible flux is probably a considerable overestimate, making the flux required from the suitable sediments even higher.

Obviously, the in situ production model (equations (1) and (2)) and the advective transport model (equation (4)) cannot both be correct. Instead, both are probably partially accurate. Advective transport of coastal methane to offshore surface waters probably supplies some, but not all, of the observed excess methane, while a significant amount of in situ methane production must also take place. Because of the great uncertainties in our understanding of the circulation pattern in this area the relative amounts of advective supply and in situ production cannot be quantified.

A number of other factors also prevent precise calculation of the rate of in situ production. First, the value of the horizontal eddy diffusion coefficient is only poorly known. Ideally, a radioactive coastal tracer (such as ^{228}Ra) should be measured in conjunction with coastal methane studies to permit us to make a more accurate estimate of this parameter. Another parameter which is not precisely known is the thin film thickness z . Radon 222 measurements would have permitted us to estimate this parameter directly. Unfortunately, facilities for these analyses were not available. The predictions of either model would be inaccurate if the values of the parameters that we used were greatly in error.

Finally, upon close examination of the data it appears that the physics of the situation off Walvis Bay is considerably more complex than that assumed by the models. In particular, the presence of a pool of low-salinity water at the surface over the edge of the continental shelf suggests that the two-end-member mixing assumption is probably unsound. It may be impossible to distinguish eddy diffusive and advective transport and in situ production of methane in a region where complicated currents and an extremely time dependent circulation pattern are present. Nevertheless, the application of models such as those used above provides considerable insight about the types of processes which are important to the methane distribution of highly productive coastal environments and suggests the need for more interdisciplinary studies of such complex regions.

CONCLUSIONS

Methane is supplied to the waters off Walvis Bay both from the sediments and by in situ biological production. In the bottom waters, diffusion from the sediments appears to be most important. In the surface waters, both in situ production and lateral eddy diffusion and advection act as sources for the excess methane, which is rapidly lost across the air-sea interface. The mechanism of methane production in an oxygenated environment is not understood in detail. However, the importance of in situ methane production has been demonstrated for Walvis Bay, and earlier conclusions about production in the western subtropical North Atlantic [Scranton and Brewer, 1977] are confirmed. To provide more quantitative estimates of the in situ production rates in upwelling regions, methane measurements will have to be coupled with measurements of other tracers and extensive physical oceanographic studies.

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