CARBON DIOXIDE FLUXES OVER THE ATLANTIC OCEAN ESTIMATED FROM MEASUREMENTS AT TIANA BEACH, LONG ISLAND, NEW YORK*

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Abstract. Mean carbon dioxide concentration gradients were measured continuously for a period of three weeks during December 1978 at Tiana Beach, Long Island, with onshore atmospheric flows. The height interval was 20 m and the fetch over the sandy beach for onshore flows was about 20 m for low tides and near zero for high tides. Measurements at the beach were thus approximately representative of over-ocean atmospheric flows. Concentration differences for this height interval were found to vary from 0.75 to 2 ppm. Approximate computations indicated this local gradient to be about two orders of magnitude greater than the values estimated from global means.

1. Introduction

There is an increasing trend in the mean global atmospheric carbon dioxide concentration due to combustion of fossil fuels. Several models to predict future CO_2 concentrations are available with numerous assumptions regarding the global cycle and sinks of CO_2. In the long run, a net CO_2 flux to the oceans is to be expected due to its reaction with carbonate ion ($CO_3^=$) and with calcium carbonate sediments ($CaCO_3$) to maintain much of the oceans near saturation with $CaCO_3$. The net rate of CO_2 uptake by the oceans is largely determined by the rate of mixing of surface waters and the deep oceans. This rate of mixing is, in turn, controlled by various physical processes in the atmosphere and the oceans.

The purpose of this paper is to report the results of a month-long preliminary experiment conducted at Tiana Beach, Long Island (Figure 1) to infer the variation of CO_2 fluxes over the Atlantic Ocean from measurements made during onshore flows and to observe any directional dependence of mean CO_2 concentrations at a land–sea interface for various meteorological conditions. Coastal meteorological studies and diffusion and air–sea interaction experiments are being conducted near this site to study air–sea exchange processes (SethuRaman and Raynor, 1975; SethuRaman, 1976, 1977, 1978; SethuRaman, 1979a; Raynor *et al.*, 1979). Results of the present preliminary study indicate the feasibility of measuring CO_2 concentration gradients and of subsequently estimating CO_2 fluxes with reasonable accuracy. Mean CO_2 concentrations were found different for fetches over land as compared with over-water flows. Previous measurements of momentum fluxes at the

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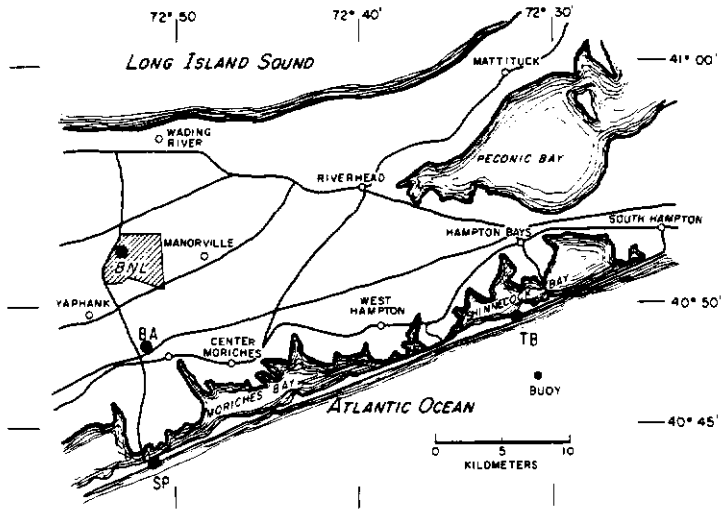

Fig. 1. Map of eastern Long Island showing relative locations of measurement sites: Brookhaven (BNL), Brookhaven Airport (BA), Smith's Point (SP), Tiana Beach (TB), and the Air–Sea Interaction Buoy (BUOY).

beach for onshore flows were found to give values of the same magnitude as observed over open oceans (SethuRaman and Raynor, 1975; SethuRaman, 1979b). Hence, the CO_2 gradients at the beach for onshore flow conditions should be representative of values over the ocean near the coastline.

2. Measurements

Mean CO_2 concentrations at heights of 2 and 22 m were made at the 24-m meteorological tower at Tiana Beach, Long Island, New York (Figure 2). After the storms of the previous winter, much of the sand at the base of the tower was washed away and the remaining bluff had receded about 10 to 20 m from the tower. Our

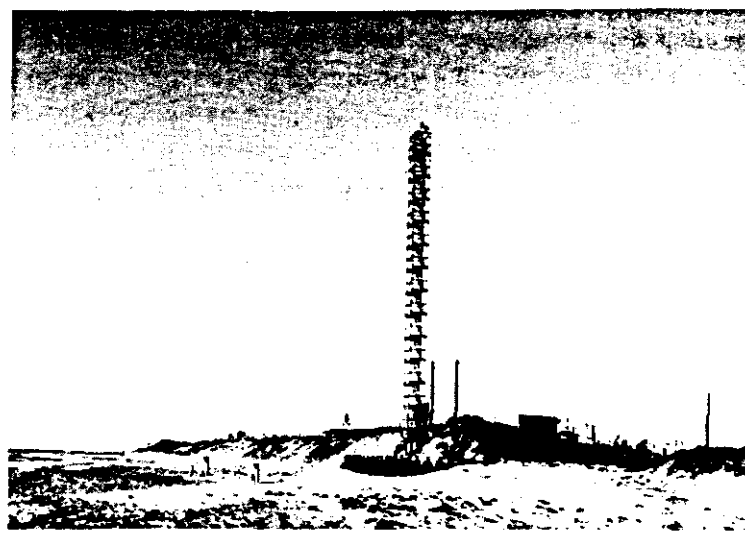

Fig. 2. 24-m-high meteorological tower at Tiana Beach. Fetch over sandy beach was about 20 m for low tides.

measurements indicate the bluff effect to be negligible except for the lowest few meters. The fetch over the sandy beach for onshore flows was about 20 m for low tides and near zero for high tides. Maximum height of the internal boundary layer at the tower was 10 m. The lower sampling tube was positioned about 20 m away from the tower on a wooden pile so that it remained above the internal boundary layer for onshore flows. Supporting meteorological measurements consisted of wind speed and wind direction at 24 m, and mean air temperature and relative humidity at 2 m. Mean sea surface temperature for this period of the year was estimated from previous measurements. Differences in mean CO_2 concentrations at the two levels were measured by pumping air through a solenoid-operated manifold to a Mine Safety LIRA Model 200 infrared analyzer. Lengths of tylon tubes from two levels were the same. A cold trap maintained at $-10\,°C$ was used to eliminate moisture from the samples. Each level was sampled for 5 minutes and the data were continuously recorded on chart paper for the entire period. The CO_2 and wind data were also recorded by an analog magnetic recorder for several 12-hour periods of onshore flows. The analyzer was operated in the 300–400 ppm range and was calibrated daily with standard gas of two different concentrations to check drifts in zero position and span. A zero drift of about 2% per day was noticed. Mean CO_2 values were corrected for this drift. There was no drift in the span thus giving accurate CO_2 gradient values. Errors due to zero drift in short duration (few minutes) analysis of mean CO_2 values were also small. The analyzer had a cell length of about 23 cm, a sensitivity of 0.1 ppm and a time constant of about 5 s. In order to avoid large sampling lags due to long tubes, two pumps were used, one drawing the sample from one elevation to the analyzer and the other maintaining the flow from the other elevation. Computations and simple experiments proved the evacuation time in the trap to be significantly less than 5 min. A line diagram of the experimental arrangement is shown in Figure 3. The tubes from two levels were interchanged to determine

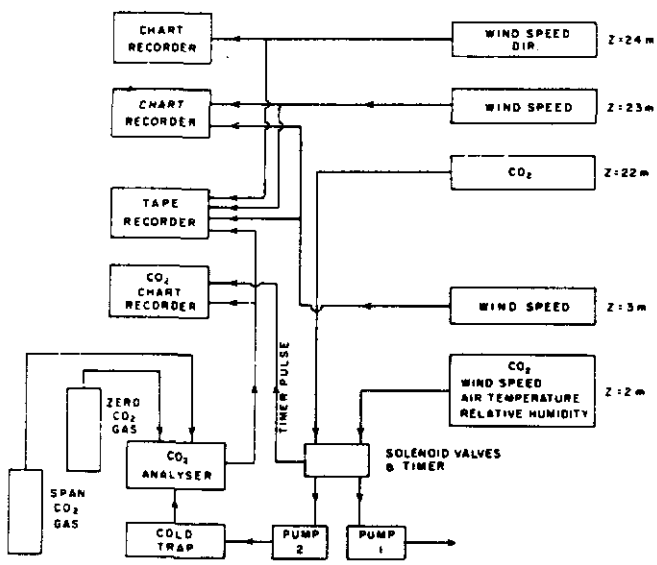

Fig. 3. A diagram showing the experimental arrangement.

any effect of the moisture on CO_2 concentration. Concentration gradients were found to be the same when the tubes were interchanged.

The CO_2 gradient measurements at Tiana Beach were made continuously for three weeks during December 1 to 21, 1978. Onshore flows from a southerly direction occurred for four periods of 48 hr each.

3. Estimated Vertical Gradient of CO_2 From Global Mean Flux

In this section, a vertical concentration gradient based on global mean values is estimated. This gradient is compared with the gradients measured at Tiana Beach in the next section. Assuming the rate of CO_2 released into the atmosphere as 5×10^{15} gm yr^{-1} (Baes, Jr. *et al.*, 1976) and assuming about 50% removal by the oceans with a total area 36×10^{7} km^2, the net flux into the oceans can be computed as 2.2×10^{11} gm cm^{-2} s^{-1}. To obtain a mean concentration gradient, a flux-profile relationship of the form

$$F = K_z \frac{\Delta c}{\Delta z} \tag{1}$$

is used where F is the CO_2 flux into the oceans, K_z is an eddy diffusivity for CO_2, and Δc the mean concentration difference of CO_2 over the height interval Δz. Assuming a friction velocity u_* of 40 cm s^{-1} and equality of K_z to momentum eddy diffusivity K_M, then

$$K_z = K_M = k u_* z \tag{2}$$

where k is Von Kármán's constant and z is height above the surface. Combining Equations (1) and (2), the concentration gradient is given by

$$\frac{\Delta c}{\Delta z} = \frac{F}{k u_* z}. \tag{3}$$

With the global mean flux of 2.2×10^{11} gm cm^{-2} s^{-1} and a friction velocity of 40 cm s^{-1}, Δc over a 10 m height interval in the marine surface layer can be estimated as 2.75×10^{-12} gm cm^{-3} or 1.5×10^{-3} ppm of CO_2.

4. Vertical Gradients of CO_2 With Onshore Winds

A typical variation of the mean CO_2 between the sampling levels for onshore flow is shown in Figure 4. Hourly mean wind speed was 8 m s^{-1} and the wind direction was south–southwest. Mean CO_2 concentration was 352 ppm and the concentration difference Δc varied from 0.8 to 1.4 ppm over a height interval of 20 m. The mean concentrations increased with height corresponding to a downward flux into the ocean. This gradient is thus about two orders of magnitude greater than the value of 1.5×10^{-3} ppm estimated from global mean values in the previous section. Corresponding fluxes will also be about two orders of magnitude higher.

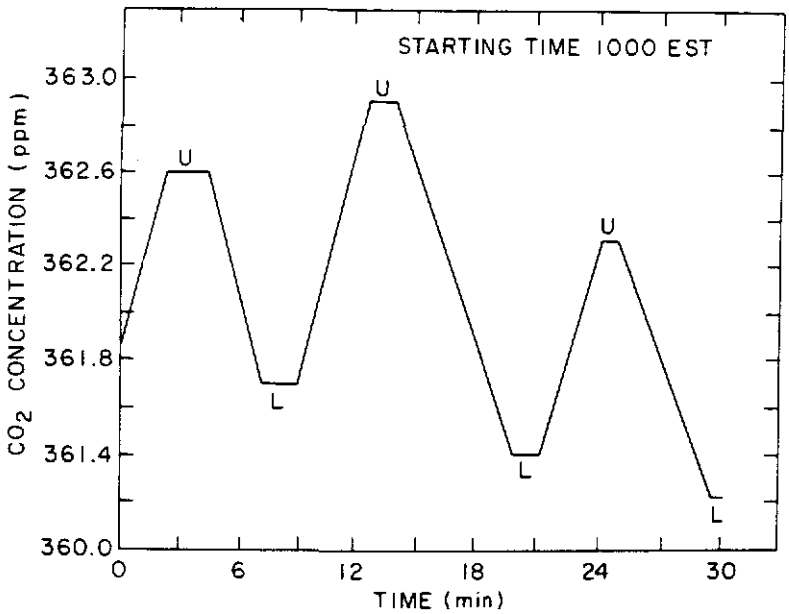

Fig. 4. Time history of mean carbon dioxide concentrations 1000–1030 EST. Sampling was done alternately at the upper and lower levels every five minutes. Height interval was 20 m. Mean wind speed ≈ 8 m s^{-1}. Mean wind direction ≈ 220 deg. U indicates upper level and L the lower sampling level.

Cold ocean temperature is believed to have caused the downward flux. Studies by other investigators have indicated the possibility of large CO_2 fluxes into the oceans in higher latitudes and out of the ocean in equatorial regions.

Time history of carbon dioxide concentration difference, Δc, for two periods with different mean wind speeds is shown in Figures 5 and 6. Figure 5 corresponds to a

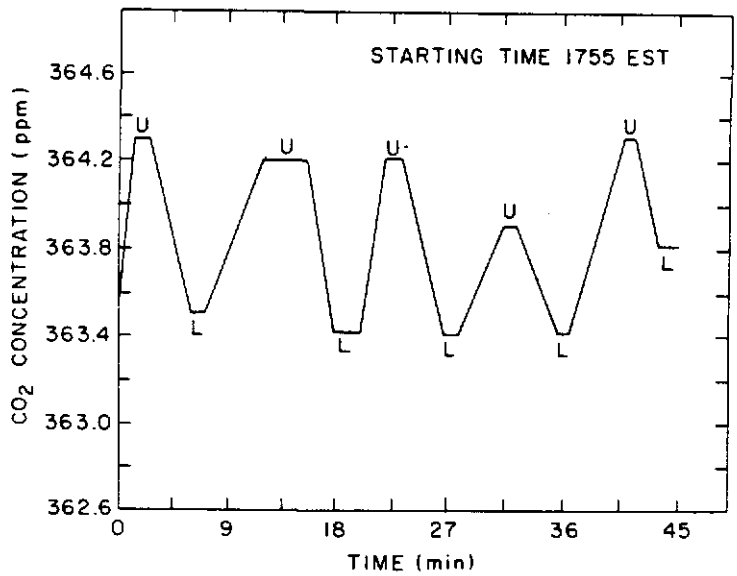

Fig. 5. Same as for Fig. 4 for a 45 min time period starting at 1755 EST. Mean wind speed ≈ 10 m s^{-1}. Mean wind direction ≈ 225 deg.

mean wind speed, $\bar{u}$, of 10 m s^{-1} and Figure 6 had $\bar{u} \simeq 12$ m s^{-1}. The mean Δc was 0.9 ppm for 1755–1840 EST and 0.6 ppm for 1915–1955 EST. Measurements during the rest of the onshore flow conditions gave similar concentration gradients of carbon dioxide.

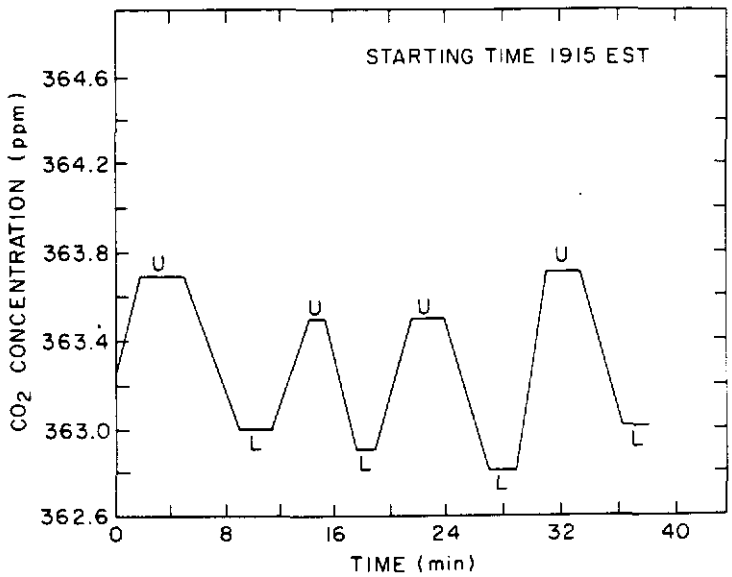

Fig. 6. Same as for Fig. 4 for a 35 minute time period starting at 1915 EST. Mean wind speed $\simeq 12$ m s^{-1}. Mean wind direction $\simeq 225$ deg.

5. Directional Dependence of Mean CO_2 at Tiana Beach

As shown in Figure 1, Long Island is approximately oriented in a northeast–southwest direction and has a straight beach line. Winds with 70 to 250° azimuth angle are onshore. The meteorological tower at Tiana is located on a barrier beach with Shinnecock and Moriches Bays located to the north. Observations of the mean CO_2 concentrations showed the effect of upwind sources. Maximum concentrations were observed with westerly flows along the beach. This phenomenon has been observed before at Long Island (Woodwell *et al.*, 1973). Flows with long fetches over water had minimum mean CO_2 concentrations. A typical example of the dependence of mean CO_2 values on wind direction is shown in Figure 7. The concentrations were minimum ($\sim$330 ppm) with a south–southwesterly wind. As the wind veered to a southwesterly direction, the mean CO_2 increased to about 362 ppm and remained reasonably constant as long as the wind direction remained the same. An increase in CO_2 is again noticed around 2100 EST as the mean wind direction became more westerly, parallel to the breach. Decrease in CO_2 after 2300 EST is probably due to travel over bay water. Further studies are needed to verify the effect of bays. Wind speed ranged from 10 to 14 m s^{-1} during this period, with good mixing in the surface layer.

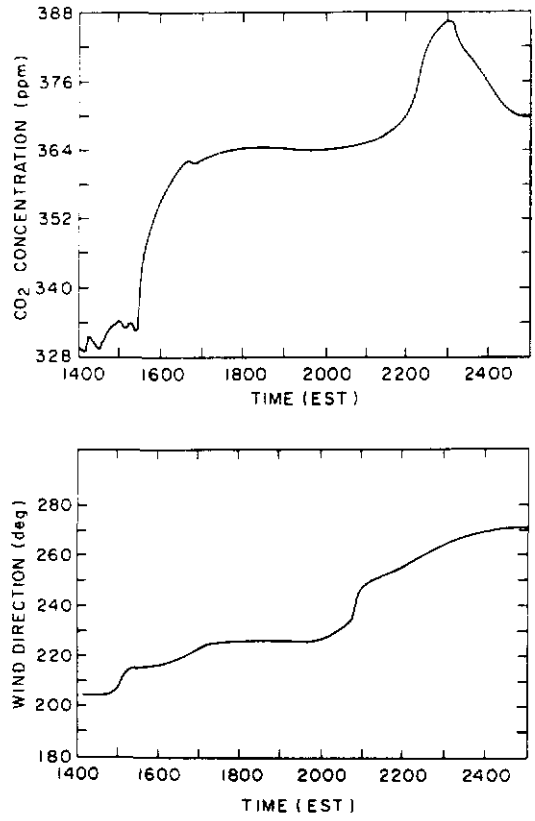

Fig. 7. Mean CO_2 variations due to changes in mean wind directions. A wind direction of 250 degrees was parallel to the beach. A sharp increase in mean CO_2 concentration as the wind direction became southwesterly can be seen.

When the wind was light with strong surface-based inversions during nights, a gradient of 10 to 15 ppm was observed for over-land flows. This is probably due to the release of CO_2 by biological activity and little mixing in the atmosphere.

6. Conclusions

Downward CO_2 gradients of 0.75 to 2 ppm were measured for onshore atmospheric flows at Tiana Beach, Long Island, over a height interval of 20 m. Measured gradients were about two orders of magnitude greater than the values that one would expect based on net global mean flux into oceans. Downward flux of CO_2 into the ocean might be due to the cooler waters off Long Island in December.

It should be stressed that these measurements were preliminary in nature and the gradient method of estimating fluxes suffers from several disadvantages such as the assumption of eddy diffusivity, correction for atmospheric stability, etc. Effect of any horizontal gradient of CO_2 due to the presence of surf and shallows is also not known at present; but the measurability of CO_2 gradient at a coastal site with onshore flow was demonstrated by this preliminary experiment. The reasons for the CO_2 gradients

being about two orders of magnitude greater than the global mean is not known. One possible reason is the nearness of the source region. In fact, minimum CO_2 concentrations were observed for southeasterly wind directions with long fetches over water and maximum values for southwesterly directions with shorter fetches from the continent. However, more comprehensive measurements will be needed to study the variation of CO_2 fluxes over oceans under various meteorological and oceanic conditions.

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