Title
The contribution of rainwater to variability in surface ocean hydrogen peroxide

Permalink
https://escholarship.org/uc/item/5h97w6r5

Journal
Journal of Geophysical Research, 92(C3)

ISSN
0148-0227

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Publication Date
1987

DOI
10.1029/JC092iC03p02970

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Abstract. Hydrogen peroxide concentrations have been determined in marine rain from the Gulf of Mexico (184-820 x 10^{-7} mol L^{-1}, \bar{x} = 402 x 10^{-7} mol L^{-1}), the western Atlantic Ocean (84-206 x 10^{-7} mol L^{-1}, \bar{x} = 127 x 10^{-7} mol L^{-1}, s = 45 x 10^{-7} mol L^{-1}), and one rain event off the Florida Keys (\bar{x} = 284 x 10^{-7} mol L^{-1}, s = 38 x 10^{-7} mol L^{-1}). In several cases, simultaneous measurements of the concentration of H_2O_2 in the surface ocean were also determined. These measurements were made with the ship under way using a continuous flow sampling system with the intake at the bow. In shallow stratified layers, rain events can increase the existing hydrogen peroxide concentration by a factor greater than 10 and dramatically increase the mean H_2O_2 concentration of mixed depth layers of 50 m or more. Rain is a significant transient source of H_2O_2 in the surface ocean.

Introduction

In recent years, we have conducted a number of field, laboratory, and modelling studies directed toward understanding the distribution of H_2O_2 and its impact on redox processes in natural waters. In the surface ocean, the principal source of H_2O_2 is the photooxidation of dissolved organic matter. This process is thought to involve O_2 as an intermediate, which subsequently disproportionates to H_2O_2 [Zika, 1981]. Spatial and diel variations in surface ocean H_2O_2 concentrations have been reported. These variations can be explained in terms of changes in solar radiation, dissolved organic carbon content, and surface ocean mixing processes [Zika et al., 1985a, b, and manuscript in preparation, 1986].

Atmospheric deposition of H_2O_2 or various precursors has also been proposed as a potential source of oceanic H_2O_2 [Thompson and Zafiriou, 1983]. Measurements of H_2O_2 levels in rainwater from marine or coastal air masses revealed concentrations of the order of 100 x 10^{-7} mol L^{-1} [Zika et al., 1982]; 2-3 orders of magnitude greater than those of surface seawater. Simple calculations suggest that episodic injections of rainfall would result in local transient increases of surface ocean H_2O_2 superimposed on the normal background H_2O_2 generated by "in situ" photochemical processes. The decay of this transient as a result of chemical reactions and mixing processes could provide an interesting field test of present concepts and numerical models of these processes. Because of the irregular spatial and temporal distribution of rainfall over the oceans and the short duration of shipboard field experiments, documentation of rainwater input of H_2O_2 to the ocean has proven elusive. On three recent cruises to the Gulf of Mexico, the western Atlantic, and off the Florida Keys, several rain events were encountered that allowed us to observe real time changes in surface ocean H_2O_2. In this report, we document these changes and briefly discuss their implications for spatial variability of H_2O_2 in the surface ocean.

Experimental

Sampling. Three types of samples were collected for H_2O_2 analysis in this study: rain water, surface ocean water at 1-2 m (continuously pumped), and discrete depth samples.

Rainwater samples were collected in hand-held vials that had been acid washed and rinsed with distilled water. Just prior to sampling, the vials were rinsed with low-residual organic water (Milli-Q water redistilled over permanganate). The samples were analyzed within 5 min of collection. The quantity of rainfall was not measured.

Two different flow-through seawater systems provided a continuous sample stream in the laboratory. The system aboard the R/V Cape Florida was constructed of polypropylene tubing and a peristaltic pump with silicon tubing. The influent tubing was attached to the bow of the ship approximately 1 m below the surface. Structurally, the tubing was cased in metal piping and extended approximately 12 cm from the end of the casing. The polypropylene tubing was enclosed in opaque hose to minimize any photochemically and thermally initiated reactions occurring in the flow-through system on deck, prior to sampling in the laboratory. The seawater flow in the system was approximately 1-2 L min^{-1} with a residence time of less than 30 s.

The systems aboard the R/V Columbus Iselin and R/V Calanus were through-the-hull Teflon©. The intake on the R/V Columbus Iselin was approximately 2 m below the surface, while that of the R/V Calanus was 1 m below the surface. Both intakes were at the bow. A positive displacement pump with a Hypalon® (DuPont, Inc.) chlorosulfonated polyethylene head was used. The flow rate was 3-5 L min^{-1} with a residence time of less than 10 s in the system, prior to sampling.

Discrete water samples were obtained in 5-L PVC Niskin samplers (General Oceanics, Miami, Florida). Samples were transferred to teflon-lined screw top glass 250-ml bottles. H_2O_2 was analyzed immediately after sampling.

Analysis. In this study, we used a recently developed continuous flow analyzer based on a...
previously described batch method using the peroxidase enzyme mediated fluorescence decay of scopoletin to measure H$_2$O$_2$ [Andreae, 1955; Perschke and Broda, 1961; Zika et al., 1982; Zika and Saltzman, 1982]. Seawater was continuously sampled from the ship's flow system via a peristaltic pump. The peristaltic pump was also used to add, in sequential order, the reagents: 0.5 mol L$^{-1}$, pH 7 phosphate buffer, scopoletin, and horseradish peroxidase. The fluorescence was monitored with a LDC FluoroMonitor III, which provided a continuous signal of the surface concentration of hydrogen peroxide while the ship was under way.

Standard curves were made up in peroxide-free seawater using a volumetric dilution of a 10$^{-2}$ mol L$^{-1}$ H$_2$O$_2$ solution, which had been standardized by iodometric titration. Peroxide-free seawater was prepared by allowing samples to stand in the dark; for open-ocean surface water this requires several weeks. An alternative method has been employed successfully, in which 0.1 mg of catalase is added to 20 L of freshly collected surface water and allowed to stand for 24 hours in the dark. Care must be taken to keep the water from light prior to use.

Direct comparison of field samples using the batch and continuous method agreed to within ±2%. Details of the continuous hydrogen peroxide analyzer will be published elsewhere.

Fluorescence of dissolved organic matter (DOM) was measured using a Turner Designs model 10 fluorometer. A CS 7-60 filter was used for excitation, and two filters, first a 2A followed by a 65A, were used for emission. Quinine sulfate dissolved in 0.1 M H$_2$SO$_4$ was used as the reference standard. A 1 µg L$^{-1}$ solution equals 1 QSU (quinine sulfate unit).

Salinity was measured continuously using a parallel flow-through system. The inlet depth was at 1-2 m. The signal was recorded at 10-min intervals on the ship's computer system.

On the R/V Cape Florida, continuous chlorophyll measurements were obtained using a Turner Designs model 10 fluorometer (excitation band centered at 430 nm and a broadband cut-off emission filter >650 nm), and the signal was recorded every 10 min on the ship's computer system. Chlorophyll was measured as a relative fluorescence during the Gulf of Mexico cruise.

On the R/V Columbus Iselin, the all-Teflon system was used, and the chlorophyll signal was recorded both on the ship's computer system (every 10 min) and the IBM PC$^*$ based data acquisition system used for H$_2$O$_2$ and DOM fluorescence. On the latter system, the chlorophyll signal was recorded every second and averaged every 10 s for display and permanent file. The chlorophyll signal was calibrated using a known concentration of fluorescein. To convert to chlorophyll, water samples with a known fluorescein fluorescence were collected and the chlorophyll was determined according to standard techniques [Strickland and Parsons, 1968]. It was found that 0.385 mg Chl m$^{-3}$ was equal to 10 × 10$^{-9}$ mol L$^{-1}$ fluorescein.

Study Area

The first study was conducted aboard the R/V Cape Florida, in the Gulf of Mexico from September 10-22, 1985 (SOLARS III cruise). Figure 1 shows the cruise track with the approximate rain sampling locations indicated by solid circles. The locations of continuous measurements are indicated on the cruise track. The depth profile was obtained while at anchor off the Dry Tortugas, Loggerhead Key, latitude 24°38.0'N, longitude 82°52.9'W.

The second study was conducted aboard the R/V Columbus Iselin in the western Atlantic from February 22 to March 10, 1986 (SOLARS VI cruise). Figure 2 shows the cruise track with the approximate rain sampling locations indicated by
solid circles. The locations of continuous measurements are also indicated on the cruise track.

On a third cruise off the Florida Keys (Lower Matacumbe), within 2 mi of shore, May 10-18, 1986 (SOLARS VII), one rain event occurred and several samples were obtained. The location of the samples is given in Table 1.

Results

Rain measurements. Table 1 summarizes the results of the analyses of rainwater H₂O₂ concentrations. In this study, a total of 36 rain samples were collected and analyzed immediately (within 5 min) to determine H₂O₂ concentration. In the Gulf of Mexico (n = 24), all of the rain events were squalls with active lightning and lasting approximately 30 min. The H₂O₂ concentration ranged from 114 x 10⁻⁷ to 620 x 10⁻⁷ mol L⁻¹, with an average of 402 x 10⁻⁷ mol L⁻¹ (s = 218 x 10⁻⁷ mol L⁻¹). The data obtained from the western Atlantic (n = 9) ranged from 84 x 10⁻⁷ to 206 x 10⁻⁷ mol L⁻¹, with an average of 127 x 10⁻⁷ mol L⁻¹ (s = 45 x 10⁻⁷ mol L⁻¹). The rain sample from near the Florida Keys (n = 3) resulted in an average of 284 x 10⁻⁷ mol L⁻¹ (s = 38 x 10⁻⁷ mol L⁻¹).

The rain storm during which sample G was collected lasted nearly 4 hours and had lightning associated with it. Rain events H and I also had lightning associated with these shorter squalls, while events J, K, and L did not.

Continuous surface ocean measurements. Figure 3 shows the H₂O₂ and DOM fluorescence data record obtained while under way from station 3 to station 4 (latitude 27°25.1'N; longitude 86°43.6'W) to station 4 (latitude 27°10.0'N; 89°01.7'W) from a depth of 1 m. The data record is 3.5 hours long and covers approximately 78 km. At 0600 (local EST) the ship was moving through heavy squalls. An almost immediate increase in the surface (1 m) H₂O₂ concentration was observed upon entering the squall. As the ship continued to steam, the hydrogen peroxide concentration reflected the recent rain activity in the area. The surface H₂O₂ concentration increased from approximately 0.85 x 10⁻⁷, 0530 (local EST) to 1.85 x 10⁻⁷ mol L⁻¹ at 0737 hours. The DOM fluorescence appeared to increase somewhat during the time the highest concentration of H₂O₂ was observed.

Figure 4 shows a second data record, obtained during the middle of the same day as Figure 3, with the ship under way from station 3 to station 4. The surface H₂O₂ concentration was initially 0.86 x 10⁻⁷ mol L⁻¹ and increased to 2.03 x 10⁻⁷ mol L⁻¹ in approximately 25 min. Once again, it was noted that the ship was steaming through rain squalls and through areas that had recently received rain, as indicated by the ship's radar. During the time in which the data for both Figures 3 and 4 were obtained, the wave height was from 0.5 to 1.5 m. It should be noted that the surface fluorescence increased during the time that the H₂O₂ concentration increased, while the salinity decreased slightly. No change in chlorophyll was observed.

Figure 5 shows another 2.0-hour record of surface H₂O₂, DOM fluorescence, salinity, and chlorophyll, obtained just prior to arriving at station 2. It is obvious that some event occurred that drastically increased the H₂O₂ concentration from an initial concentration of 0.76 x 10⁻⁷ to a maximum concentration of 1.92 x 10⁻⁷ mol L⁻¹ in approximately 15 min. Rain was not noted during this time and the ocean was calm, with waves less than 10 cm. (The approximate location of this event was latitude...
TABLE 1. Hydrogen Peroxide Concentration in Rainwater Collected in the Gulf of Mexico, Western Atlantic, and Florida Keys

<table>
<thead>
<tr>
<th>Sample</th>
<th>Date</th>
<th>Location</th>
<th>Time, hours EST</th>
<th>(10^{-7} \text{ mol L}^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Gulf of Mexico, (\bar{X} = 402 \pm 218)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>September 14, 1985</td>
<td>27°10.3N, 89°01.7W</td>
<td>2025</td>
<td>168</td>
</tr>
<tr>
<td></td>
<td>September 15, 1985</td>
<td>26°31.7N, 89°52.3W</td>
<td>1930</td>
<td>386</td>
</tr>
<tr>
<td>B</td>
<td>September 16, 1985</td>
<td>26°46.3N, 86°52.5W</td>
<td>0800-0900</td>
<td>396</td>
</tr>
<tr>
<td>C</td>
<td>September 16, 1985</td>
<td>24°38.0N, 82°52.9W</td>
<td>0015-0030</td>
<td>513</td>
</tr>
<tr>
<td>D</td>
<td>September 17, 1985</td>
<td>21°59.2N, 79°33.5W</td>
<td>2130</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>February 23, 1986</td>
<td>25°52.9N, 78°13.4W</td>
<td>2255-2321</td>
<td>206</td>
</tr>
<tr>
<td>E</td>
<td>February 25, 1986</td>
<td>24°35.2N, 71°20.4W</td>
<td>2210-2220</td>
<td>187</td>
</tr>
<tr>
<td>F</td>
<td>February 26, 1986</td>
<td>20°31.1N, 68°44.1W</td>
<td>1025-1030</td>
<td>154</td>
</tr>
<tr>
<td>G</td>
<td>February 26, 1986</td>
<td>19°22.9N, 67°04.4W</td>
<td>1800-1805</td>
<td>106</td>
</tr>
<tr>
<td>H</td>
<td>February 26, 1986</td>
<td>19°05.4N, 67°54.7W</td>
<td>1940-1950</td>
<td>99</td>
</tr>
<tr>
<td>I</td>
<td>May 14, 1986</td>
<td>25°13.5N, 81°12.8W</td>
<td>1320</td>
<td>243</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Florida Keys, (\bar{X} = 284 \pm 38)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

27°04.1'N; longitude 84°07.8'W.) The magnitude of this increase was greater than that observed over an entire day in similar oceanic environments with no rain [Zika et al., 1985a]. The DOM fluorescence appeared to increase slightly at the time the high \(H_2O_2\) concentrations were observed. The salinity decreased slightly during this time, and no noticeable change was observed in the chlorophyll.

Figure 6 is a comparison of two continuous nighttime data records, each of which is approximately 5 hours in duration (102 km). The data record at the left was collected during a rain storm (sample G, Table 1), and for comparison, the data on the right were collected on the following evening with no rain. The data gaps in the \(H_2O_2\) record indicate where the rain samples were analyzed. The surface ocean \(H_2O_2\) data for the evening with no rain was somewhat variable with a mean of between 0.5 and 0.6 \(10^{-7}\) mol L\(^{-1}\). On the other hand, the \(H_2O_2\) data for the evening with rain shows an initial surface ocean concentration of approximately 0.5 \(10^{-7}\) mol L\(^{-1}\), increasing to as much as 1.3 \(10^{-7}\) mol L\(^{-1}\). After the rain had ceased, the levels in the surface water decreased to 0.3 - 0.4 \(10^{-7}\) mol L\(^{-1}\).

A comparison of the DOM fluorescence between the two samples indicates that some variability did occur but no noticeable increase was observed.
Fig. 3. Surface ocean measurements of \( \text{H}_2\text{O}_2 \) and DOM fluorescence, midway between station 3 and 4, SOLARS III.

during the rain. This is somewhat different than we observed in the earlier data, from the Gulf of Mexico. The continuous chlorophyll data records for each night showed several patches but were in general comparable with no relationship to either \( \text{H}_2\text{O}_2 \) or DOM fluorescence.

Figure 7 is a 3-hour data record (61 km) sampled during the middle of the day. During this time, the ship was moving through a rain squall that ended at 1040 hours (EST) (event I, Table 1). The \( \text{H}_2\text{O}_2 \) data record shows the initially high surface values of approximately \( 1.40 \times 10^{-7} \text{ mol L}^{-1} \), associated with the rain, decreasing to \( 0.6 \times 10^{-7} \text{ mol L}^{-1} \). This decrease was followed by a slight increase as the day progressed, to \( 0.65 - 0.70 \times 10^{-7} \text{ mol L}^{-1} \). The DOM fluorescence and chlorophyll data records did not show any difference between the time it was raining and when there was no rain.

Water column study. While anchored in the Dry Tortugas, Loggerhead Key (latitude 24°38.0'N; longitude 82°52.9'W), several rain events occurred. The water depth was approximately 10 to 11 m. Several water profiles of salinity and temperature suggested a homogeneous water column. Samples of the water column were obtained using a rosette with five 5-L Niskin bottles (Figure 8). The samples showed no variation in \( \text{H}_2\text{O}_2 \) concentration with depth, as expected in a well-mixed system.

To examine the impact of rain on the water column \( \text{H}_2\text{O}_2 \) concentration, we obtained samples at five depths during a light rain (Figure 8). During the rain the \( \text{H}_2\text{O}_2 \) concentration increased, with the increase at the surface significantly greater than that at depths greater than 4 m.

Discussion

Hydrogen peroxide concentrations in marine rain. The \( \text{H}_2\text{O}_2 \) concentration in rainwater is a complex function of gas and liquid phase photochemistry, the dynamics of transport across the gas-liquid interface, and the macroscopic dynamics of transport within the cloud. The current state of knowledge of cloud chemistry, including \( \text{H}_2\text{O}_2 \), has been the subject of a number of recent reviews [e.g., Chameides, 1984; Calvert et al., 1986; Jacob, 1986]. In this discussion we will only briefly mention those characteris-
Fig. 4. Surface ocean measurements of H$_2$O$_2$, DOM fluorescence, chlorophyll, and salinity, nearing station 4, SOLARS III.

The principal pathway for the formation of tropospheric H$_2$O$_2$ is the disproportionation of HO$_2$ radicals in either gas or liquid phase; hence the production of H$_2$O$_2$ is increased by factors leading to the formation of HO$_2$ and decreased by reactions that consume HO$_2$. One of the major reactions consuming HO$_2$ is with NO:

\[
\text{NO} + \text{HO}_2 \rightarrow \text{OH} + \text{NO}_2
\]

The low levels of NO characteristic of marine air result in less effective recycling of HO$_2$ to OH and, as a result, increased peroxide production relative to continental air. The situation may be further complicated in polluted air by the presence of variable concentrations of organic...
compounds such as aldehydes and unsaturated hydrocarbons, which promote peroxide formation via production of gas phase peroxy radicals [Bufalini et al., 1972].

Another factor influencing the concentration of H$_2$O$_2$ in rain is the abundance of SO$_2$. Dissolved SO$_2$ reacts rapidly with H$_2$O$_2$ in droplets in the pH range of cloud and rainwater [Kuenen et al., 1983; Martin, 1984]. In clean marine air, SO$_2$ concentrations are low and unlikely to modify the levels of H$_2$O$_2$ concentration in either cloud or rainwater. This is quite different from polluted air, where SO$_2$ concentrations may equal or exceed those of H$_2$O$_2$, resulting in rapid depletion of H$_2$O$_2$ within the cloud droplets [Jacob, 1986]. This effect may be offset to some extent in urban air by the presence of formaldehyde, which can stabilize
Fig. 6. Comparison between surface ocean H$_2$O$_2$, DOM fluorescence, and chlorophyll during a rain and with no rain, SOLARS VI. Rain occurred between longitude 78°50'W and 78°12'W. The location of the "no rain" was longitude 74°45'W and 73°00'W.

Survey of hydrogen peroxide in rain. In comparing data on the concentration of H$_2$O$_2$ in rain, it is necessary to recognize that many of the early reports used the chemiluminescent luminol method. This method has since been shown to have interferences from SO$_2$ [Yoshizumi et al., 1984] and several heavy metals [Ibusuki, 1983]. However, several reports using alternate or modified methods have been recently published, and these data bases are briefly discussed here.

Zika et al. [1982] reported H$_2$O$_2$ concentrations in rain collected in Miami, Florida, and the Bahamas. The H$_2$O$_2$ concentrations ranged from 115 to 750 x 10$^{-7}$ mol L$^{-1}$, with a mean of 312 x 10$^{-7}$ mol L$^{-1}$. They noted that their data reflected substantial input of oceanic air. Yoshizumi et al. [1984] reported data from rain collected near Tokyo, Japan. Over the entire year they observed monthly averages ranging from 3.15 to 134 x 10$^{-7}$ mol L$^{-1}$, with a yearly average of 64 x 10$^{-7}$ mol L$^{-1}$. Kelly et al. [1985] reported data from nonurban areas in the southeastern United States. Fifty percent of the samples (total samples n = 54) in that study had less than 50 x 10$^{-7}$ mol L$^{-1}$ H$_2$O$_2$, and another 20% fell between 50 and 100 x 10$^{-7}$ mol L$^{-1}$.

In general, our data from the Gulf of Mexico...
The effect of marine rain on surface ocean hydrogen peroxide:

We have presented measurements of marine rain $\text{H}_2\text{O}_2$ concentrations and have shown that the surface $\text{H}_2\text{O}_2$ concentrations can be dramatically affected by local rain events. The effect of rain in elevating surface concentrations of $\text{H}_2\text{O}_2$ will depend on the extent of rain events, the $\text{H}_2\text{O}_2$ concentration in rain, and mixing (R. G. Zika et al., manuscript in preparation, 1986). The effect of varying amounts of rainfall on the concentration of $\text{H}_2\text{O}_2$ in homogeneous mixed layers to different depths is shown in Figure 9. It is obvious that when conditions exist that support stable near-surface stratification (i.e., $0.1$-$2.0$ m), the $\text{H}_2\text{O}_2$ concentration can attain levels that are $1$-$2$ orders of magnitude higher than the mean concentration normally found at this time of year in the Gulf of Mexico. Heavy rains, such as those encountered in the tropics or in hurricanes, can substantially increase the mean water column $\text{H}_2\text{O}_2$ concentration locally to depths of $50$ m and greater.

Further, Zika et al. [1985a] have shown diel variations in $\text{H}_2\text{O}_2$ concentration in several areas of the Gulf of Mexico that result primarily from photochemical processes. In general, there is an increase in surface $\text{H}_2\text{O}_2$ concentration during the

![Graph showing $\text{H}_2\text{O}_2$ concentration depth profile](image)

Fig. 8. Hydrogen peroxide concentration depth profile while at anchor in the Dry Tortugas (latitude 24°38.0'N, longitude 82°32.9'W). Crosses show $\text{H}_2\text{O}_2$ concentration before rain, and squares show $\text{H}_2\text{O}_2$ concentration during a light rain.
Fig. 9. Model calculations of the impact of rain on the concentration of $H_2O_2$ at different depths of a homogeneous mixed layer in the Gulf of Mexico.

day. At night the $H_2O_2$ concentration decreases as a result of a combination of chemically and biologically mediated processes, as well as convective mixing of the water column. The changes in $H_2O_2$ concentrations observed in this study were, in most cases, rapid and of a magnitude that far exceeded the normal diel variability in the open ocean. The increases and decreases observed during the day were superimposed on the variability caused by the photochemical processes leading to the formation of $H_2O_2$.

The persistence of a transient input, such as rain, on surface ocean $H_2O_2$ concentrations is possible, in the event of weak mixing. An example is shown in Figure 5, where a rapid increase in the $H_2O_2$ concentration most likely resulted from an earlier rain squall. In environments where rainfall is common, local patchiness is likely to be observed and may account for the significantly greater spatial variability than would otherwise have been present under clear conditions in the same environments [Zika et al., 1985a].

The increase in fluorescence in surface water, associated with the rain events in the Gulf of Mexico, is presently unexplained. It is possible that these increases are associated with terrestrial input of DOM in the surface ocean from major tributaries (i.e., Mississippi River) in the Gulf of Mexico. The coincidental occurrence of freshwater sources and rainwater input occurring several times during the cruise is unlikely. These increases may reflect rain input; however, this was not confirmed with the data obtained while in the western Atlantic. Further studies are in progress to investigate this phenomenon.

It has recently been reported that $H_2O_2$ may be formed in association with freshwater algae [Zepp et al., 1987], and the possibility of this in marine waters has been suggested Palenik and Morel, 1985]. From the data presented here, in areas of low productivity, there does not appear to be a relationship of chlorophyll $a$ and $H_2O_2$ concentration. It is necessary to extend these studies to other environments to better define these relationships.

In summary, we have shown that rain may significantly increase the $H_2O_2$ in surface oceans. Variations of the magnitude we have shown could significantly affect the redox
chemistry of the surface ocean [van der Weijen and Reith, 1982; Sunda et al., 1983; Moffett and Zika, 1983, 1987, and Reaction kinetics of hydrogen peroxide with copper and iron in seawater, submitted to Environmental Science and Technology, 1986].

Acknowledgements. This research was supported through the office of Naval Research on grant N00014-80-G-00042 and the Drinking Water Research Center, University of Florida. The authors wish to thank the captain and crew of the R/V Cape Florida, R/V Columbus Iselin, and R/V Calanus for their cooperation. The technical assistance of Robert G. Petasne, Cynthia A. Moore, and David S. Odum is greatly appreciated.

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(Received April 25, 1986; accepted June 19, 1986.)