# Carbon Dioxide Variability and Atmospheric Circulation[1]

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## ABSTRACT

Hourly values of the concentration of atmospheric carbon dioxide at Mauna Loa Observatory (MLO) formed the basis for an investigation of concentration fluctuations on daily to monthly time scales. In agreement with earlier studies we found no evidence linking the fluctuations with large-scale variations in the atmospheric circulation. Neither did local cane fires produce any measurable effects. A diurnal variation that comprises daytime forest depletion and nighttime enhancement by outgassing from the summit caldera need not affect overall data quality. We conclude that MLO is an excellent site for monitoring atmospheric carbon dioxide.

## 1. Introduction

Previous studies (Pearman, 1979; Miller, 1979) have shown little relationship between the variability of atmospheric carbon dioxide ($CO_2$) at Mauna Loa Observatory (MLO) and the large-scale atmospheric circulation. For the 20-year period 1958–77, Pearman related daily $CO_2$ anomalies from the long-term mean to the wind at the height of MLO measured by the Hilo rawinsonde. There was no significant correlation; at best the differences in $CO_2$ concentration between westerly and easterly winds amounted to only 0.1 ppm. From his statistical study of the local meteorology, Pearman could not conclude that the $CO_2$ variations were due to large-scale synoptic meteorological factors and recommended case studies of specific events. Miller related daily 10-day back trajectories of air arriving at Mauna Loa in the 3000–5000 m layer to the average $CO_2$ concentration for the period February 1975–February 1977. He concluded that concentration does not depend on trajectory.

This report describes our investigation of the relationship of $CO_2$ fluctuations to the circulation of the lower and upper troposphere from daily to monthly time scales. The case studies focus on extreme specific events on the basis that if there is a large-scale meteorological cause it will show best in the extreme events.

## 2. Data and processing

### *a. Carbon dioxide*

The hourly values of $CO_2$ measured at MLO from May 1974 to March 1981 were obtained on tape from the Air Resources Laboratories (ARL) of NOAA. The data had been screened by the normal editing routine at ARL to eliminate hours with large within-hour variability (Peterson, 1977). They were processed for individual and long-term monthly means, long-term trend, annual cycle, and anomalies for various frequencies after removal of the annual cycle and long-term trend.

### 1) ANNUAL CYCLE

Fig. 1 shows the monthly averages in Scripps 1959 Adjusted Index Scale. The average amplitude of the annual cycle for the seven years is 5.45 ppm. This is slightly less than the 5.94 ppm amplitude reported by Pearman (1979) for the 20-year period ending in 1977.

### 2) SECULAR TREND

The trend for the seven years was determined by a linear least squares fit to the monthly anomalies from the seven-year monthly means. The secular trend line of 1.32 ppm per annum is shown in Fig. 1.

### 3) ANOMALIES

Monthly anomalies were determined after removing the annual cycle and the secular trend from the data and are shown in Fig. 2 plotted about the trend line. Running mean departures of 3, 5, 7 and 15 days were also computed and those exceeding threshold values of ±1.25 and ±1.50 ppm were listed for selecting periods of extreme departures. Running means of 3 and 15 days for the $CO_2$ observations are shown in Fig. 3.

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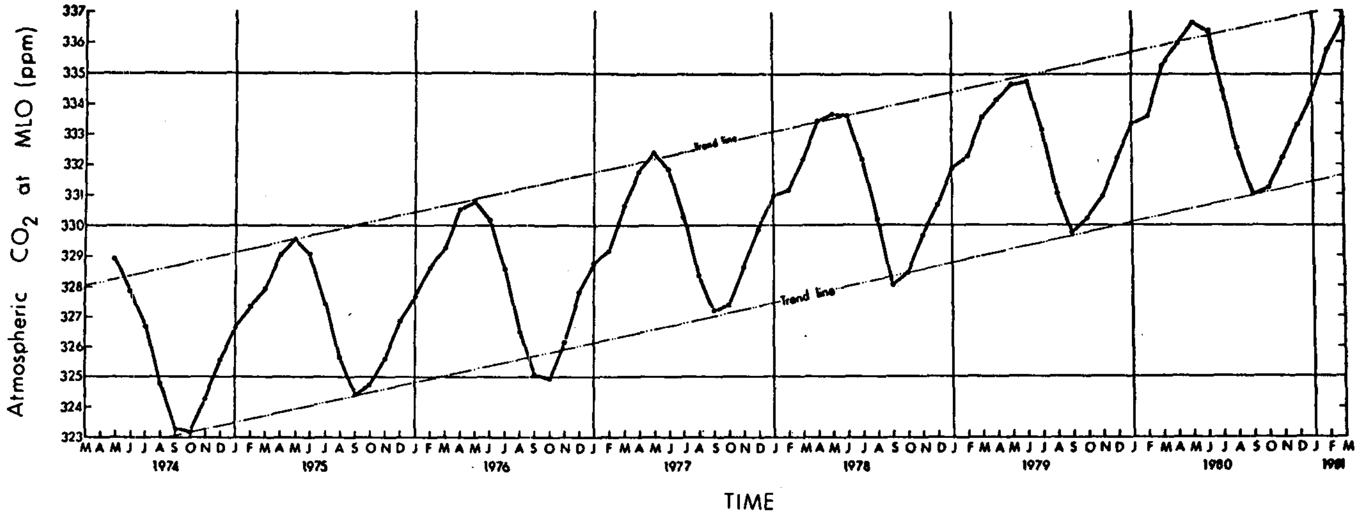

FIG. 1. Monthly mean atmospheric carbon dioxide at Mauna Loa Observatory.

### *b. Atmospheric circulation*

Wind observations are sufficient to determine the large-scale circulation over the Pacific Ocean at only three levels. A combination of aircraft winds and a few rawins are available for the upper troposphere. Since 1975 these can be augmented by upper-level winds determined from satellite observed cloud motions (sawins). Ship observations are the major source at the surface while low-level sawins are representative of the 1000 m level.

#### 1) UPPER TROPOSPHERE

Winds from commercial jet aircraft were composited by 5° grid squares and combined with rawins to produce monthly mean resultant wind analyses over the Pacific Ocean for the period 1966–73 (see Figs. 4 and 5). Data extracted at 2.5° points were used to produce monthly mean fields of divergence. Beginning in November 1975 monthly mean resultant wind analyses were produced from upper-level sawins obtained from the GOES West satellite. These data extend westward to only 180° and were used to describe the circulation over the eastern Pacific.

#### 2) LOWER TROPOSPHERE

The low-level sawins from the GOES West satellite were composited and averaged to produce monthly mean circulation maps of the eastern Pacific. In addition to mean trajectory information an index of the trade wind strength in the Hawaiian Islands was derived from these data. Analyzed surface maps were available from the Honolulu Weather Service Forecast Office of the National Weather Service.

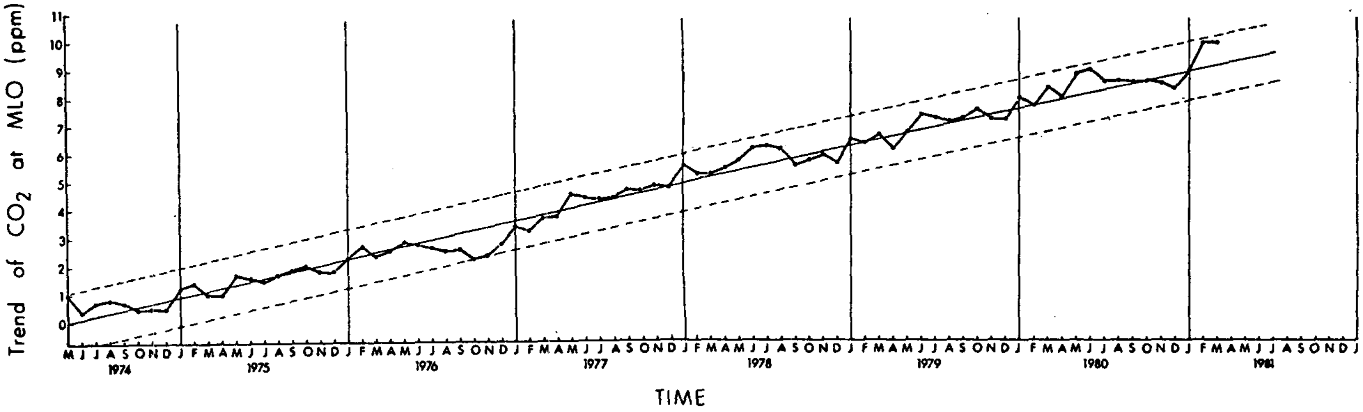

FIG. 2. The $CO_2$ monthly anomalies at MLO from the seven-year monthly means plotted about the seven-year trend line. The trend line is the linear least squares fit to the monthly anomalies. Dashed lines delineate the +1 to −1 anomaly range.

## 3. Large-scale influences

### *a. Upper-tropospheric circulation and contrasting synoptic regimes*

The monthly mean resultant winds at 35 000 ft over Hawaii blow from the southwest in summer and the northwest in winter; however, the air originates from higher latitudes in summer than in winter since in summer it moves around the upper-tropospheric trough lying between Hawaii and Midway Island. The trajectory passes north of Japan in summer and south of Japan in winter. Particularly during winter the monthly mean upper-level circulation is an excellent indicator of the shorter period synoptic variability over Hawaii. The daily synoptic features associated with mean zonal flows differ from those associated with a large amplitude wave; whether the mean trough lies west or east of Hawaii determines which of two contrasting synoptic regimes prevails. Figs. 4 and 5 show two extreme January flow patterns. In January 1971 the southern end of an intense trough lay just west of Hawaii and the jet stream was deflected southward across the islands (Fig. 4). Associated synoptic events included frontal passages and cutoff lows (Kona storms), heavy rainfall (Table 1) and persistent lower-tropospheric southwesterlies (Table 2). The month saw three distinct storm systems accompanied by widespread heavy rain and surface southwesterlies exceeding 15 m $s^{-1}$.

By contrast, near-zonal flow prevailed in January 1973 (Fig. 5) with the jet stream north of Hawaii near 32°N. This upper-tropospheric flow was associated with deep dry trade winds over Hawaii (Tables 1 and 2).

Although deep trade winds versus deep southwesterly flow produce the largest contrast in wind direction at, and air trajectories reaching, the MLO, the $CO_2$ anomaly at MLO during both Januarys was positive and greater than 0.5 ppm. This confirms the findings of Miller (1979) and Pearman (1979), respectively, that concentrations of $CO_2$ at MLO do not depend on air trajectory nor is there a significant relationship between wind direction and $CO_2$ concentration.

In addition to the upper-level flow patterns the $CO_2$ variability was related to the upper-level divergence. We assumed that if there is a vertical gradient of $CO_2$ in the Pacific the concentration at MLO in sinking air would differ from the concentration in rising air. As with the flow patterns no significant relationship was found.

### *b. Lower-tropospheric circulation and contrasting synoptic regimes*

Sawins, which have been available for the Hawaiian region since mid-1975, enable the trade winds to be monitored (Sadler and Kilonsky, 1981). Monthly trade wind anomalies were determined for the Hawaiian area (17.5–25°N and 150–160°W) and compared to the background $CO_2$ anomalies (Fig. 6). There is no relationship between the two curves ($r = -0.03$).

As with the upper troposphere, low-level flow varies most in winter. Figs. 7 and 8 show December extremes. In December 1978 (Fig. 7) with the subtropical ridge near 35°N, the very strong northeasterly trade winds over the Hawaiian Islands originated from north of 40°N. During December 1980 (Fig. 8) the subtropical ridge lay across the island chain. While the northern islands of Kauai and Oahu experienced mean westerly flow Hawaii had light east-southeasterlies. Air had reached Mauna Loa from the east and from latitudes south of 20°N. Associated with the contrasting mean circulations were of course contrasting daily synoptic regimes, yet the $CO_2$ anomaly was identical (Fig. 2) for the two months.

In the previous sections extreme monthly flow patterns were compared to the $CO_2$ anomaly. Here we evaluate the longest period of 3-day running mean $CO_2$ anomalies greater than 1.25 ppm in terms of the surface synoptic pattern. Negative anomalies exceeded −1.25 ppm from 17–28 February 1977 with little variation (Fig. 3). The large-scale surface synoptic pattern, however, changed drastically. A near-record cyclonic storm with central pressure below 960 mb covered the eastern North Pacific at the start of the period and westerlies reached the Hawaiian Islands (Fig. 9). By the end of the period the cyclonic circulation was replaced by a large anticyclone with central pressure above 1040 mb (Fig. 10).

### *c. Seasonality of significant $CO_2$ variations*

The variability of the atmospheric circulation in Hawaii is seasonally dependent. In summer (May–September) the subtropical high in the eastern Pacific is very persistent and positioned near 40°N and steady northeast trades cover the islands to a depth greater than the height of MLO. In winter (November–March) the circulation is much more variable. The mean subtropical ridge lies near 30°N and deep troughs in the midlatitude westerlies penetrate south of the islands with frontal passages and occasional deep cutoff lows (Kona storms) and the upwind trajectories from Mauna Loa alternate between a westerly and easterly direction. If significant $CO_2$ variations are due to variations in the large-scale synoptic flow, they should be greatest in winter. During this seven-year record there were 31 3-day running mean periods of $CO_2$ variations greater than 1.25 ppm ranging from one to nine days duration. Nine of the periods totaling 25 days were in winter while 22 to-

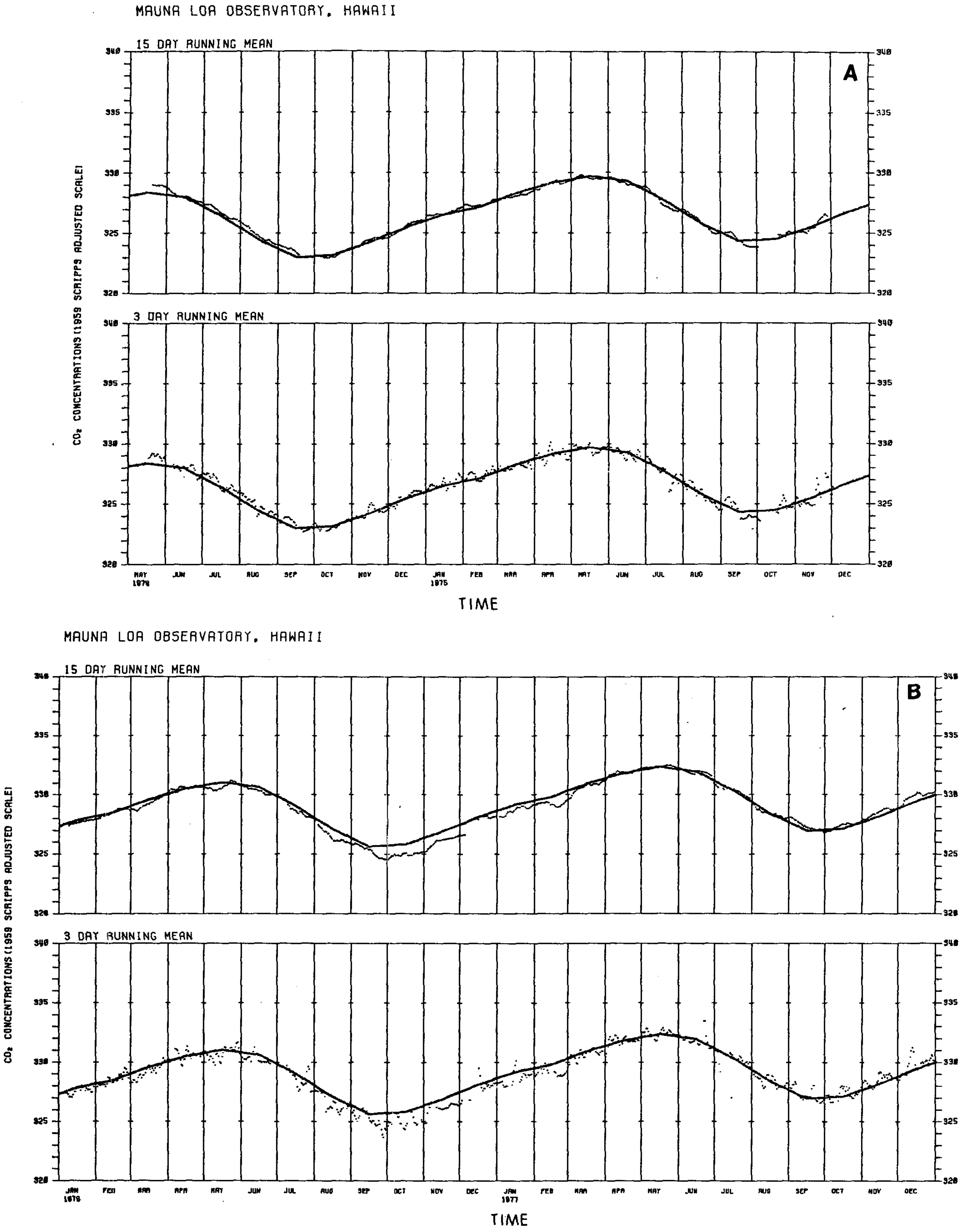

FIG. 3. Fifteen-day and three-day running means of $CO_2$ at MLO. Full lines show seven-year monthly means with trend incorporated.

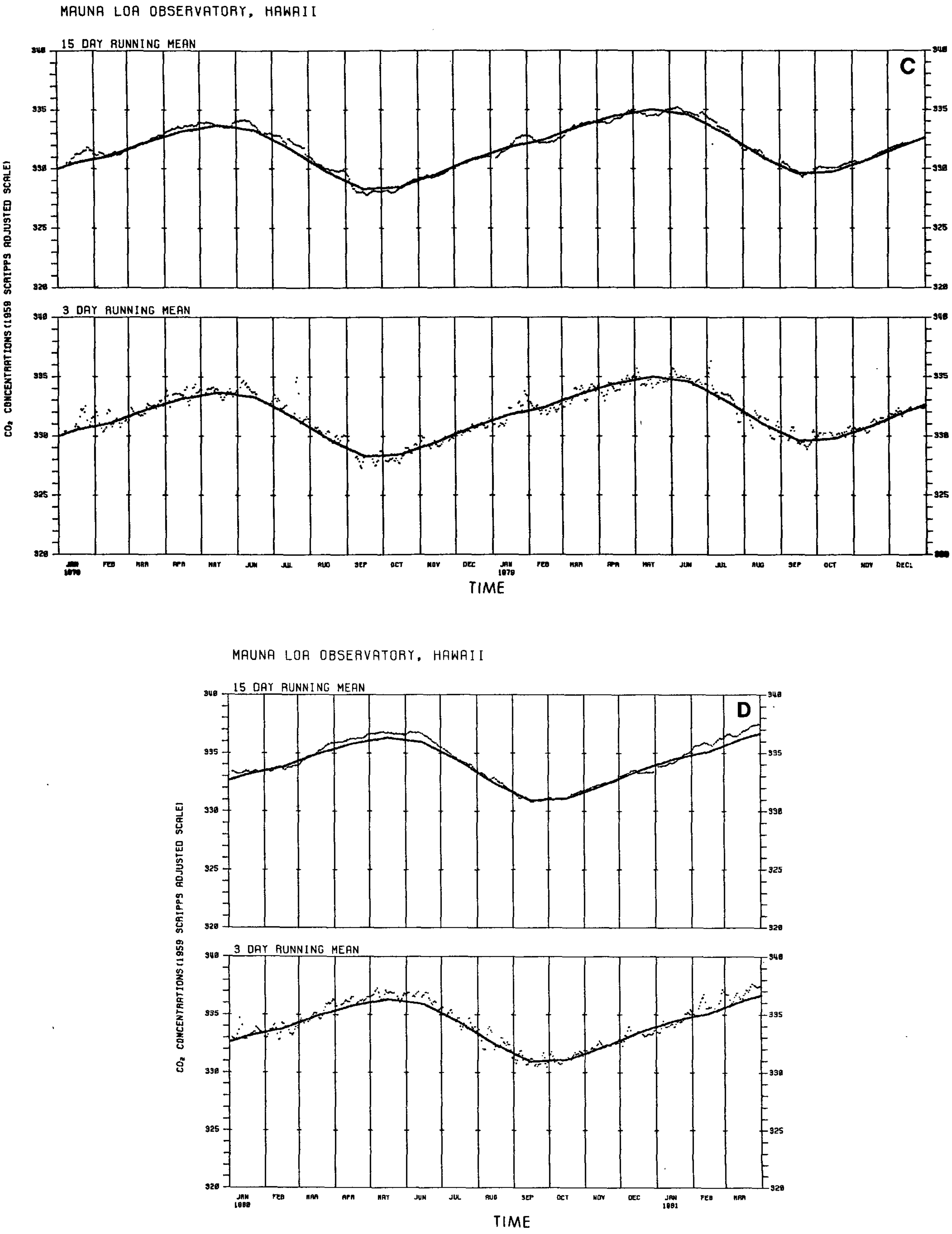

FIG. 3. (*Continued*)

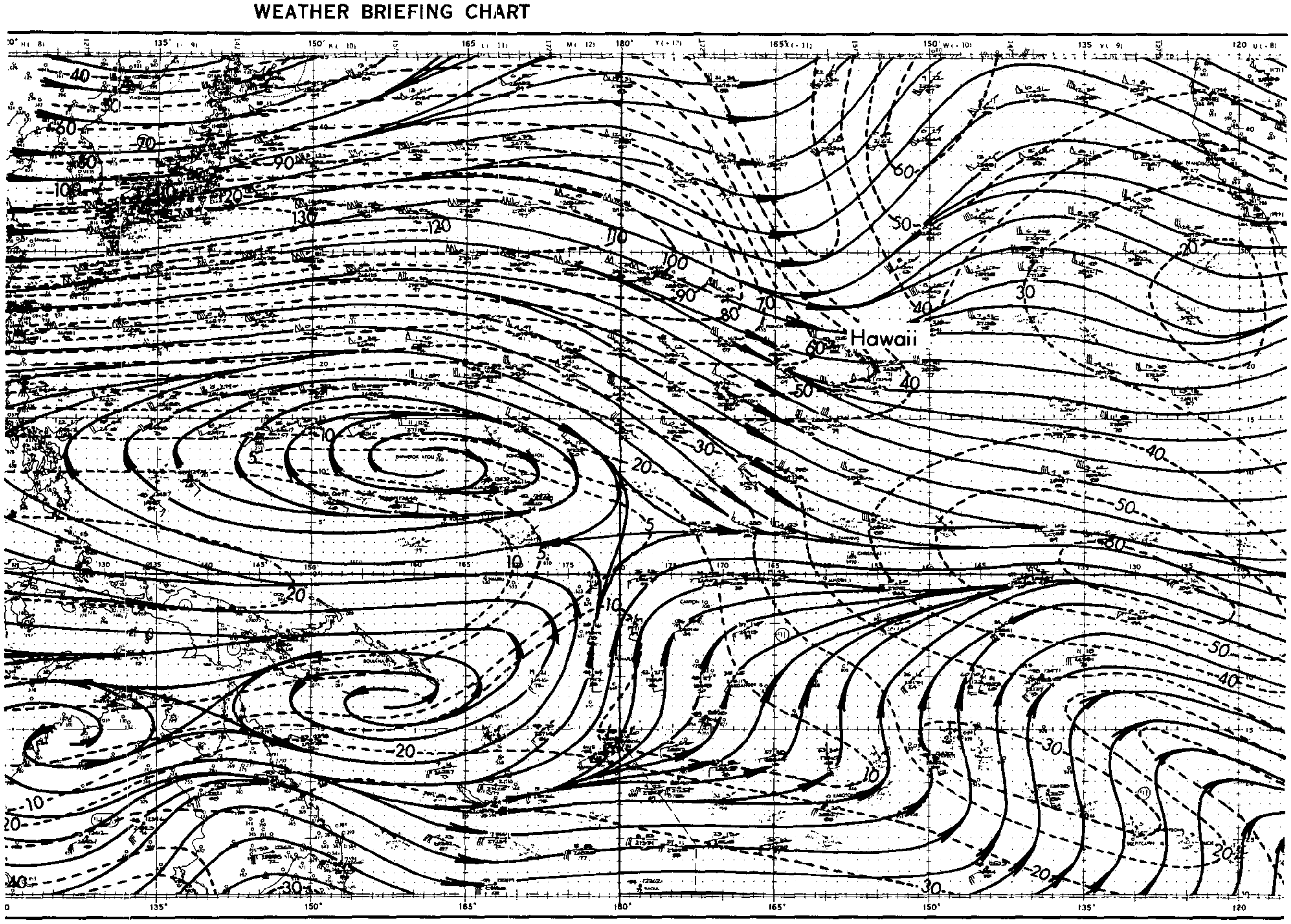

FIG. 4. The January 1971 mean flow (kt) at 35 000 ft.

taling 57 days were in summer. The greater variations of $CO_2$ during the summer when the wind steadiness is greatest and the air trajectories are least variable again confirm the conclusions of Pearman (1979) and Miller (1979) that the $CO_2$ variations at MLO are not dependent on wind direction at MLO or on trajectories of the air reaching MLO, respectively.

TABLE 1. Monthly rainfall.

| | January 1971 | | January 1973 | |
|---|---|---|---|---|
| | Rainfall (mm) | Departure from mean (mm) | Rainfall (mm) | Departure from mean (mm) |
| Hilo, Hawaii | 342 | +40 | 88 | −213 |
| Kahului, Maui | 347 | +267 | 54 | −25 |
| Honolulu, Oahu | 157 | +62 | 17 | −78 |
| Lihue, Kauai | 302 | +163 | 26 | −114 |

## 4. Carbon dioxide and the Southern Oscillation

Several recent studies have related $CO_2$ anomalies to changes in sea surface temperature or to the Southern Oscillation or El Niño (Bacastow, 1976; Newell and Weare, 1977; Newell *et al.*, 1978; Rust *et al.*, 1979; Bacastow *et al.*, 1980). From these and the recent observations during the 1976 moderate El Niño, it is not yet clear what, if any, is the relationship; nor have the cause-effect linkages been established. Bacastow (1976) correlated the Southern Oscillation Index (SOI), defined as the 12-month running average of the pressure difference between Easter Island and Darwin, with $CO_2$ anomalies at the South Pole and MLO for the period 1958–74. The correlation was best at the South Pole but only 0.40 and at the 83% confidence level. The correlation with MLO was 0.14. The $CO_2$ variations led the SOI by three and six months at the South Pole and MLO, respectively. Bacastow and Keeling (1981) found a

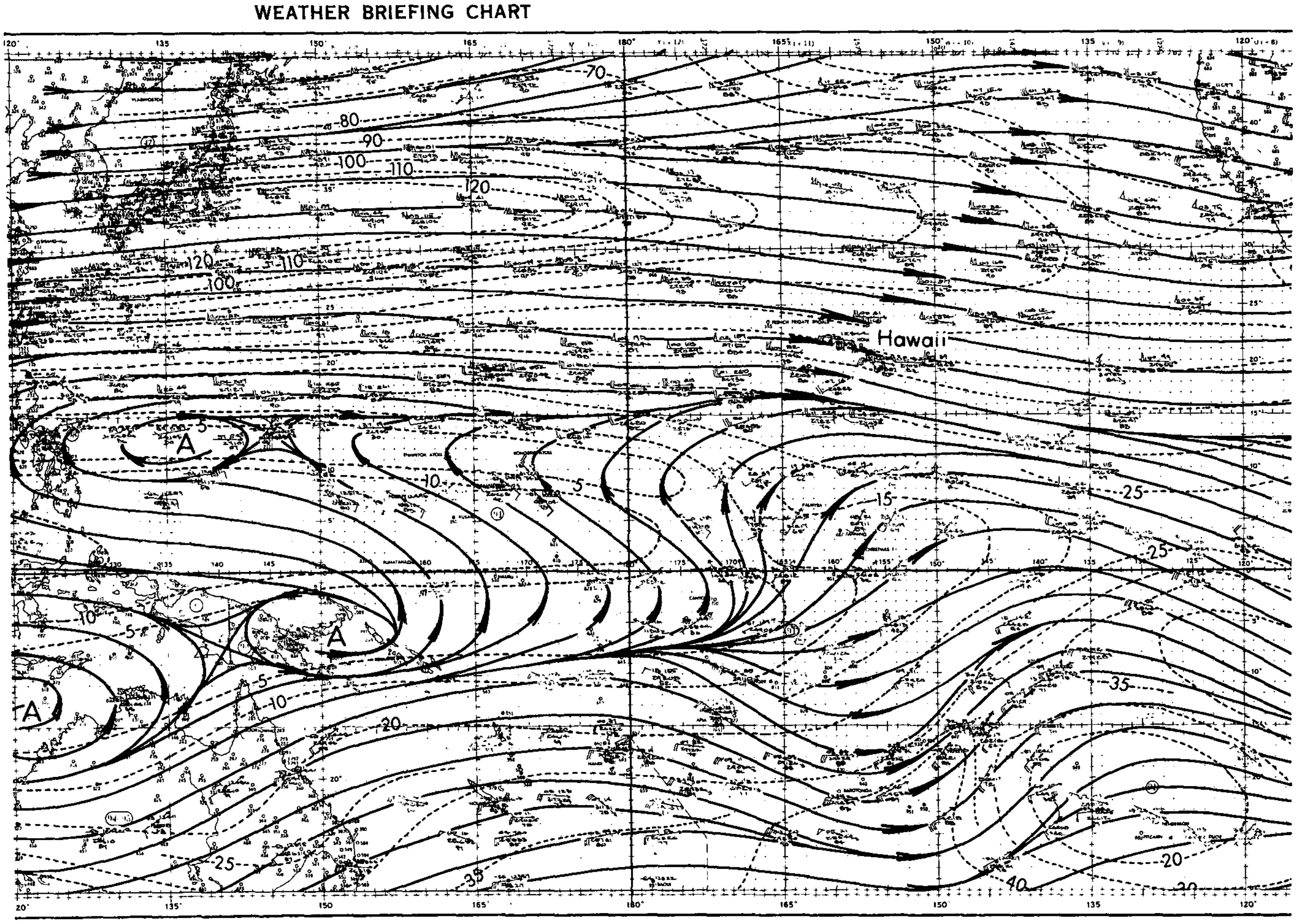

FIG. 5. The January 1973 mean flow (kt) at 35 000 ft.

much better relationship with the rate of change of $CO_2$ anomalies. The correlation was −0.73 and −0.60 at the South Pole and MLO, respectively, and was near the 95% confidence level at the South Pole. The SOI led the $CO_2$ rates of change by six months at the South Pole and by three months at Mauna Loa. Bacastow (1976) postulated a $CO_2$ sink in the Southern Hemisphere westerlies whereby during a high SOI the $CO_2$ uptake by the ocean due to increased westerlies would be greater than the atmospheric $CO_2$ increase due to the greater $CO_2$-enriched cold water upwelling along the equator and the west coasts. Increased midlatitude westerlies during a high SOI period have not been confirmed and in fact there are findings to the contrary (Chiu and Lo, 1979). Newell and Weare (1977), using the first

TABLE 2. Upper winds at Hilo.

| Level (mb) | January 1971 | | | January 1973 | | |
|---|---|---|---|---|---|---|
| | Direction | Speed (m $s^{-1}$) | Steadiness (%) | Direction | Speed (m $s^{-1}$) | Steadiness (%) |
| 850 | 203 | 4 | 59 | 99 | 2 | 43 |
| 700 | 231 | 8 | 81 | 74 | 1 | 20 |
| 500 | 246 | 11 | 80 | 65 | 3 | 42 |
| 300 | 265 | 22 | 75 | 278 | 19 | 83 |
| 200 | 280 | 27 | 79 | 281 | 23 | 83 |

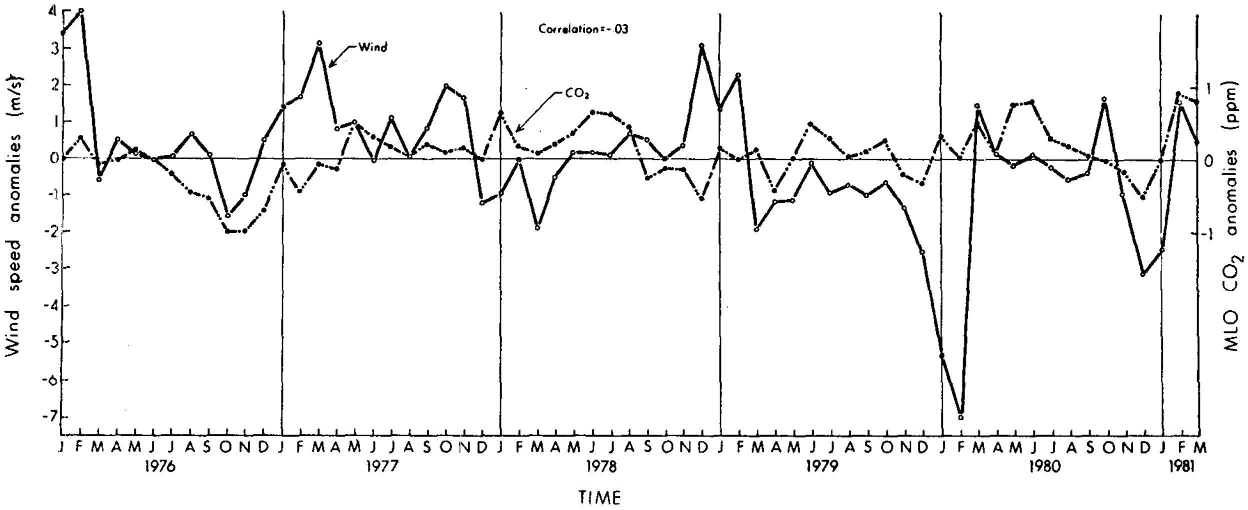

FIG. 6. Monthly anomalies: solid line—trade wind speed in Hawaii from sawins; dashed line—carbon dioxide at MLO.

empirical orthogonal function of Pacific sea-surface temperature (SST) to describe the SOI, also found a high correlation between the Bacastow $CO_2$ change data at the South Pole and MLO and Pacific SST. The $CO_2$ lagged the SST by one to two months at MLO and by about five months at the South Pole. Their explanation for the increasing and higher $CO_2$ during warm water periods contradicts Bacastow's. They suggest that when the equatorial Pacific is warm, upwelling is weak, nutrients are low, $CO_2$ in

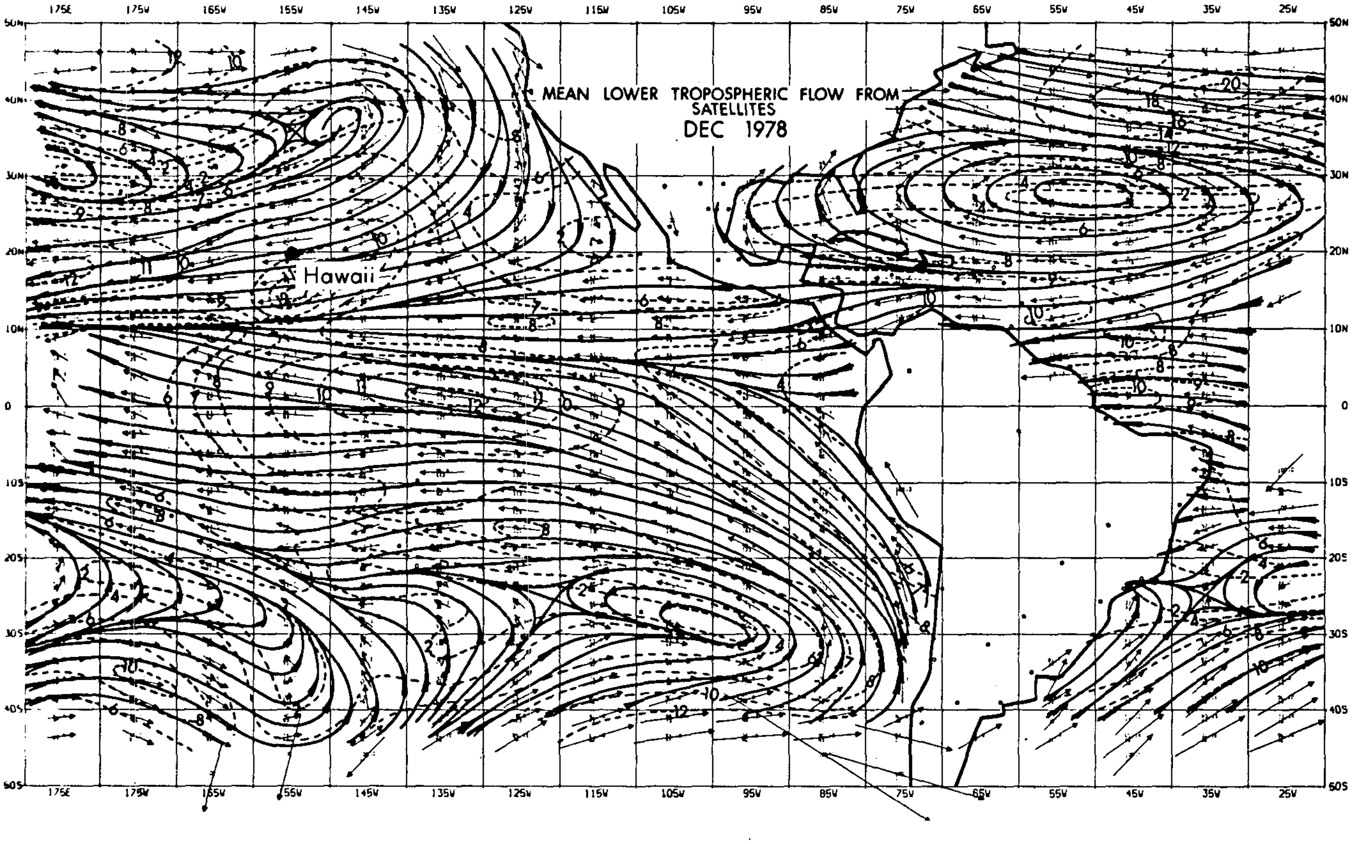

FIG. 7. The December 1978 mean flow (m $s^{-1}$) at 1000 m from sawins.

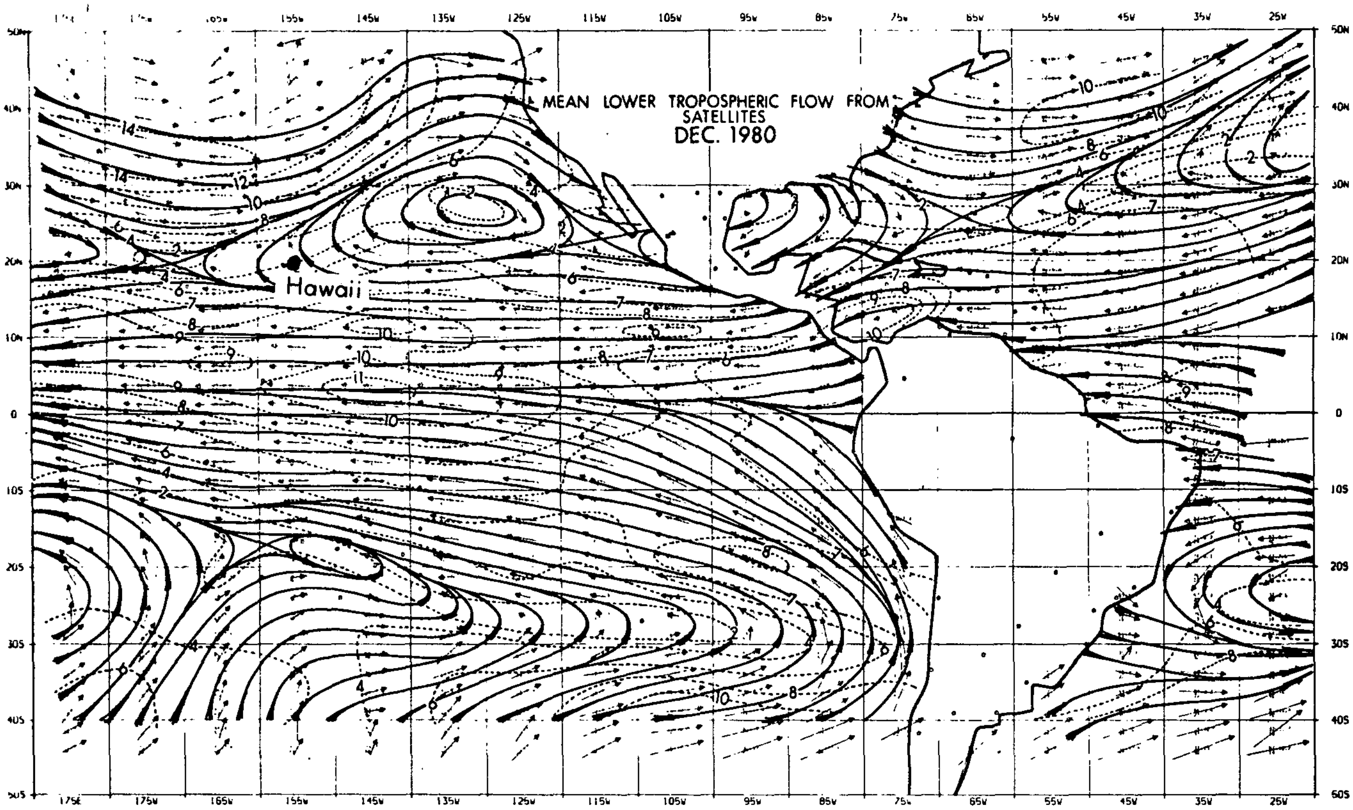

FIG. 8. The December 1980 mean flow (m $s^{-1}$) at 1000 m from sawins.

the water is high because photosynthesis is less than average and there is a flux from sea to air, leading to enhanced atmospheric concentration. The opposite is proposed for the cold water periods.

The largest and most persistent anomalies in our data base were observed during the moderate El Niño of 1976–77; however, they were negative (Fig. 2) while the anomalies during previous El Niños were all positive.

## 5. Small-scale influences

### a. Cane fires

On the island of Hawaii sugar is grown extensively along the Hamakua Coast, northeast of MLO. During the dry season, fields of mature sugar cane are burned before being harvested. Since burning is confined to daytime, anabatic winds and a "leaky" trade wind inversion could combine to bring the $CO_2$-enriched air to MLO.

Unfortunately, the sugar plantations keep rather meager records of burning—the beginning and ending dates of each burning season and whether a month within the season was "good" or "poor" for burning. On this basis we found no evidence for a cane burning effect on $CO_2$ levels at MLO.

We sought additional evidence from the character of the diurnal variations of $CO_2$ level during burning and nonburning months. If appreciable burn-generated $CO_2$ reaches MLO during the afternoon, one would expect that the normal afternoon $CO_2$ minimum would be less pronounced in burn months than in nonburn months. This proved not to be so, with the median diurnal ranges differing by less than 0.03 ppm.

### b. Diurnal variations

Hourly average $CO_2$ concentrations (Fig. 11) and hourly average standard deviations ($\sigma$) of $CO_2$ concentrations (Fig. 12) have been computed for MLO for both summer (May–September) and winter (November–March) for the seven-year period of this study.

At night a katabatic wind effectively seals off MLO from the vegetated lower slopes of the mountain and from local anthropogenic sources (Mendonca, 1969; Mendonca and Iwaoka, 1969). In view of the findings of the earlier sections and of Miller and Chin (1978), the nocturnal maximum probably combines a global background with fluctuating local source—outgassing from the summit caldera of Mauna Loa. Over the period of averaging, the latter

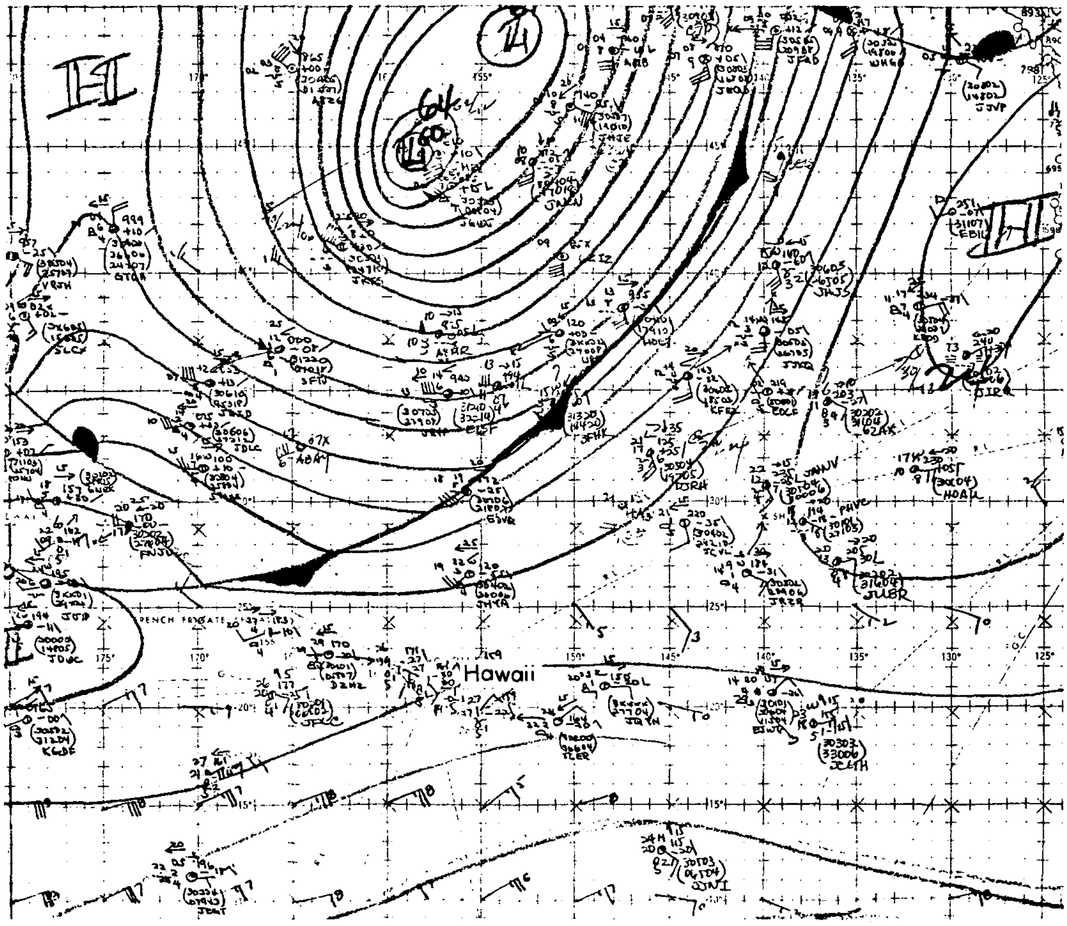

FIG. 9. Surface pressure analysis at 0000 GMT on 18 February 1977. (From National Weather Service, Honolulu Airport.)

can be assumed to exert a random effect. Consequently, the negligible nocturnal difference between the two seasons might well reflect a correspondingly negligible true global difference.

During the day the heated mountain generates anabatic winds which usually breach the inversion along the mountainside and bring $CO_2$-depleted air from across the forested lower slopes. The resulting mid-afternoon minimum is less marked in winter, probably because the vegetation is less luxuriant and the anabatic winds about a third less common than in summer, when the mountain heats more.

Both seasons show a small secondary maximum for the hour ending at ~1000 LT. Since staff arrive on duty about this period, an anthropogenic source appeared likely. At Bernard Mendonca's suggestion the hourly readings for 1980 were stratified into weekdays and Sundays (day off). Weekdays had the peak; Sundays did not.

Fig. 12 reveals more details of diurnal variations, particularly during the transitions between katabatic and anabatic winds.

The nighttime katabatic winds are much more persistent than the daytime anabatic winds, blowing for more than 90% of the time (Mendonca, 1969). MLO is 7 km distant from the summit caldera. As downslope flow intensifies through the night, caldera air undergoes less and less diffusion before reaching MLO and $CO_2$ concentration increases to a maximum around dawn. The in-phase increase in $\sigma$ can be attributed to the same process with the difference in $CO_2$ concentration between outgassing and quiet periods increasing as the night advances.

In both seasons, the daytime anabatic winds occur during a secondary maximum in $\sigma$, reflecting the often intermittent character of upslope flow. The larger values for summer may arise from the larger concentration difference between mountain and forest.

With onset of the evening and morning transitions the slope winds disappear. Since $CO_2$ measurements are now affected neither by upslope bursts of $CO_2$-depleted air nor by downslope bursts of $CO_2$-enriched air, $\sigma$ diminishes to a minimum. The early morning

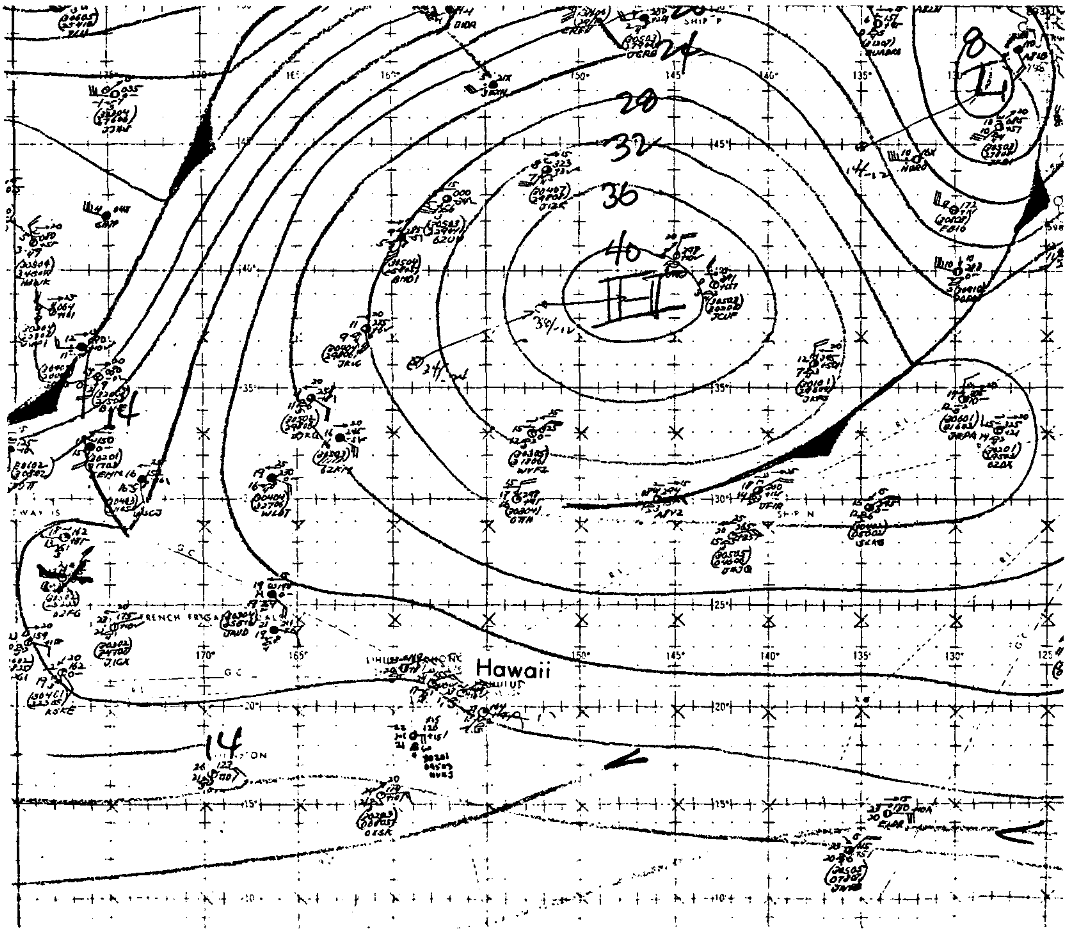

FIG. 10. Surface pressure analysis at 0600 GMT on 28 February 1977. (From National Weather Service, Honolulu Airport.)

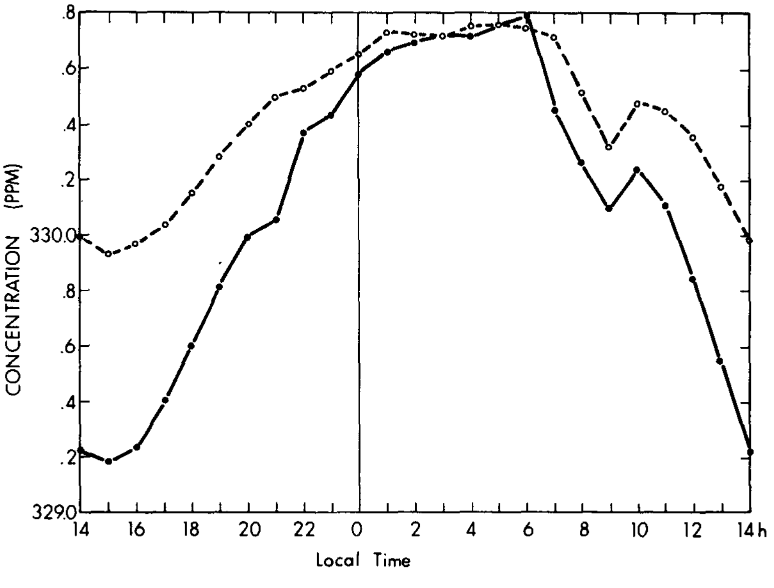

FIG. 11. Diurnal variation of $CO_2$ concentrations at MLO for summer (full line) and winter (dashed line).

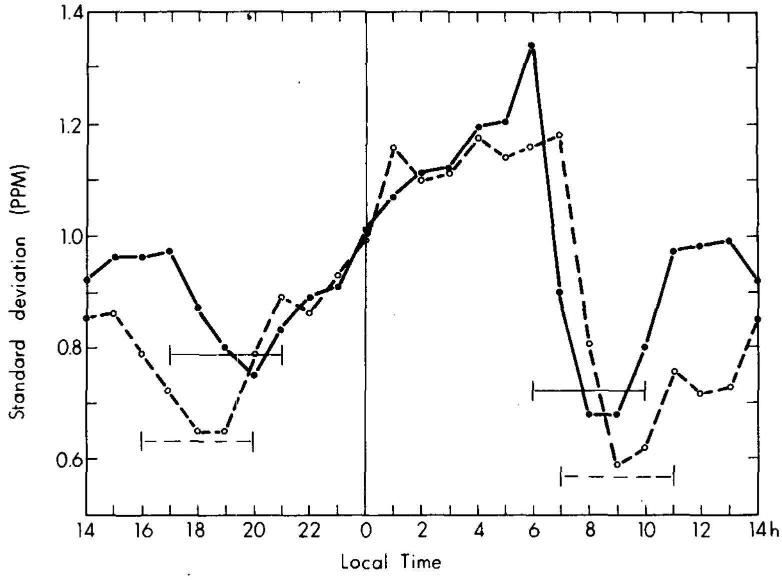

FIG. 12. Diurnal variation of the standard deviation ($\sigma$) of $CO_2$ concentration at MLO for summer (full line) and winter (dashed line). Transition periods between downslope and upslope winds are denoted by corresponding full and dashed lines (after Mendonca, 1969).

drop is particularly precipitous. In the stably stratified downslope flow $CO_2$ injections from the summit caldera are relatively little diffused before reaching MLO and so cessation of the downslope flow sharply reduces $\sigma$.

## 6. Conclusions and discussion

In agreement with Miller (1979) we could find no evidence that $CO_2$ variations at MLO are related to large-scale variations in the atmospheric circulation. The fears of Newell *et al.* (1978) that "Trajectory changes induced by changes in the standing wave pattern may influence the values at Mauna Loa and mask real long-term changes" are unfounded. The fact that the South Pole $CO_2$ anomalies are more highly correlated with the SOI is insufficient justification for classifying the site as superior but only raises the additional question of why is the relationship better at the South Pole? At present there are opposing arguments concerning any physical connection between $CO_2$ and SOI variations and inconsistencies in the sign and phase of the relationships.

As with large-scale influences, $CO_2$ generated in local cane fires diffuses so rapidly into the large atmospheric volume that it exerts no detectable effect on average MLO measurements. A diurnal variation of between 1–2 ppm stems from slope winds and a combination of forest depletion during the day and enhancement by summit outgassing at night. Local distortions are least just after dusk and just after dawn, when slope winds are absent.

We conclude from our study that MLO is an excellent site for monitoring atmospheric $CO_2$. Air reaching Hawaii has been so thoroughly mixed that it retains no evidence of specific sources or sinks. In this respect, MLO rivals the South Pole station. The local biospheric sink and volcanic sources scarcely affect site quality for their distortions tend to remain much the same from year to year. Intense outgassing episodes can be readily eliminated from the record.

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