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Low nocturnal atmospheric dispersion capacity of the Venezuelan savannah

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ABSTRACT

Daily measurements of the variation of CH_4 and O_3 concentration in the Venezuelan savannah have been made over the course of a year. Additionally, temperature profiles with altitude were measured with a tethered balloon for 60 days. The temperature profiles show that during the night, the lower portion of the atmosphere becomes very stable. From the CH_4 and O_3 measurements, it is possible to conclude that a period of low dispersion capacity in the lower atmosphere occurs every day, and that no significant differences exist between the dry and wet seasons. The possible air quality implications are discussed.

1. Introduction

There have been few studies of air pollution in the tropics (Sanhueza et al., 1982); thus, very little is known about background levels of atmospheric constituents and the meteorological characteristics of the lower atmosphere. Since the large amount of experience acquired in developed countries located in the middle latitudes can not be extrapolated a priori to tropical regions, studies characterizing the atmosphere in various regions of the tropics are an important prerequisite for the development of an effective protection policy, particularly of the natural areas that are beginning to undergo industrialization.

Venezuela is beginning to exploit and develop the Faja Petrolifera del Orinoco (F.P.O.), one of the largest accumulations of heavy crude oil in the world. The oil deposits cover an area beneath approximately 42,000 km^2 of the Venezuelan tropical savannah. This paper presents some of the results obtained in the air quality and meteorological base-line characterization of the F.P.O. which demonstrate the low capacity of the atmosphere in the tropical savannah to disperse contaminants during the night.

2. Field measurements

Details of the design, installation and operation of our regional air quality network in the eastern portion of the F.P.O. have been given elsewhere (Octavio et al., 1982). Only pertinent aspects will be presented in this paper.

2.1. CH_4 and O_3 measurements

From March 1982 through March 1983, CH_4 and O_3 concentrations were measured continuously at three (Campo Morichal, Soledad and Los Pozos) and four (the same and Uracoa) different sites, respectively (see Fig. 1).

(i) Campo Morichal, located inside the traditional area of light crude oil extraction in the study region.

(ii) Soledad, approximately 85 km downwind of Campo Morichal and not influenced by local sources of pollution.

(iii) Los Pozos, a site not influenced by nearby hydrocarbon emissions.

(iv) Uracoa, the most easterly station, located closest to the Atlantic Ocean.

From April to August 1984, additional methane measurements were made in San Tomé, a

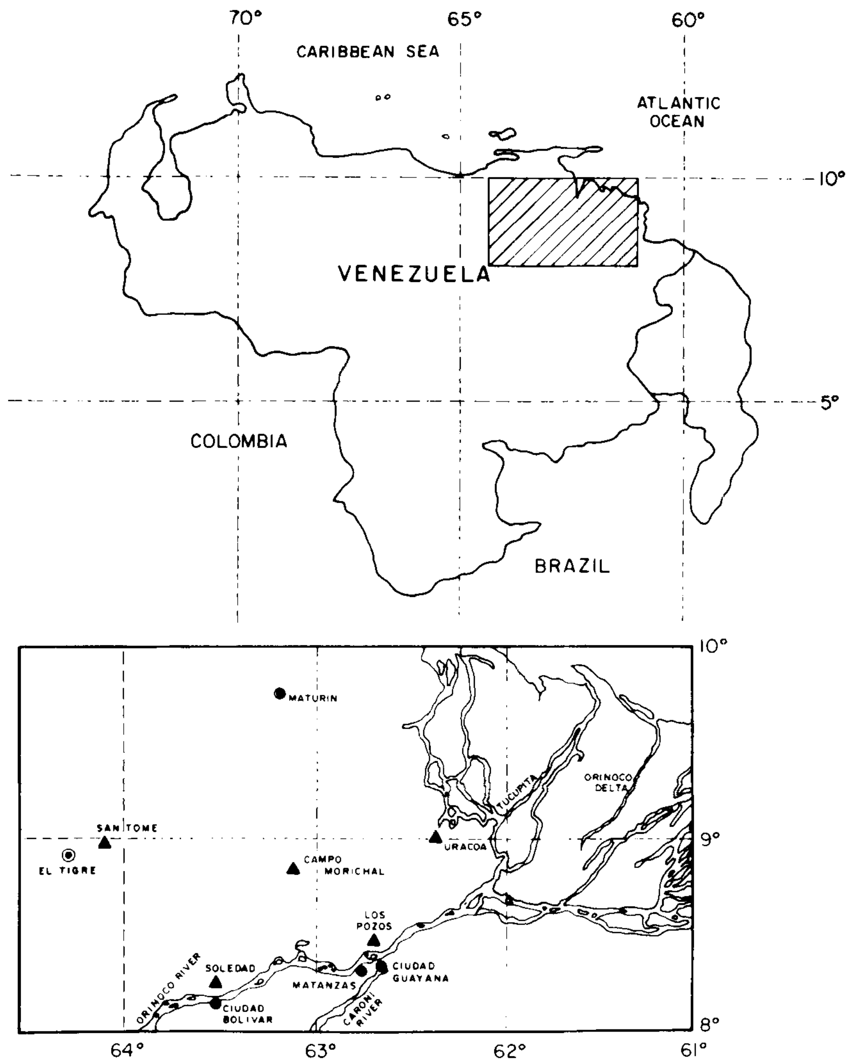

Fig. 1. Location of the study region, measurement sites (▲) and principal cities (●).

station which is located downwind of several oil fields.

All CH_4 measurements were made with flame ionization hydrocarbon analyzers (Bendix Model 8202) and ozone measurements with chemiluminescence analyzers (Meloy model OA350-2R). All analyzers were located in temperature-controlled shelters. The initial calibration of the instruments was set by manual multi-point calibration, after which the instruments were subjected to a daily microcomputer-controlled automatic calibration check (RADIAN Corp. Dart 11-Rad 11 system) of the zero and span. Adjustments and multipoint calibrations were performed as necessary. Hourly averages, calculated from 5 min averages, were not considered valid if less than 20 min worth of data for a given hour were reported.

Fig. 2 shows the average diurnal behaviour of CH_4 (based on the hourly averages) for several cases. For Campo Morichal, where the nocturnal increase of CH_4 is larger, two monthly average diurnal variation plots are given, one for the dry season (February) and the other for the rainy season (July). The results obtained in the other

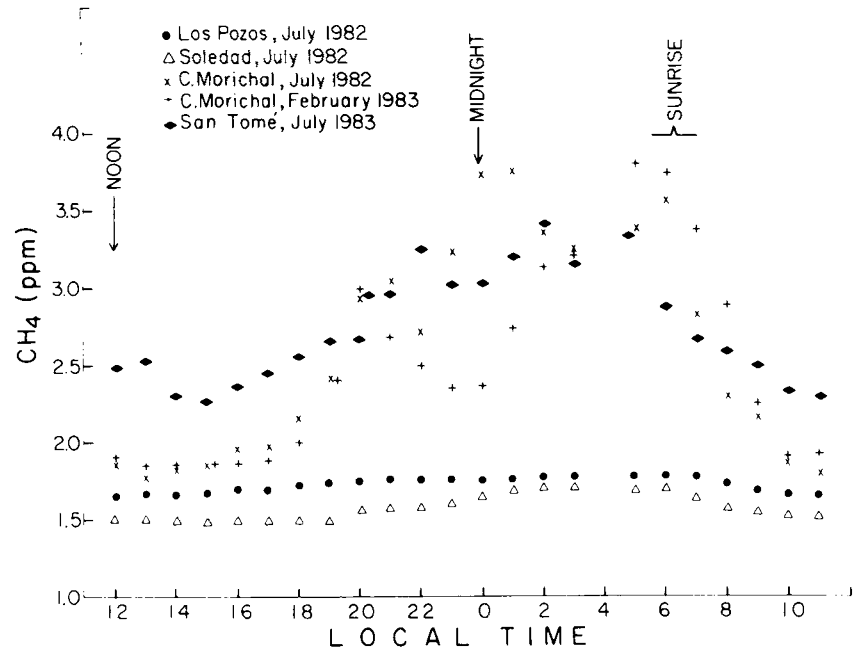

Fig. 2. Comparison of the monthly averages of daily CH_4 concentration variations in the measurement sites for typical conditions.

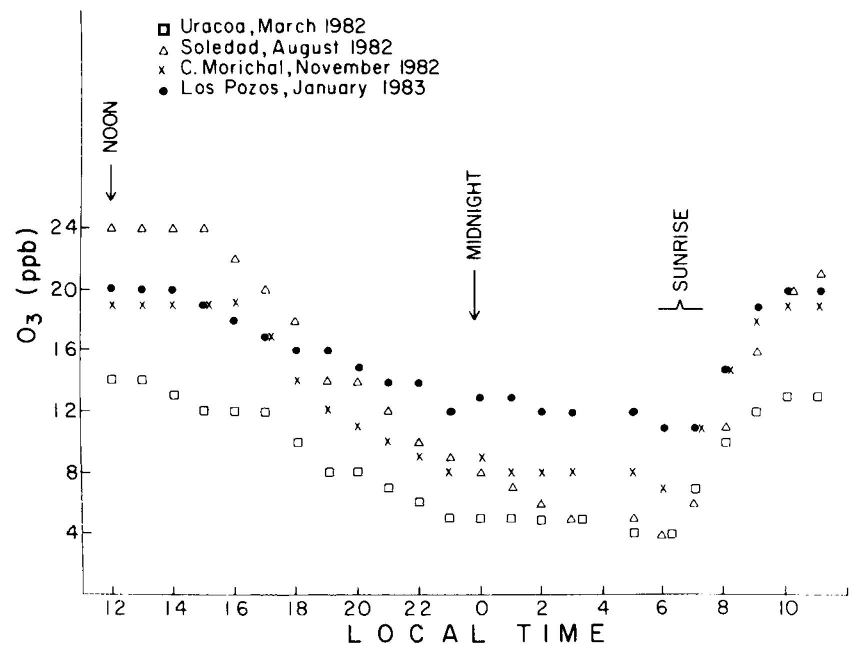

Fig. 3. Comparison of the monthly averages of daily O_3 concentration variations in the measurement sites for typical conditions.

months of the study are similar and have been given in detail in the original report (Arrocha et al., 1983).

Fig. 3 shows the diurnal variation of the average ozone concentration at the four stations in different months. January and March are typical dry season months; August and November belong to the rainy season. Similar variations were observed throughout the year in all the stations, and the complete set of data has been given elsewhere (Arrocha et al., 1983).

2.2. Temperature profiles

Meteorological conditions as a function of height were determined in Campo Morichal during 1981 (154 flights on 60 different days) using an Atmospheric Instrumentation Research, Inc. model TS-1A Tethersonde. The majority of the measurements were taken at 08.00 or 14.00 local time; however, a significant number of balloon flights were made between 05.00 and 07.00 and between 19.00 and 21.00 with a few additional flights in mid-morning and in mid-afternoon. Details of the experimental technique and other aspects of the data (e.g., wind speed and direction profiles) have been given elsewhere (Barnett et al., 1981).

Fig. 4 shows an example of the temperature profiles reported by the Tethersonde equipment during various flights carried out in August 1981. Temperature gradients, and their frequency of occurrence during the different hours of the day, for various layers of the lower atmosphere, are summarized in Table 1. Flights made in the rain have been excluded from the table. In almost all of the flights made in the rain, or shortly thereafter, the atmosphere was markedly more stable compared to the average of values observed at all hours of the day when it was not raining. In these flights, temperature inversions at low altitudes (up to approximately 30 m) were notable during the hours in which a large inestability is normally observed (14.00–15.00).

2.3. Surface wind speed

Surface meteorological conditions (e.g., temperature, wind speed and direction) were observed at 10 m with Met-One equipment simultaneously with the ozone and methane measurements in each of the five stations. As an example, Fig. 5 shows the average daily wind

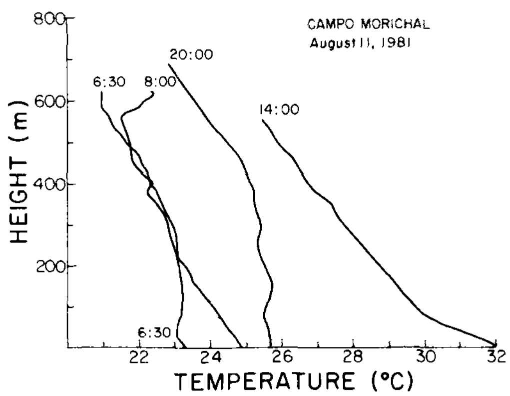

Fig. 4. Typical temperature profiles over the course of a day in Campo Morichal.

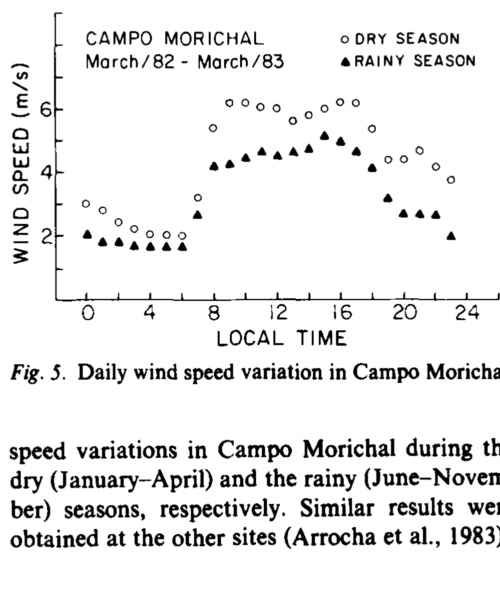

Fig. 5. Daily wind speed variation in Campo Morichal.

speed variations in Campo Morichal during the dry (January–April) and the rainy (June–November) seasons, respectively. Similar results were obtained at the other sites (Arrocha et al., 1983).

3. Discussion

3.1. Low nocturnal atmospheric dispersion

The temperature profiles obtained between 19.00 and 21.00 (see Table 1) show that by that hour, a temperature inversion has been established in the lowest layers of the atmosphere.

Measurements were not made later in the night, but the results obtained in the early morning hours (05.00–06.00) indicate that the inversion persists throughout the night. The inversion breaks up between 06.00 and 07.00, and during the rest of the day there exists a sufficiently

Table 1. *Temperature gradient as a function of height in Campo Morichal*

Local time	0 to 40 m	30 to 180 m	90 to 180 m	180 to 250 m	180 to 360 m
05.00 to 06.00	D[a] (1/4)[b] E (3/4)	F (4/4)	E (4/4)	D (1/4) E (3/4)	F (2/2)
06.00 to 07.00	D (5/10) E (5/10)	D (1/10) E (9/10)	D (2/10) E (8/10)	D (1/9) E (8/9)	E (4/4)
07.00 to 09.00	A (16/52) B (9/52) C (6/52) D (20/52) E (1/52)	D (48/52) E (4/52)	A (1/52) D (43/52) E (8/52)	D (30/52) E (22/52)	D (23/40) E (17/40)
09.00 to 11.00	A (12/18) B (2/18) D (3/18) E (1/18)	A (1/18) B (1/18) C (3/18) D (13/18)	D (18/18)	D (15/17) E (2/17)	D (15/15)
13.00 to 15.00	A (26/38) B (3/38) D (6/38) E (3/38)	A (3/46) C (9/46) D (31/46) E (3/46)	A (1/46) B (1/46) C (5/46) D (37/46) E (2/46)	A (1/45) C (3/45) D (33/45) E (8/45)	D (33/35) E (2/35)
15.00 to 17.00	A (1/2) D (1/2)	D (2/2)	D (2/2)	D (2/2)	D (1/1)
17.00 to 19.00	D (2/2)	D (1/2) E (1/2)	D (1/2) E (1/2)	E (1/1)	
19.00 to 21.00	D (2/7) E (3/7) F (2/7)	D (1/7) E (5/7) F (1/7)	D (3/7) E (4/7)	D (3/7) E (4/7)	D (2/4) E (2/4)

a) A < −1.9; B −1.9 to −1.7; C −1.7 to −1.5; D −1.5 to −0.5; E −0.5 to 1.5; F 1.5 to 4.0 in units of °C/100 m.

b) Fractions in parenthesis indicate number of occurrences of given class divided by number of flights in the interval.

negative temperature gradient that the atmosphere is unstable, giving a high dispersion capacity.

The temperature profiles were interpreted to estimate mixing height (Goldman, 1980). During hours of high incident solar radiation (09.00–17.00), the mixing layer height was almost always found to be higher than the range of the tethered balloon (850 m). During the night, preliminary estimates based on wind velocity profiles (Clarke, 1970; Yu, 1978) give a value of only 150 ± 50 m for the nocturnal mixing height. During the morning transition period (07.00–9.00), the data show that for around 50% of the time, the mixing depth was higher than the altitude reached in the sounding, showing a quite fast change between the nocturnal and diurnal atmospheric conditions. Only two flights were carried out near sunset (17.00–19.00); the vertical temperature profiles (Golman, 1980) show that the mixing heights were below 250 m. This provides preliminary evidence that the mixing height decreases very rapidly as the sun sets.

Fig. 5 shows that the surface wind speed is much lower during the night than during the day. The data also demonstrates that the wind speed in the dry season is higher than in the wet season; this is due to the seasonal migration of the equatorial trough (Riehl, 1979). The nightly decrease in wind speed diminishes even more the nocturnal atmospheric dispersion capacity of the Venezuelan savannah, already lower due to the nocturnal atmospheric stability.

The observed average daily CH_4 variations (see Fig. 2), particularly those for Campo Morichal and San Tomé, where natural gas emission occurs upwind of the station, confirm that during the night, dispersion is low and contaminants accumulate in the lower portion of the atmosphere. The small increase observed in Los Pozos and Soledad might well be produced by methane emissions from the savannah soil.

In contrast to the temperature profile measurements, which were only made in selected months, the CH_4 measurements were made almost every day over the course of 13 months. The daily methane variation shows that the nocturnal temperature inversion occurs consistently throughout the year. In spite of the fact that the hydrocarbon emissions in Campo Morichal are probably somewhat higher during the day due to increased evaporation from storage tanks and open storage pools (Sanhueza et al., 1980), the CH_4 concentration levels observed during the hours of high incident radiation (10.00–17.00) are very close to those measured in the other two monitoring stations (Los Pozos and Soledad) which are not directly affected by anthropogenic emissions. This demonstrates that, in contrast with what happens in the night, during the day, the vertical dispersion of contaminants is extremely efficient.

A detailed discussion of the methane-related atmospheric chemistry of the region, based on a statistical analysis of the available data, will be presented separately.

A similar conclusion, about the daily occurrence of a period of low nocturnal atmospheric dispersion capacity in the savannah region can be obtained from the ozone data. The nightly ozone concentration decrease shown in Fig. 2 can be attributed to ground-level destruction and/or reaction with gases emitted by plants of the ozone trapped in the nocturnal boundary layer. The increase after sunrise, when the inversion breaks up, is due to the entrance and/or mixing down of ozone-rich air from the low troposphere not affected by the nocturnal inversion. Similar diurnal atmospheric boundary layer O_3 concentration variations have been reported by other authors (Galbally, 1971; Fabian and Pruchniewicz, 1977; Singh et al., 1978; Oltmans, 1981; Kelly et al., 1984).

A detailed discussion of the boundary-layer ozone levels in the Venezuelan savannah is presented by Sanhueza et al. (1985). As with the CH_4 measurements, in this paper, the daily O_3 variations are interpreted, in conjunction with the meteorological measurements.

It is worth emphasizing that all the available CH_4 and O_3 measurements, as well as the meteorological observations, show no significant differences between the nocturnal atmospheric stability in the rainy and the dry seasons.

3.2. *Regional air quality implications*

It is usually considered improbable that the air in tropical areas can become polluted to harmful levels (Stern et al., 1973; Florida Department of Pollution Control, 1972; Ng'ang'a, 1980). For instance, the 1972 Florida State Air Implementation Plan States: "Because of the general pattern of terrain and the trade wind circulation, meteorological conditions that aggravate air pollution do not often occur at any place in Florida". Stern et al. (1973) holds that, in general, the air pollution potential (inability of atmosphere to disperse pollutants) of the tropical region is low. However, in this paper, we show that in the Venezuelan savannah, a nightly period of low dispersion capacity in the lower atmosphere occurs almost every day. Another tropical meteorological characteristic, the very constant direction of the trade winds, also increases the potential for air pollution problems (Sanhueza et al., 1982).

The Venezuelan savannah region under study is presently very little affected by human activity. There are obvious exceptions such as the petroleum activities in several oil fields, but in general it can be said that, to a large degree, the area remains in its natural state (Sanhueza et al., 1980). For example, the atmospheric concentrations of the typical anthropogenic elements Pb, Zn, Ni, Cd and V are much lower than the reported values for North American and European rural areas, and are quite similar to the levels observed in semi-remote sites of the world (Sanhueza et al., 1986). However, possible future emissions from the production of heavy crudes by steam injection, crude oil upgrading plants, refineries, power plants, increased automotive traffic and increased boat traffic on the Orinoco River could produce drastic changes in the situation if proper precautionary measures are not taken.

Since the majority of the industrial activities contemplated in the development of the F.P.O. will emit atmospheric contaminants continuously, the nocturnal atmospheric stability could result in high night-time levels of some contaminants (e.g., SO_2, if high sulphur fuel is burned) with associated health hazards. Given the excellent diurnal dispersion, 24 hour average concentration could be substantially lower than 12 hour (19.00–07.00) averages. It is recommended that air quality standards representative of the night-time situation be studied and established. Furthermore, estimations of contaminant concentrations based on mathematical models should take into account the large difference in stability of the lower layers of the atmosphere (0–100 m) that exists between the day and the night. It is also important to point out that plumes located above the nocturnal inversion or within the nocturnal surface layer where there is little dispersion could fumigate in the morning when the lower part of the atmosphere become unstable.

Although this paper has placed emphasis on the possible problems due to the high nocturnal stability of the tropical savannah atmosphere, and the important potential impact of pollutant emissions on the surrounding areas, other regional problems could result from development of the region. For example, high HC emissions and an increase in NO_x emissions could produce high ozone concentrations during the day downwind of the sources; high SO_2 emissions could contribute to acid deposition in the region.

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