Reports

Radon-222 in the North Atlantic Trade Winds: Its Relationship to Dust Transport from Africa

Abstract. *The concentration of radon-222 in air was measured during a flight from Miami to Barbados to Dakar and return; concentrations ranged from 1 to 55 picocuries per standard cubic meter of air and were highest in areas of dense haze, which were present along most of the flight path across the Atlantic Ocean. The haze is attributed to dust originating from the arid regions of western Africa. Radon-222 may be useful as a tracer for African air parcels over the equatorial Atlantic.*

Radon-222 is a naturally occurring radionuclide (half-life, 3.82 days), which usually is present in readily measurable concentrations in the lower atmosphere over land. The radon is produced by the decay of uranium in soils; subsequently it migrates toward the air-soil interface and into the atmosphere. Because radon is gaseous and chemically unreactive, it should be an ideal tracer for the study of atmospheric transport processes. Radon has been used for this purpose over land masses with some success, although there are difficulties associated with the interpretation of results, particularly in the assessment of the relative importance of rates of radon emanation from the soil, vertical mixing rates in the atmosphere, and horizontal transport by wind (*1–3*). Some efforts (*2*, *4*) have been made to use radon as a tracer for continental air parcels over the ocean where the radon emanation rates are exceedingly low; however, except for the recent work of Rama (*4*), these measurements have been too restricted in scope to be very meaningful.

We report here on an extensive series of radon measurements made over the equatorial North Atlantic Ocean in the trade wind belt, a layer of deep and persistent easterly winds approximately situated between 8°N and 25°N. Occasionally, a part of this airstream, prior to joining the general maritime trades, crosses the western edge of the landmass of Africa and becomes laden with dust generated by the very strong turbulent mixing taking place over the heated deserts and arid lands. Normally, air parcels from this area cross the Atlantic in about a week. During this time a significant fraction of the original dust load has fallen out. Frequently, however, the dust concentration is still sufficiently high to produce haze conditions in the Caribbean (*5*). The data presented here indicate that these areas of dense haze are characterized by high concentrations of radon-222; this correlation suggests that radon may serve as a useful atmospheric tracer for the study of the movement and modification of air masses from Africa as they pass over the ocean.

The measurements were made aboard a DC-6 meteorological research aircraft belonging to the Research Flight Facility, Environmental Science Services Administration (ESSA), Miami. The aircraft flew from Miami to Barbados, West Indies, on 8 October 1968, and on the following day to Dakar, Senegal; on 11 October, the aircraft returned to Barbados, with a stop at Sal, Cape Verde Islands, and thence to Miami on 12 October. The primary purpose of the flight (the first of its kind by a meteorological aircraft) was to investigate tropical disturbances moving from West Africa to the Caribbean and to map the cloud patterns and wind distribution through the disturbances.

Air was sampled by means of an I2B ram filter system and IPC 1478 filters (Institute for Paper Chemistry, Appleton, Wisconsin); the airflow rate through the filter was determined from calibration curves (*6*) of flow rate versus speed as a function of altitude. The filter removes only the particulate matter from the air; thus, only the radon daughter products are collected in the decay series:

$$Rn^{222} \xrightarrow[3.82d]{\alpha} Po^{218} \xrightarrow[3.1m]{\alpha} Pb^{214} \xrightarrow[26.8m]{\beta} Bi^{214} \xrightarrow[19.7m]{\beta} Po^{214} \xrightarrow[1.6\times10^{-4}s]{\alpha} Pb^{210} \xrightarrow[22y]{\beta}$$

With the possible exception of nuclides in air close to the soil surface, the members of the decay series preceding lead-210 are essentially in secular equilibrium in the atmosphere (*1*, *7*). The IPC filtration efficiency for these radon daughter products was approximately 45 percent at the velocities measured through the face of the filter in this work (*8*).

Filters were exposed for 30 minutes; then the radioactivity was counted by means of an end-window Geiger counter apparatus (*9*) for 10 minutes, beginning 60 seconds after termination of the sampling period (*10*). Essentially all detected radiation can be attributed to the beta particles and conversion electrons of lead-214 and bismuth-214; the counting efficiencies for these nuclides are approximately equal, 15 percent. Parent radon concentrations were calculated from the air concentrations of these two daughter nuclides (*11*). Since the sampling is essentially continuous, the data presented here may be regarded as a good average of the radon distribution along the entire flight path, each half-hour sample representing a sampled volume of about 60 m^3 along a path 175 km long.

Radon concentrations (Fig. 1) ranged from 1 to 55 pc (*12*) per standard cubic meter of air. The highest concentrations occurred in the eastern Atlantic in areas of dense haze. Typically, the air samples in these areas yielded net count rates in excess of several hundred counts per minute with a maximum of 800 count/min; in contrast, the detector background was about 50 count/min.

In order to better visualize the radon distribution, we have corrected the individual concentrations for decay en route from the African coast. This we did by constructing a mean time-averaged trajectory for the air parcels and then inserting the calculated transit times for the individual parcels of air into the standard equation for radioactive decay; representative decay

curves are depicted in Fig. 1. The normalized radon concentrations are presented in Fig. 2; also shown in this figure are the flight meteorologist's sketches of conditions along the flight path. These data indicate that hazy areas have significantly higher radon concentrations than the haze-free areas do. That the haze is due to dust is evident from the striking red-brown coloration of filters exposed in these areas. The color is similar to that of dust collected near sea level at Barbados where it is not uncommon to measure dust loads in excess of 10 μg per standard cubic meter of air during the summer and early fall (*5*); high concentrations of dust of similar color and composition (and presumedly derived from the same African sources) have been found during the summer months as far north as Bermuda (*13*).

The normalized radon concentrations show a maximum of about 75 pc per standard cubic meter of air (30° to 35°W, 9 October); if we extrapolate the trajectory of these air parcels to the likely source of origin of the dust (western North Africa) and extend the decay curves shown in Fig. 1, this implies a concentration in excess of 100 pc per standard cubic meter of air at 10,000 feet (3.05 km) altitude. Concentrations of this magnitude are typical for air within a few tens to hundreds of meters of the soil surfaces (*1–3*). In contrast, concentrations over remote areas of the ocean are a hundredfold lower (*2*, *4*). The presence of such high concentrations of radon over large areas and at the relatively high altitude of our flight suggests that unusually large quantities of radon are liberated from the soils, probably as a consequence of the vigorous stirring and "turbulent pumping" of the dry soils (*14*) by the winds in the region of dust storms.

Visual observations indicate that the haze top was sharply defined in the hazy portions of the flights and was between 11,000 and 12,000 feet. On other occasions, persons flying over the tropical Atlantic have observed widespread haze having a well-defined lid at about these elevations. The significance of this dust lid is that it corresponds to the top of the layer of air undergoing convective and mechanical stirring over Africa. Soundings made on 11 October show that the temperature structure at Port Etienne (Fig. 1d), north of Dakar, was almost identical to that at Sal, 480 km from the coast; both soundings show a homogeneous (isentropic) layer of very warm and dry air, character-

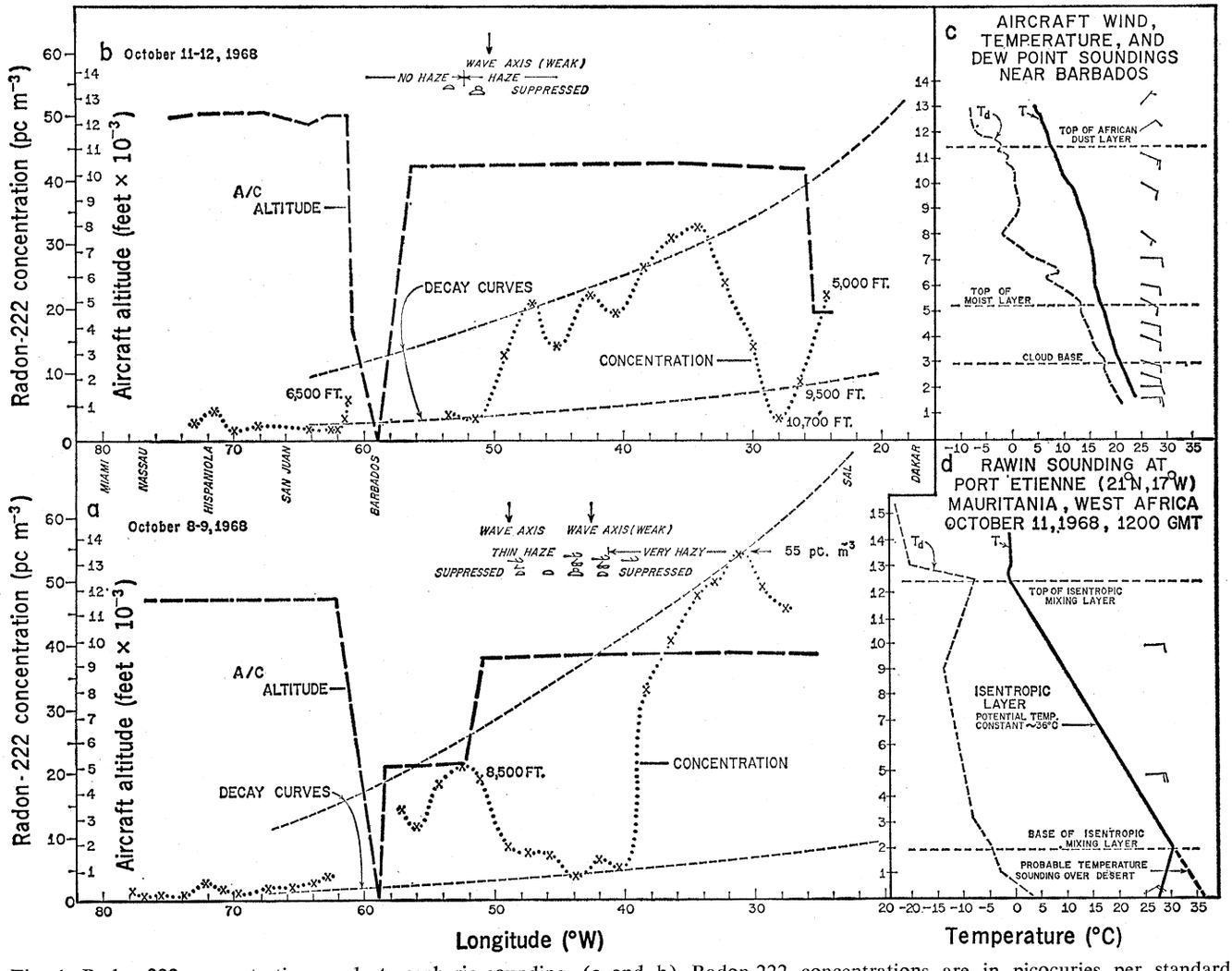

Fig. 1. Radon-222 concentrations and atmospheric sounding. (a and b) Radon-222 concentrations are in picocuries per standard cubic meter of air as calculated from daughter product activities. Decay curves indicate the expected descrease in activity due to the decay of Rn^{222} during transit from Sal on the basis of the computed trajectory speed (see text and Fig. 2); *A/C altitude*, aircraft altitude. (c and d) Temperature (T) and dew point (T_d) soundings at Barbados and Port Etienne on 11 October 1968.

istic of a desert origin, which extended from near the ground to about 12,500 feet where it was capped by a strong inversion.

Normally the maritime trade wind inversion would lie well below 12,000 feet at a level determined by the extent of the vertical exchange of heat and water vapor taking place in the cumulus clouds of the trade winds as the air mass progresses westward. This effect is apparent in Fig. 2, which shows a gradual increase in the amount and depth of the cumulus cover from east to west along the flight path; near Barbados the cumulus tops consistently reach the level of the aircraft. The effect of mixing is also reflected in the humidity measurements (not presented) made during the flight, which show a systematic moistening toward the west between Sal and Barbados. A comparison of the two soundings in Fig. 1 reveals that the moistening trend was not associated with a corresponding net average warming over the lower 10,000 feet, although the lapse rate of the air in this layer became progressively more stable. Thus, as the air moves over the ocean it becomes modified by the radiational and convective processes characteristic of the maritime environment. Although this leads to the formation of a lower (trade wind) inversion at progressively higher altitudes as the air mass moves toward the west, the depth of the original dust-laden air remains virtually unchanged except for some sinking of the top in response to large-scale subsidence of the air mass.

The visual observations indicate that the large fluctuations in radon concentrations are not the result of an inadvertent penetration of the aircraft through the top of the dust layer or of a temporary lowering of the haze top. Rather, these variations are due to dramatic horizontal discontinuities in the air mass resulting from differences in the earlier history of the airstream with respect to its passage over Africa. In particular, in dusty air there is a marked tendency for suppression of cloudiness and for subsidence of the air mass, whereas in haze-free areas there is pronounced cloud buildup; these effects are most apparent in the region of transition between hazy and haze-free areas (see Fig. 2: on 9 October, at 55° to 57°W, at 47° to 51°W, and at 41° to 44°W; on 11 October, at 49° to 52°W). However, the temperature and humidity show no systematic changes across the dust front. (Two very weak easterly wave disturbances were encountered at 50° to 60°W on 9 October; however, these displayed little in the way of significant weather.)

The apparent rate of movement of the radon (and dust) "front" was determined from the change in position during the interval between measurements. The front was encountered at about 39°W on 9 October and at about 49° to 50°W on 11 October; the elapsed time between penetrations was 48 hours. The calculated westward velocity of 22.2 km/hr is close to the mean trajec-

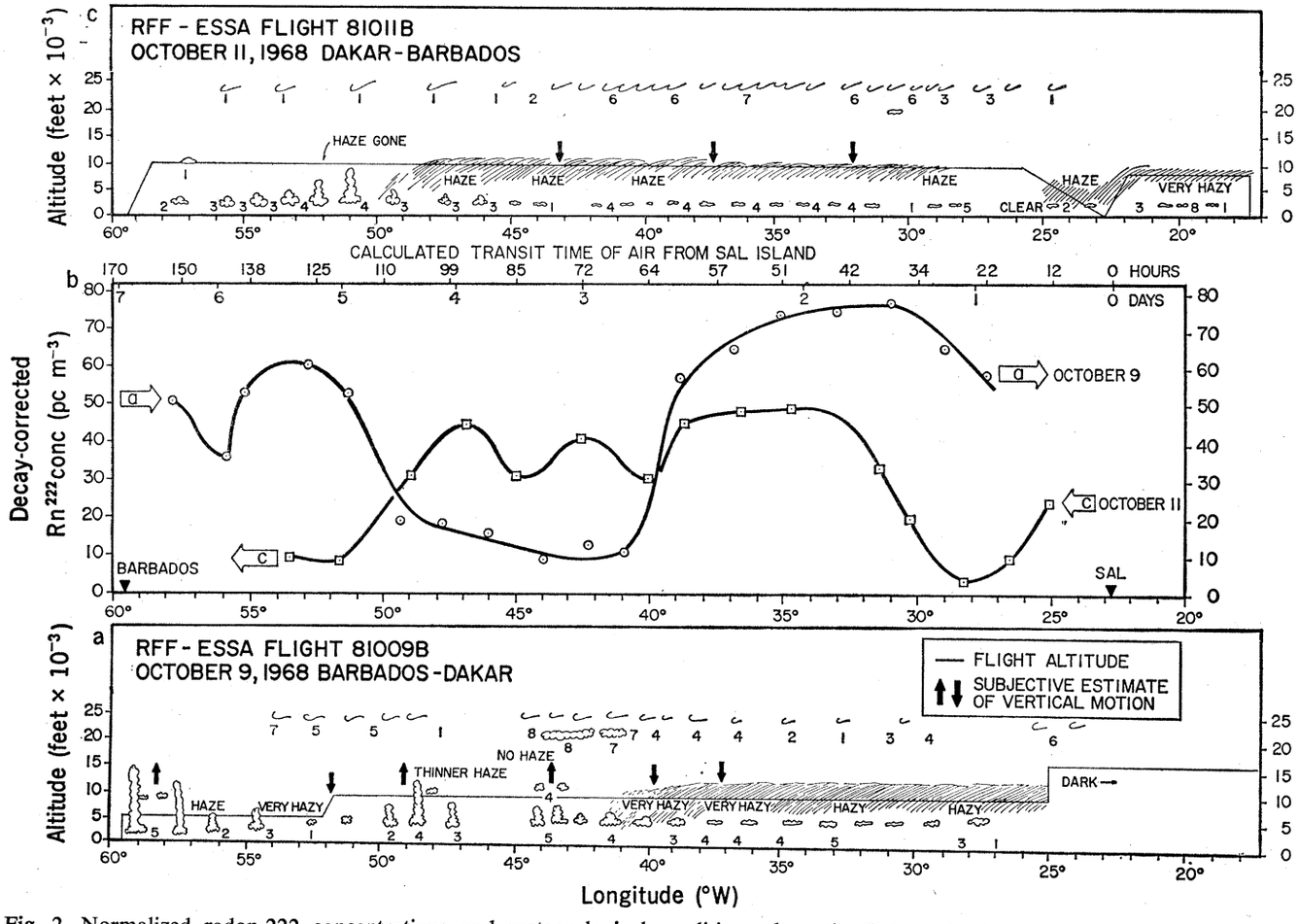

Fig. 2. Normalized radon-222 concentrations and meteorological conditions along the flight path. (a and c) Flight meteorologist's sketches. Numericals indicate cloud cover in tenths. The altitude of the haze top is based on visual estimates; the width of the haze hatching is not intended to be representative of the thickness of the haze layer which was difficult to estimate under flight conditions. (b) Radon-222 concentrations corrected for decay in transit from Sal; calculated transit times are shown at the top of the figure.

tory speed for this part of the Atlantic.

A sharp decrease in radon concentration with height above the dust layer is implied in the results of radon measurements made between Miami and Barbados. Figure 1 shows that these values are almost uniformly an order of magnitude or more below the higher values obtained immediately east of Barbados. These Miami-Barbados measurements were all obtained at an altitude of 12,000 to 13,000 feet and are evidently representative of air above the general haze top and, therefore, of air not previously in recent history subjected to convective contact with the African soil. This distribution is analogous to the vertical distribution of water vapor which, like radon gas, is also introduced from a ground source and stirred by convection to higher levels. We would expect the radon and water vapor concentration to decrease fairly rapidly in the lowest hundreds of meters and then to remain nearly constant or to decrease slowly with height to the top of the mixing layer; above this point we would expect the values to once again tend toward a rapid decrease with height. Except for a small peak near Hispaniola, West Indies, the radon values measured west of Barbados were close to the level of background radiation. The peak at Hispaniola is most likely a geographical phenomenon resulting from an enhancement of local cumulus convection over this large island, thus causing a penetration of the inversion and bringing up a fresh supply of radon and dust from below.

We believe that radon-222 can be extremely useful as a tracer for air moving from Africa into the equatorial Atlantic. The circulation patterns in this part of the tropical Atlantic are not well known; in addition, it has recently been established (*15*) that Africa is a dominant source region for Atlantic tropical disturbances, some of which develop into hurricanes. Furthermore, a significant fraction of the dust associated with the hazy radon-rich areas consists of clay minerals known to be efficient as ice nuclei (*5*).

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6. Calibration curves were provided by L. Machta, Air Resources Laboratory, ESSA, Silver Spring, Maryland.
7. J. R. Gat, G. Assaf, A. Miko, *J. Geophys. Res.* **71**, 1525 (1966); J. R. Gat and G. Assaf, *Science* **159**, 977 (1968).
8. We determined the IPC filtration efficiency by comparing its performance with that of Gelman fiber glass filters which are essentially 100 percent efficient for radon daughter products (*1*). In these tests we took simultaneous samples of maritime air at sea level on the coast during sea breezes; the air flow velocity through the IPC filters was approximately equal to that obtained during flights.
9. The apparatus employed in this work is the same as that used by C. R. Hosler and L. B. Lockhart, Jr. [*J. Geophys. Res.* **70**, 4537 (1965)].
10. The radioactivity of the filter was counted for a second time, again for 10 minutes, beginning 60 minutes after the end of the first counting period in order to verify the decay of the radon daughter products which collectively have an apparent half-life of approximately 35 minutes.
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12. One picocurie = 10^{-12} curie = 2.22 disintegrations per minute.
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16. We thank N. Frank (National Hurricane Center, ESSA, Miami), meteorological observer on these flights, for the use of his sketches; the staff and crew of the Research Flight Facility, ESSA, for their cooperation in making these measurements; and L. Machta (Air Resources Laboratories, ESSA) for the use of the radiation counting equipment. These flights were authorized by the National Hurricane Center, ESSA, Miami. Supported in part by the Office of Naval Research under contract Nonr 4008(02). Contribution No. 1144, University of Miami, Rosenstiel School of Marine and Atmospheric Sciences.

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Active Submarine Volcanism in the Austral Islands

Abstract. *An active submarine volcano has been found on a southeastward extension of the Austral Islands chain. Its last eruption, in May 1967, was detected by North Pacific hydrophones. The position computed by sofar was 32 kilometers northwest of that found in a search by echo sounder, 29°01'S, 140°17'W. The minimum depth encountered was 460 meters.*

On 29 May 1967 a 4½-hour sequence of explosions was recorded on sofar hydrophones arrayed across the North Pacific. The source location was computed as 28.8°S, 140.5°W, on a southeastward extension of the Austral Islands chain. Norris and Johnson (see *1*) ascribe the origin of this sequence, and similar sequences from other regions, to submarine volcanic eruptions.

Marine acoustic detection of volcanic eruptions along the Andesite Zone has been reported on a number of occasions (*2–5*). The Austral Islands event is unique, however, in two respects: the source was in the central Pacific Basin and the source was remote from previously known active volcanoes.

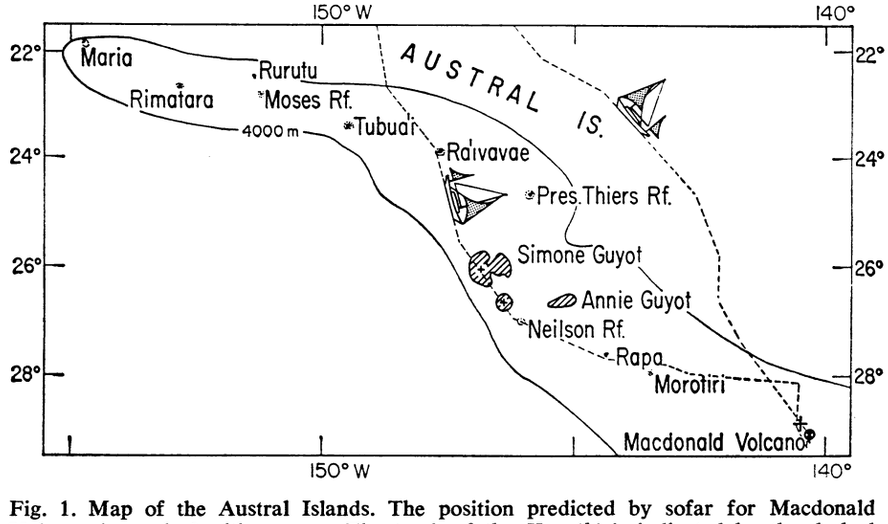

Fig. 1. Map of the Austral Islands. The position predicted by sofar for Macdonald Volcano is marked with a cross. The track of the *Havaiki* is indicated by the dashed line.