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WEATHER FACTORS AFFECTING SOIL-GAS RADON CONCENTRATIONS AT A SINGLE SITE IN THE SEMIARID WESTERN U.S.

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ABSTRACT

Concentrations of radon-222 in soil gas, measured at a long-term radon monitoring site on the Denver Federal Center (DFC), Colorado, vary by as much as an order of magnitude in response to short- and long-term weather variations. The primary weather factors influencing soil-gas radon concentrations are precipitation and barometric pressure, with lesser effects attributed to temperature and, possibly, wind. Soil characteristics are highly significant in determining the magnitude and extent of the soil's response to weather changes. The soil at the DFC site is clay-rich and develops an extensive system of desiccation cracks that impart a moderate permeability to what would otherwise be a relatively impermeable soil. A capping effect caused by frozen or unfrozen soil moisture is a primary radon concentrating mechanism.

INTRODUCTION

Although geologic and soil characteristics are primarily responsible for determining the concentration of radon in a given soil, soil-gas radon concentrations at a site fluctuate under the influence of meteorologic factors. Evaluations of radon potential are typically designed to differentiate areas based on their characteristic radioactivity and soil-gas radon concentrations, but weather-related enhancement or depletion of soil-gas radon may cause misinterpretations of soil-gas radon data. An understanding of seasonal and weather-related variations in soil-gas radon concentrations is essential for accurate site evaluations and can aid in planning indoor radon testing programs and mitigation schemes. The results of this study provide insights into possible causes of non-geologic variations in measured soil-gas radon concentrations.

SITE DESCRIPTION AND METHODS

Concentrations of radon in soil gas were monitored from March, 1987 to April, 1988 at a site on the Denver Federal Center (DFC) in Denver, Colorado. The monitoring site instrumentation consists of three stainless steel soil gas probes, approximately 8 mm O.D., inserted to depths of 50, 75, and 100 cm. In addition, a surface radon collection chamber, consisting of a polystyrene box approximately 30 x 45 x 10 cm, inverted and sealed onto the soil surface, was installed in December 1987. Soil gas samples were extracted from each probe and from the surface radon collection chamber with syringes and injected into the sampling cell of an EDA RDA-200 or Pylon AB-5 radon detector to determine the radon concentration at each depth. Samples were generally collected between 10 am and 2 pm each day to minimize diurnal effects.

Additional information on the probe design and methods used is given by Reimer (1). Soil moisture monitors (tensiometers and gypsum blocks) were also installed at these depths, and temperatures were monitored at the ground surface and at depths of 10 and 60 cm. Soil-gas radon concentrations were compared with weather data from a nearby permanent weather station operated by the U.S. Bureau of Reclamation and with soil moisture and temperature data collected at the site. One soil-gas radon measurement was made at each depth each weekday, but weather data was collected hourly.

The DFC soil-gas monitoring site is situated on flat-lying, unirrigated ground at least 100 meters from the nearest building, major highway, or other man-made structure. The climate of the area is semiarid, with mean annual precipitation of 36-40 cm, about 70 percent of which falls in the spring and summer months. Spring weather is typically characterized by several days of cool temperatures and rain or snowfall that alternate with periods of mild, dry weather, whereas summer is generally warm and dry except for occasional late-day, short-duration thunderstorms. Winters are cool and relatively dry, with daytime temperatures that fluctuate above and below freezing throughout the season. Temperatures range from a mean January low of -9 to -7 °C to a mean July high of 23 to 27 °C (2).

The soil underlying the DFC site is derived from alluvium, mudstones, and shales, and has a high clay content, much of which is smectitic (swelling) clay, but it also contains pebbles and cobbles. It is overlain by approximately 30 cm of locally-derived fill similar in appearance and soil properties to the underlying natural soil. Because of the high clay content and shrink-swell potential of this soil, it develops a system of desiccation cracks that extend to a depth greater than 1.2 meters and impart a prismatic structure to the soil. The crack system has both vertically and horizontally oriented components, but the vertical cracks are more extensive and better developed. Because it is comprised primarily of clay, the soil has a very low intergranular permeability, but the crack system imparts a moderate gas permeability (approximately 10^{-9} cm^2 at 100 cm) (3) to the soil under dry conditions. The crack system was present from May to October, except for short periods following storms.

METEOROLOGICAL EFFECTS ON RADON GENERATION AND TRANSPORT

Meteorological factors affect the generation, migration, and concentration of radon in soil gas. The primary weather variables affecting soil-gas radon concentrations are precipitation (which affects soil moisture) and barometric pressure, with lesser effects due to temperature and wind. A general discussion of radon generation and transport processes, and how they are affected by meteorological factors, provides a background for the discussion of empirical data from this study.

The amount of radon generated by a soil is generally referred to as its "emanation coefficient". The meteorologic factors affecting radon emanation are soil moisture and, to a lesser degree, temperature. Radon emanation rates are highest when soil moisture is between 15 and 20 percent by weight (4, 5, 6). At these soil moisture levels, pore water exists in thin coatings on soil grains that absorb some of the recoil energy of radon atoms as they escape, preventing them from burying themselves in adjacent soil grains and thus increasing the chance that the recoil path will terminate in a pore space (7, 8). At higher levels of soil moisture, the thicker liquid coating on soil grains traps the radon atoms in the pore liquid. They may then move by diffusion through the liquid or into the gas phase, where they can then move by diffusion, convection, or a combination of both, provided the soil is not saturated and the gas-filled pores are interconnected.

A temperature effect on radon generation has also been noted. In one experiment, radon exhalation rates in soil and shale samples increased by 50 to 200 percent in response to increasing the temperature from 5 °C to 22 °C (6), whereas another experiment yielded an approximately 10 percent increase in radon activity when granite samples were heated from -20 °C to 22 °C (9).

Radon transport in soils occurs by two processes, diffusion and convection. Diffusion is the process by which radon atoms move through the pore fluids (gases and/or liquids) in response to a concentration gradient, as described by Fick's Law. Convective transport occurs when the pore fluids move through the soil pores under the influence of an external driving force such as a pressure gradient, carrying the radon atoms along with them, as described by Darcy's Law. Diffusion is the dominant radon transport process in soils of lower permeability (generally less than 10^{-7} cm^2), whereas convective transport processes tend to dominate in more permeable soils (generally greater than 10^{-7} cm^2) (10).

Radon transport distances in soils are related to the type of transport mechanism involved. During its average lifespan, approximately 5.5 days, a radon atom in relatively dry, permeable soil can travel up to one or two meters from its source by molecular diffusion. During the same time period, however, a radon atom may move up to several tens of meters from its source by convective transport (7).

Meteorologic conditions have a marked effect on radon transport in soils. The most important factors appear to be precipitation (as it affects soil moisture conditions) and barometric pressure. Temperature and wind appear to have less discernable effects, and there are conflicting observations in the literature concerning these factors.

If we restrict the discussion of meteorologic effects on soils to the vadose (unsaturated) zone, we may assume an approximately direct correlation between wet and dry weather periods and soil moisture conditions. This constitutes somewhat of an oversimplification when individual precipitation events are examined in that it disregards the importance of antecedent soil moisture conditions, an example of which will be discussed in a following section. In a seasonal context, however, this relationship is a valid one.

Soil moisture affects both radon generation and transport. As discussed previously, radon emanation is enhanced at low to moderate soil moisture levels and inhibited at higher levels of soil moisture. In contrast, radon transport is generally inhibited by soil moisture because water tends to block soil pores, reducing the gas permeability of the soil. Radon atoms can move by diffusion through water, but whereas a radon atom can travel about one meter by diffusion through dry soil during its mean lifespan, it may migrate only 1-2 cm in saturated soil during the same time period (7). In finer-grained soils, especially those with high clay contents, less moisture is necessary to inhibit transport because (a) the pore spaces are smaller, (b) interlayer water molecules are electrostatically bound to the clay particles, so clay-rich soils hold moisture longer and tend to dry out more slowly, and (c) expandable clays swell with the addition of moisture, closing pore spaces and cracks in the soil more readily than in a coarser-grained soil.

Capping is a moisture-related effect that tends to increase measured soil-gas radon concentrations. Capping effects occur when the uppermost soil layers become saturated or the moisture in them is frozen, inhibiting the release of radon to the atmosphere and allowing radon to concentrate beneath the capping layer. The capping layer isolates the soil from the atmosphere, suppressing barometric, thermal, and wind effects. Although heavy rainfall can produce an effective moisture cap (11, 12), freezing of the moisture in the uppermost soil layers appears to be a more common and efficient capping mechanism (5, 13, 14). The capping effect may be enhanced during spring and fall, when the diurnal freeze-thaw cycle allows moisture to infiltrate the near-surface soil layers during the day and subsequently freeze at night, as was observed at the DFC site. Capping occurs more readily in smectitic soils because the surface layers swell shut, blocking both radon exhalation and further infiltration of moisture. This effect may be quite dramatic in soils with clayey 'B' horizons that act as the capping layer (12).

Barometric pressure changes have been found to cause significant changes in measured soil-gas radon concentrations. Falling pressure tends to draw soil gas out of the ground, increasing the radon concentration in the near-surface layers. Conversely, high or increasing barometric pressure forces atmospheric air into the soil, diluting the near-surface soil gas and driving radon deeper into the soil (5, 11, 13, 14). Kirov (15) found that a decrease in pressure causes an increase in radon exhalation "proportional to the square of the pressure drop rate, [and to the] square of the gas permeable soil layer depth, and [it] increases linearly with time". Clements and Wilkening (16) noted that pressure changes of 1-2 percent associated with the passage of weather fronts could produce changes of 20-60 percent in the radon flux, depending on the rate of change of pressure and its duration. Wind turbulence and the Bernoulli effect imparted by wind blowing across an irregular soil surface can draw soil gas upward from depth in a manner similar to that of decreasing barometric pressure (13, 14, 17).

Some authors suggest that temperature has little or no effect on soil gas radon content (5, 14). However, Ball and others (18) found that soil-gas radon concentrations correlate with changes in soil temperature and, to a lesser extent, with air temperature changes. Kovach (14) reported higher radon emanation during temperature lows. Jaacks (19) observed negative correlations between both soil and air temperature and radon concentrations, and suggested that temperature gradients within the soil, or between the soil and air, can induce convective soil-gas transport.

WEATHER AND SOIL-GAS RADON AT THE DFC SITE

Soil-gas radon concentrations at the DFC site show a marked seasonality, with an order-of-magnitude difference between seasonal soil-gas radon maxima and minima (figure 1). Radon concentrations are highest in the late winter and early spring, a period characterized by relatively wet, unstable weather, and lowest in the fall, a season with typically dry, stable weather. Soil-gas radon concentrations generally increase with depth; 50-cm concentrations are generally greater than surface exhalation, and though the 75-cm and 100-cm concentrations are generally similar, they are both higher than concentrations at shallower depths. Radon concentrations at all measured soil depths appear to react similarly to seasonal and shorter-term meteorologic changes, suggesting that sufficient vertical permeability exists for barometric influences to affect soil gases at depths up to one meter during most of the year.

During the period of mid-January to early March, 1988, radon concentrations at 100 cm depth could not be measured because apparent excessive soil moisture conditions at that depth prevented gas samples from being collected. In addition, the seemingly anomalously low soil-gas radon values at 100 cm recorded in late March and early April, 1987, may be due to low gas permeability caused by wet soil conditions at that depth during that period. This is suggested by the wet soil conditions that existed prior to the start of the study, compounded by regularly occurring precipitation throughout March and early April (figure 2). Because we did not have 50- and 75-cm soil gas probes or soil moisture monitors installed at that time, we cannot confirm that the soil column was uniformly saturated.

Seasonality is reflected in most of the weather variables. Precipitation events were of greater intensity, duration, and frequency from March through early July, 1987, followed by a six-month dry period during which there were only four rains (figure 2). Barometric pressure fluctuations (figure 2) also follow seasonal trends. Larger variations in barometric pressure associated with frontal weather systems during the period of March to June, 1987, were followed by a period of relatively stable weather with less pronounced barometric pressure variations from June through mid-December, except for two storms in late October and early November. Air and soil temperatures follow seasonal trends as well (figure 2). Late winter and early spring is typically a period with increased wind velocities (figure 3), but these do not appear to correlate noticeably with changes in soil-gas radon concentrations at the DFC site.

In contrast to longer-term seasonal trends, in which higher radon values (hundreds to thousands of pCi/L) are associated with seasons with unstable, wet weather, and lower radon values (tens to low hundreds of pCi/L) are associated with seasons of dry, stable weather, shorter-term variations in soil-gas radon concentrations are caused by changes in weather associated with discrete storms. There is a relatively good correlation between precipitation (figure 2) and radon in soil gas at all depths (figure 1) with a few exceptions. One exception is the precipitation event in mid-October that had virtually no effect on soil-gas radon values, illustrating the importance of antecedent conditions in influencing the extent of the soil's response to weather changes. Because the October storm was preceded by a long period of dry weather, the soil was so dry that the approximately 25 mm of precipitation that fell were apparently insufficient to significantly affect soil moisture conditions at the site, and thus had little or no effect on soil-gas radon concentrations. In contrast, each rainfall in April, May, and early June caused soil-gas radon concentrations at 100 cm-depth to increase by several hundred pCi/L because (a) soil moisture levels were already high, so that less moisture was required to induce capping and close surface cracks, and (b) rainfall amounts from spring storms were generally greater than those of summer and fall storms. It appears that capping is the most important soil-moisture related effect at the DFC site. The intensity of this effect is due largely to soil characteristics, which will be subsequently discussed.

Barometric pressure correlates negatively with soil-gas radon concentrations, in that falling pressure is associated with increasing concentrations and vice versa. As in the case of precipitation, the smaller peaks and troughs on the radon curves coincide with changes in barometric pressure. The correlations appear to be better during the "stormy" seasons (for example, during May and June) than during the "stable weather" seasons. This may be because the magnitude and rate of pressure change are more important than the actual value of the barometric pressure. For example, a change in barometric pressure from 630 to 625 mm Hg should cause an increase in soil-gas radon concentration similar to that of a change from 625 to 620 mm Hg because the change in pressure in both cases is the same.

A change in barometric pressure produces a pressure gradient between the atmosphere and soil that induces vertical soil gas transport. The strength of this effect is determined by the magnitude of the pressure gradient. Thus a change from 630 to 620 mm Hg should have a more pronounced effect than a change from 625 to 620 mm Hg. If the magnitude of the barometric pressure change is relatively small, or the change is gradual, the gas pressure in the soil pores should be able to more easily equilibrate with the barometric pressure of the air, so pressure-gradient induced soil gas transport is less likely to occur or its effect may be diminished. In addition, pressure-induced transport can only occur if the soil is permeable enough to allow vertical convective transport to occur. Because the major permeability in the DFC soil is due to cracks, this phenomenon is only likely to occur when the soil is dry enough for a network of desiccation cracks to develop.

The effect of temperature on soil-gas radon concentrations appears to be relatively minor compared to those of precipitation and barometric pressure. There is some suggestion that air temperature lows correlate with soil-gas radon highs, but there is no discernable correlation between soil temperature at 60 cm and soil-gas radon values (figure 2). In theory, temperature gradients between the soil and air could induce thermal convection that would cause soil gas to flow in a vertical direction (14, 19). Again, however, soil permeability is important in determining whether such convective transport is possible in a given soil. At the DFC site, soil permeability is low except when enhanced by cracking, and it is unlikely that thermally-induced convection is a major driving force at this site.

Another temperature-related phenomenon may play a significant role in radon accumulation during winter months—capping effects due to freezing of water in the uppermost soil layers. Frozen capping layers may enhance indoor radon levels because the capping layer inhibits radon release to the atmosphere, but also prevents additional moisture from infiltrating the soil, so that the gas permeability of the underlying soil is maintained. Beneath the capping layer, the soil is likely unfrozen and relatively permeable and the soil gas at that depth contains radon that has concentrated to elevated levels. This is likely an important factor in producing elevated indoor radon levels during winter months in many areas.

At the DFC study site, moisture capping occurs when precipitation infiltrates the uppermost soil layers, causing the clays to swell and cracks to close. Because of its low intergranular permeability, percolation through the clayey soil is slow, so pores and cracks deeper in the soil may remain open for a considerable time after the surface has swelled shut, and radon may accumulate to elevated levels beneath the capping layer. An example of the capping effect at the DFC site occurred in early January, 1988, when radon concentrations at all depths, including surface radon exhalation, increased from a few hundred to more than 1000 pCi/L (figure 1). This increase coincided with several minor storms (compare with precipitation and barometric pressure curves, figure 2), but more importantly, with the period during which the near-surface soil temperature (10-cm depth soil temperature curve, figure 2) dropped and remained below freezing.

Note that although the soil-gas radon concentrations increased and remained elevated beginning in early January, the surface radon exhalation decreased after about a month's time, corresponding to an increase in soil temperature at 10-cm depth from below to above freezing (figure 2). This observation is curious because one would expect that a frozen cap would prevent radon exhalation to the surface so that these values would have been lower during that period. A proposed explanation is that the plastic box that comprises the surface radon collection chamber initially prevented moisture from infiltrating the soil directly beneath it, and when the surrounding soil froze, soil gas was still able to escape into the collection chamber. Additional precipitation during January was unable to infiltrate the soil, nor could moisture in the uppermost soil layers move laterally because of its frozen state. After the capping layer thawed, a liquid moisture cap remained, so soil-gas radon concentrations stayed elevated, but soil moisture was able to migrate laterally, saturating the soil beneath the surface radon collector and inhibiting radon escape, so radon levels in the chamber dropped. A moisture cap is easier to maintain during cooler months because evaporation rates are lower, so the soil dries out more slowly. At the DFC site, the latter part of the winter corresponds roughly with the first part of the wetter season (spring and early summer), providing favorable conditions for the formation and maintenance of moisture caps (frozen or unfrozen).

DISCUSSION

Soil characteristics are extremely important in determining how a particular soil responds to climatic and weather factors. In the case of the DFC site, the clayey texture and dry climate interact to produce the desiccation crack system that imparts significant gas permeability to what would otherwise be an almost impermeable soil. The swelling of expandable clays in response to the addition of a relatively small amount of moisture allows for rapid changes in soil permeability, which may exaggerate their responses in comparison with different soils in similar climates, or with similar soils in different climates. However, the basic concepts and relationships described in this paper should be applicable to virtually any site, as long as careful investigation and interpretation of soil properties and seasonal climatic variations at each individual site is undertaken.

Determining the influence of individual weather factors and their effects on radon migration and concentration in soils is complicated by the fact that several weather factors may change simultaneously. For example, storms are generally associated with precipitation, lower barometric pressure, lower temperatures, and often, wind. Comparing plots of these factors with soil-gas radon concentrations may lead to the conclusion that all of these factors cause soil-gas radon concentrations to increase, and this is correct to some degree. However, weather can be at least as strange and inexplicable as geology or radon, and it is possible to find examples of weather factors that occur independently of some or all of the others at different times. By examining the radon and weather data from the DFC study site and other published data, we have established a hierarchy of weather factors that affect soil-gas radon concentrations.

Seasonal variations are by far the most striking of those observed during this study. The combination of weather factors associated with different seasonal weather regimes produces a relatively consistent set of conditions for sustaining high or low soil-gas radon levels for extended periods of time. Whereas short-term weather variations caused measured soil-gas radon concentrations to vary by as much as a factor of two, seasonal extremes in radon values differed by as much as a factor of ten.

The most important weather-related parameter affecting soil-gas radon concentrations is soil moisture, and by association, precipitation, as it provides the moisture. Nearly every precipitation event recorded during the study period evoked a noticeable change in radon concentrations in soil gas. Barometric pressure appears to be the next most important parameter. Inverse correlations between barometric pressure and soil-gas radon values were noted during periods when large-scale barometric pressure changes occurred without associated precipitation. The magnitude of change of radon values in response to barometric pressure changes alone were generally less than that of precipitation alone or of a combination of the two, however.

Temperature may be the next most important factor, but the importance of this and other weather factors is difficult to determine. The fact that changes in all of the weather factors often occur together makes the task of determining the relative influence of each individual factor difficult. In addition, the factors for which we can determine relatively consistent correlations—precipitation and barometric pressure—appear to be stronger driving forces and thus tend to overshadow the weaker effects of temperature, wind (except in extreme cases), and other factors such as relative humidity and insolation. Unless each factor's effects can be isolated in a controlled environment, we may not be able to definitively determine the relative importance of each weather factor.

SUMMARY

Radon concentrations in soil gas at the DFC site vary by as much as an order of magnitude between seasons, and by as much as 200 percent in response to day-to-day weather variations. Although the seasonality of these variations may be different in different areas, there is reason to believe that similar magnitudes of variations may occur in other soils and climatic zones. There appears to be a hierarchy of factors affecting soil-gas radon concentrations:

1) Precipitation (as it affects soil moisture)

2) Barometric pressure

3) Temperature, wind, and other factors.

The influence of temperature, wind, and other weather factors is undetermined, because the more dominant factors tend to overshadow the effects of those factors with less strong influences. Effects of factors lower on the list are best evaluated in the absence of those higher on the list.

The data presented here suggest that evaluations of building tracts or sites made on the basis of a single or a few soil-gas radon measurements could be misleading if they are made without considering the potential variability imposed by seasonal and day-to-day weather variations. Additional data from other soil types and climatic zones should be collected to provide a better base for evaluating the validity of individual soil-gas radon measurements.

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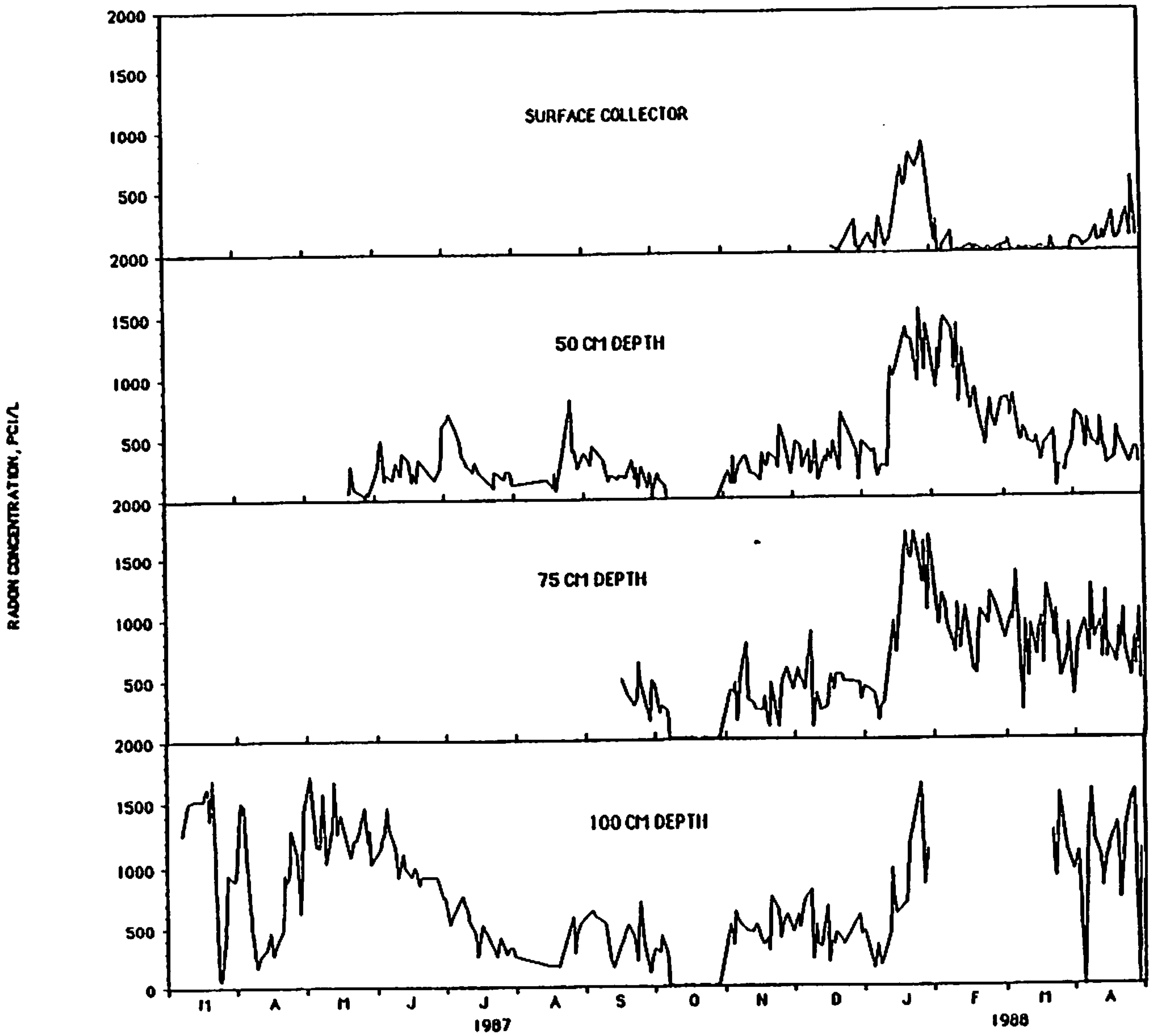

Figure 1. Radon concentrations in soil gas at 50, 75, and 100 cm depths and in the surface radon collector.

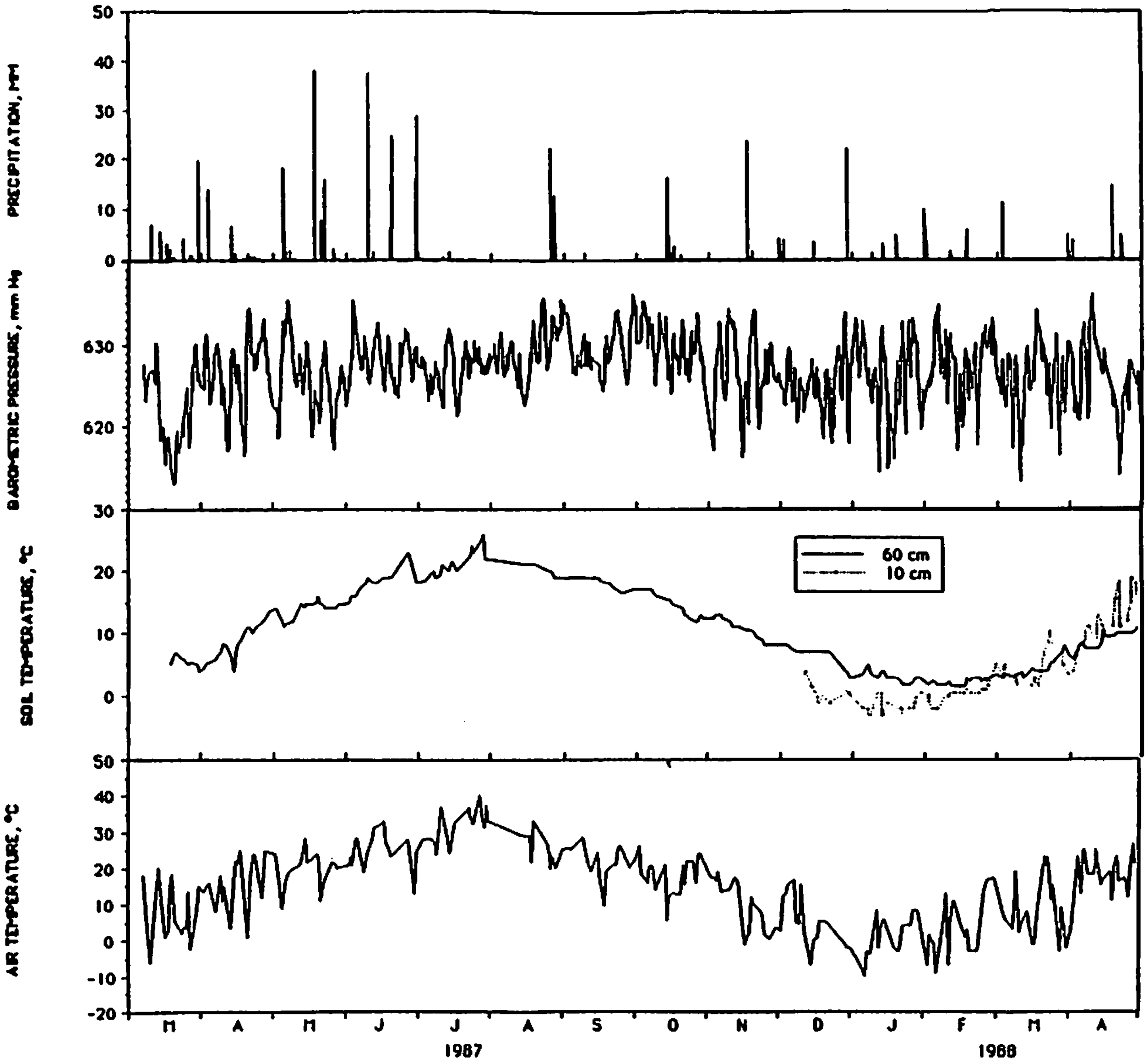

Figure 2. Precipitation, barometric pressure, soil and air temperatures at the DFC site.

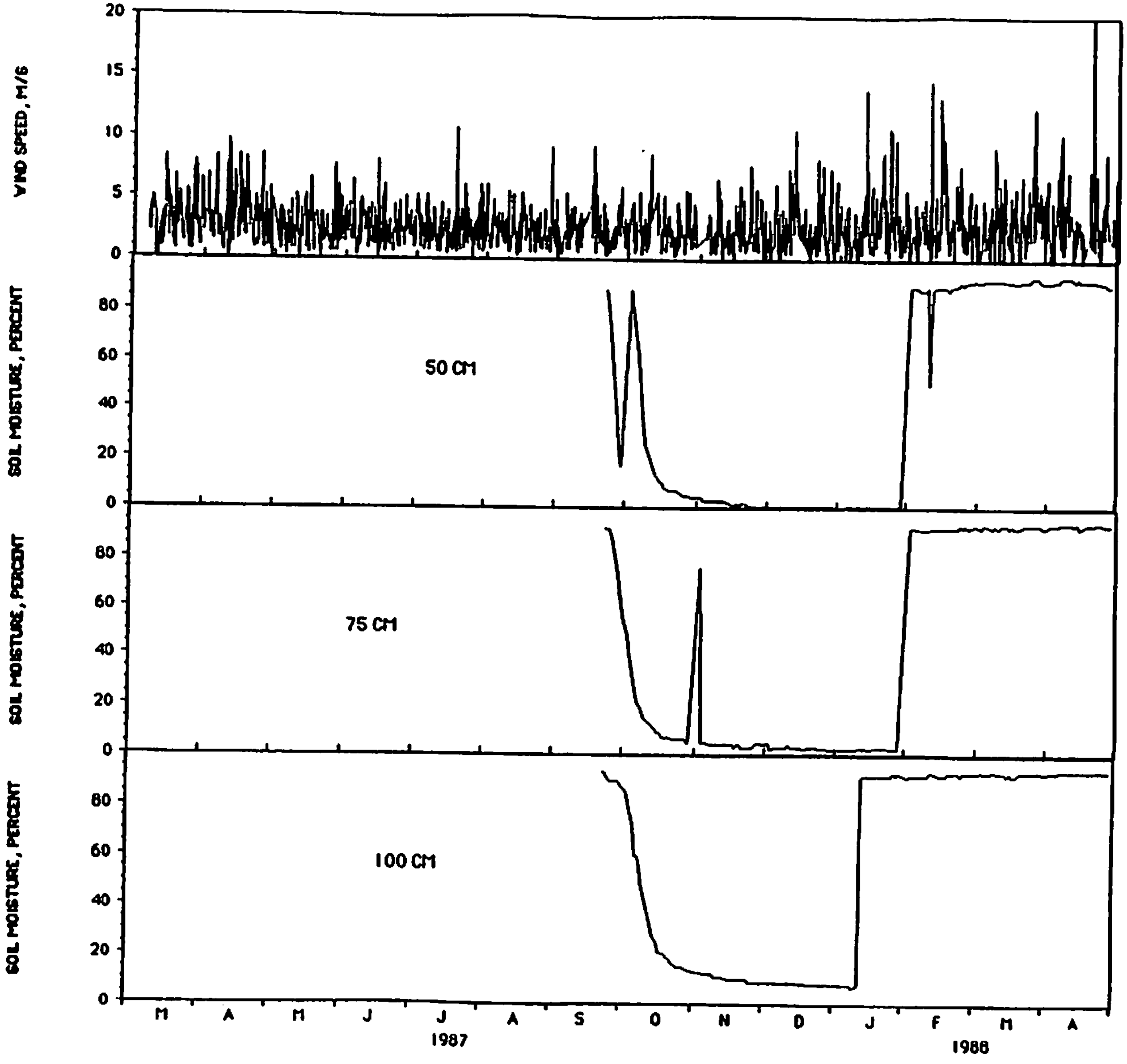

Figure 3. Wind speeds and soil moisture, in percent of saturation, measured by gypsum block monitors.