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Dynamics of Air Avalanches in the Access Pit of an Underground Quarry

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Temperature measurements have been performed in the vertical access pit of an underground quarry. During autumn, air avalanches induce an initial thermal feedback and a stationary mixing state characterized by spatially coherent broad-band fluctuations with a standard deviation of about 0.2 °C, linearly increasing with the inside-minus-outside temperature difference. Phase changes of water are shown to contribute to the onset condition, the feedback, and the stationary mixing state. This experiment may give insight on turbulent thermal and compositional convection with nonadiabatic boundaries.

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Laboratory experiments studying heat transport in fluids through turbulent buoyant plumes have revealed many unexpected features [1,2] such as anomalous scaling, intermittent bursts, or the onset of oscillations above a critical Rayleigh number [3]. In a natural environment, coherent temperature and humidity oscillations have been observed at the rock-atmosphere interface in an underground quarry [4]. Underground sites, which are thermodynamically stable, are particularly interesting in order to study the nonlinear dynamics of air at intermediate scales, from about 1 m to several hundred meters. Such sites also offer a unique opportunity to study open systems with the additional effects of time dependent flows, nonadiabatic boundaries [5], and phase changes. Indeed, one important feature of natural caves or underground quarries is the prevailing presence of water. Here we report observations associated with cold avalanches in the air of the access pit of an underground quarry located in Vincennes, near Paris.

The abandoned “La Brasserie” limestone quarry [6] consists of pillars and rooms having an average height of 2.4 m and spread over an area of 32 000 m², located about 18 m below the ground surface. It has an average temperature of 12.7 °C, with variations over one year remaining within 0.12 °C in the atmosphere and within 0.05 °C in the rock. The relative humidity of the atmosphere is high, with values compatible with saturation given the measurement accuracy. The quarry is connected to the outside by a single large access pit with a diameter of 4.6 m (Fig. 1). The upper part of the pit reaches in a building, but broken panes in windows with a surface area of about 2.3 m² allow air exchange.

With the simple geometry of the access pit (Fig. 1), two regimes are expected. As long as the outside temperature remains higher than the average temperature of the quarry, the atmosphere of the pit and of the quarry remains water saturated and stable, at least for a stable atmospheric pressure. When the outside air temperature is smaller than 12.7 °C, however, a natural ventilation mixing is expected [5]. This simple mechanism is complicated by the fact that the quarry air and the outside air have different humidity, and by the fact that water and heat can be exchanged with the walls.

In order to study this natural ventilation, a first set of ten thermistors were installed at the beginning of 2000 in the pit (Fig. 1) near the metallic staircase. These thermistors have a diameter of 5 mm, a length of 30 mm, and a sensitivity of about 135 Ω/°C at 12 °C [7]. They were not calibrated individually but were sorted to have similar characteristics in the laboratory so that differences in their relative calibration can be neglected in the present experiment. A common average calibration was applied to convert resistance values to degrees. Given their size, these thermistors have a thermal response time of the order of 30 s, and temperatures are recorded with a sampling time of 1 min.

Typical temperature records obtained during the transition period between summer and winter are shown in Fig. 2. Two regimes are observed. The first regime (summer regime) is characterized by a stable temperature at a depth larger than 10 m in the pit (sensors TP1 to TP3). The second regime (winter regime) is characterized by a decreased temperature in the pit, particularly for sensors TP1 to TP3. Simultaneously, fluctuations of about 0.5 °C peak to peak appear systematically on all sensors. This regime appears when the temperature in the upper part of the pit (sensor TP10), which in a first approximation reflects the outside air temperature, drops below some threshold close to the average temperature of the quarry. This winter regime can therefore be associated with cold air avalanches in the pit.

This is further illustrated in Fig. 3 where all data from March 2000 to September 2001 have been incorporated. In this figure, average temperature values of sensors TP1, TP4, and TP8, obtained over 2-hour sections, are displayed as a function of the corresponding average value
for sensor TP10. As long as the average temperature of sensor TP10 is larger than 12.7 °C, the temperature of sensor TP1 remains extremely stable. When the average temperature of sensor TP10 is lower than 12.7 °C, the temperatures of TP1 and TP4 drop and are similar, indicating an efficient vertical mixing. In Fig. 3, the standard deviation of temperature TP1 is also shown. The amplitude of the fluctuations also has a sharp transition at 12.7 °C and is increasing linearly when the temperature difference between the equilibrium quarry temperature and the outside temperature is increasing.

The temperature fluctuations have a similar peak to peak amplitude from TP1 to TP10 (Fig. 2). In contrast to the oscillations observed in the RB laboratory experiments [2,3], they do not show resonant frequencies. The spatial coherence of the fluctuations can be characterized by the coherency matrix $c_{ij}$ defined by

$$c_{ij} = \frac{\sum_k T_i(k)T_j(k)}{\sqrt{\sum_k T_i(k)^2}\sqrt{\sum_k T_j(k)^2}}, \quad (1)$$

where $T_i(k)$ refers to a given temperature time series for sensor TPi and $T_j(k)$ the corresponding time series for sensor TPj. In order to isolate the fluctuations, the slow temperature variations are approximated by a polynomial fit and subtracted from the measured time series. A typical spatial dependence of the sensor to sensor coherency is shown in Fig. 4. The coherency is rather large ( > 0.7) for a short distance and is decreasing smoothly with distance. A typical coherence length of about 4 m is observed, of the order of the pit diameter. The region between the surface and a depth of the order of 3 to 4 m seems to have a different behavior, with a larger coherency over a short distance. This is probably due to the close distance to the air exchange windows or an effect of wind. The
pattern of correlation displayed in Fig. 4 does not depend
on the particular time series chosen. Additional experi-
ments also indicated that the horizontal coherence of
the temperature fluctuations during the winter regime
is larger than 0.7 over the whole diameter of the pit. The
large vertical coherence length and this strong coherence
over a horizontal section of the pit reflect an efficient
global organization of the air dynamics.
Such broad-band coherent temperature fluctuations are
intriguing. Pressure variations can induce temperature
fluctuations that are coherent over large distances but
amplitudes are smaller than 0.05 °C [7]. The temperature
fluctuations must be associated with a random vigorous
stirring associated with the falling cold plumes. To un-
derstand the underlying processes, two important addi-
tional features of the reversible transition between the two re-
gimes have to be pointed out in Fig. 2. First, a reproduc-
ible feedback response follows the initiation of the air
flow. This is especially noteworthy for sensor TP1 for
which the initial temperature drop (\(T_{a1}-T_{a0}\)) is
equal to the equilibrium quarry temperature, 
\(T_{e}\), and water content \(c_{w}^w\). This box is in contact with an external reservoir
of temperature \(T_{e}\) and water content \(c_{w}^w\), then natural
ventilation [8] occurs if the buoyancy defined by
\[g' = g \left(\frac{T_a - T_e}{T_0} + (c_{w}^w - c_{w}^w) \frac{V_a^M M_a - M_w}{M_w M_a}\right),\]
where \(T_0\) is the absolute equilibrium temperature of the
quarry and \(g\) is the acceleration of gravity, is positive. By
similarity with other flows [5], the mixing flow rate can be
estimated as \(C_D A \sqrt{g' H}\), where \(A\) is the area of the
opening (2.3 m²) and \(H\) is the height of the box. The
discharge coefficient \(C_D\) takes into account the shape of
the opening and a value of 0.6 is used [5,8]. Assuming
\(T_a - T_e = 1\) °C and \(RH_a = RH_e = 0\), the flow rate
amounts to 1.2 m³/s, corresponding to velocities of
15 cm/s, assuming that down-going and up-going flows
each share half of the pit section (16.3 m²). If a cold
avalanche falls down the pit with this velocity, then the
transit time of the perturbation from TP10 to TP1 is about
80 s, compatible with the observation (Fig. 2).
The time evolution of the water content \(c_{w}^w\) can then be
described by an equation with a mixing term and a
relaxation term:
\[\frac{dc_{w}^w}{dt} = -\alpha \frac{1}{\tau_w} (c_{w}^w - c_{w}^w) - \frac{1}{\tau_w} (c_{w}^w - c_{w}^w),\]
where \(\alpha = C_D A \sqrt{g' H}/V_a\), \(c_{w}^w\) is some reference water con-
tent at the wall and \(\tau_w\) is a relaxation time for water
exchange. Here we assume that \(c_{w}^w\) is the water content of
the atmosphere at saturation at the wall temperature \(T_0\).
Similarly, the air temperature in the box is described by
\[\frac{dT_a}{dt} = -\alpha \frac{1}{\tau_0} (T_a - T_e) - \frac{1}{\tau_0} (T_a - T_0) + \beta (c_{w}^w - c_{w}^w),\]
where $\tau_0$ is a thermal relaxation term [7]. The last term corresponds to the latent heat associated with the water exchange and $\beta = L/\rho_0 c_w c_a$, where $c_w$ is the specific heat of dry air (10$^3$ Jkg$^{-1}$K$^{-1}$) and $L$ the latent heat of water (2.5×10$^3$ J/kg). The relaxation times $\tau_0$ and $\tau_0$ do not need to be identical. Actually, general considerations [9] suggest that $\tau_0/\tau_0$ is scaling as $1/Le^{2/3}$ where $Le$ is the Lewis number ($\approx 1.2$). We shall therefore concentrate on the case $\tau_0 < \tau_0$.

The coupled equations (4) and (5) describe our simplified system. When $g' < 0$, then no mixing is present, and the system is described by the same equations, putting $\alpha = 0$. In this case, the coupled equations predict a relaxation of $T_a$ and $c_a^m$ towards the equilibrium values $T_0$ and $c_a^m$. In the general case, for given time series $T_a(t)$ and $c_a^m(t)$, the resulting time series $T_a(t)$ and $c_a^m(t)$ can be calculated numerically. One example is shown in Fig. 5 assuming $\tau_0 = 15$ min, $\tau_0/\tau_0 = 0.3$, and $RHe = 0.4$ constant with time. The calculated air temperature has both a feedback response at the onset of the flow and an oscillatory behavior during the stationary phase.

This model does not claim to be a comprehensive representation of the quarry pit. In particular, the spectral content of the fluctuations remains to be understood. This model however supports the hypothesis that water, potentially, can be the physical parameter controlling the initial thermal feedback response and that it can also contribute to the large spatial organization of the thermal broad-band fluctuations. The fluctuations themselves probably result from turbulent swirling motions, which are, for example, observed when a colored salt solution is put in contact above a beaker of clear water. The side walls must play an important role in the spatial organization of the buoyant plumes, and therefore the dynamics could be significantly different in a free atmospheric column of air. Taking time sections of the order of 1 h, the coherence of the fluctuations of TP1, TP2, and TP3 is increased if a positive delay of about 5 s for TP2 and about 27 s for TP3 is introduced with respect to TP1. These delays correspond to up-going velocities of about 10 and 27 cm/s, respectively. These velocity values are comparable with the value 15 cm/s for the mixing velocity derived above. Most of the kinetic energy of the cold avalanches appears to be absorbed by the stationary fluctuations. The fact that the standard deviation of the fluctuations increases with the temperature gradient (Fig. 3) further suggests that the mixing flow due to the cold avalanches may lead to a reduced ventilation of the quarry. This blocking effect remains poorly quantified at this state.

This phenomenon is interesting to study in detail because it could be relevant in many practical applications of economic and cultural importance. In the context of underground waste repositories, natural ventilation is the main cooling process considered and the effects of water need to be understood. Combined heat and water exchange is also important in the context of the preservation of painted caves [10]. More generally, the observations in the Vincennes quarry pit may improve our understanding of combined thermal and compositional convection in fluids, which is an important key to the dynamics of the atmosphere and the interior of the Earth [11].

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