Answers to Reviewer #1

We thank the reviewer for in detail study of our manuscript and providing comments and valuable remarks that help improving presentation of the results of the heat experiments in an isolated room of the Vincent quarry. Our responses to each of the reviewer's comments are given in red through the text of his or her **Review**.

Review of manuscript:
Intermittent heat instabilities in an air plume

Submitted to Non Linear Processes in Geophysics.
Author(s): Jean-Louis Le Mouël[1], Vladimir G. Kossobokov[1,2], Frederic Perrier[1], and Pierre Morat.
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General comments

This paper presents a novel plume experiment which dimensions are not the typical ones. The presented experiment is very interesting and original because it is between the laboratory and the real geophysical situations. It is clearly stated by the authors that they experimental results agree with the classical model of Morton et al. (1956). The paper studies the heat instabilities of the plume dynamics which behaviour is not well understood and it is an important topic for industrial and geophysical situations. The authors of this work propose to examine the dynamical behaviour of these instabilities and they clearly show that the instabilities have an intermittent character which is presented by means of different kind of figures. The researchers stablish that this dynamics is a universal feature of turbulent plumes in geophysical environments and it could be represented by a smooth spatial function with a global temporal intermittent function. Related to this question, the authors should explain better what is their objective at introduction, at sections 5 and 6 (conclusions). It should be better to introduce a basic description of heat instabilities and intermittency (at introduction). The authors should explain better how their results are important implications for geophysical or industrial situations.
This paper should undergo a minor revision before being considered for publication.

We added a paragraph at the end of Introduction, which was originally excluded for sake of shortening the size of the manuscript.

Specific comments

Sub-Section 2.1. The Vincennes quarry
☐**Page 2, Lines 23-24.** What is the reason for the temperature increase of about 0.1ºC per year? Why it is different from the annual variation (0.8 ºC)?

The paragraph refers to the estimations obtained in the earlier studies that are well cited. The annual average temperature in the quarry increased from 12ºC in 2003 to 12.2ºC in 2005 which change is well in range of the local change of the annual average temperature in Paris (13.2ºC in 2003, 13.0ºC in 2004, and 12.9ºC in 2005), while the annual variance of the temperature remained about the same (i.e., 0.8ºC). To avoid any misinterpretation we have changed the text to the following –

> Temperature had been measured in the quarry since 2001, giving in 2003-2005 an annual mean temperature in range from 12°C to 12.2°C with a seasonal variation of the order of 0.8°C related to natural ventilation through the access pit (Perrier et al., 2004; Perrier and Richon, 2010).

☐**Page 2, Lines 29.** You speak about the exceptional conditions of stability. How do you characterize and measure this stability? At this point, I understand that is stable stratified but do you mean that the air of the quarry has a stable stratification or a neutral one?

The preceding paragraph demonstrates quantitatively how stable are temperatures and humidity in the abandoned quarry as a whole. The conditions in the room S15 which is far away of the entrance to the quarry are even more stable as can be judged from the temperature measurements at the times of no visits and of those not affected by heating experiments (i.e. from Wednesday to Sunday) and estimated ventilation rate ("of the order of 2×10^{-6} s^{-1} ").

☐**Page 3, Lines 2-5.** You speak about the air exchanges. What is the effect of natural ventilation on stratification of the quarry air?

☐ Could you also explain in more detail the effect of the quarry walls and ceiling on your experiment and your results?

We presume that the air exchanges in room S15 with such a low ventilation rate are negligible in relation to the natural stratification of the air in its volume of about 400 m^3. Having in mind the location and dimensions of resulting plume in our heating experiments we may also consider negligible the effect of the distant walls, while the ceiling is acting as the limiting boundary in the system. Naturally, the ceiling, walls, and the floor act as cooling elements of the system where hot air rising from the heat source is spreading through the volume of the room.- This is added at the end of section 2.1.

Sub-Section 2.3. Configuration of the measurement device of the experiment

☐**Page 4, Lines 2.** This is the first time you mention the screen ("*and that of the screen*"). Therefore, you must explain here what the screen is. This explanation is written in lines 14-15: "*To study the possible contribution of sideway radiations, a screen was placed around the source in 15 experiments A3, A5-A7 (Table 1)*". Eliminate these lines and write this explanation in line 2.

Done.

☐**Page 4, Line 9.** You write that "*Most of the heating experiments (……….) lasted for 24 hours*". Explain how such 24 hours experiments affect on the stratification of the room. Has the heating source of power 100 W been switched on during the 24 hours experiments or only some hours, minutes? The time that the heating source is on, could it have some effect on the plume behaviour?

We added "when the heat source was switched on" and "when the heat source was switched off" for a clarification.

Sub-Section 3.1. The horizontal recordings at 1.00 m

☐ Sensor 7 is symmetrically placed with respect to the sensor 5. Why their measures are different (figure 3, for example).

We are sorry, but it is hard observing any symmetry in between sensors 5 and 7. Yes, you are right, at 1 m height sensor 6 was the first affected with the rising hot air, but in about 6 hours the axis of the plume had developed next to sensor 5 as can be judged from the A5 heating experiments at 1 m height (Fig. 3 shows A5a, and A5b looks very similar). One should try finding some symmetry between sensors 4 and 6, 3 and 7, etc., as clearly confirmed by space-time diagrams in Figs. 4 and 5.

☐**Page 5, Line 9.** You write "*These heat pulses of instability should not be taken as physical drops of air observed at a given time*". Do you think there is a relation between these pulses and the continuous or intermittent hot air supply (it depends on whether the heat source is turned on all the time).

Yes, the heat source was turned on during all the 24 hours in each experiment, and we believe that an intermittent pattern of heat pulses and their absence is due to a non-linear effect involving stream of hot air in a stratified environment.

Sub-Section 3.5. Joint study of the various time series

☐**Page 6, Line 21.** Why the threshold is 12 minutes?

Yes, 12 minutes = 720 s is an arbitrary choice of the threshold that determines a classification into short and long intervals between heat pulses. Some motivation could be related to the selected sampling interval of 120 s = 2 minutes in the experiments A6 and A7 or to doubling of the typical decay time of one pulse ~360 s, as well as to the change in the slope of the empirical distribution functions given in Fig. 13.

Section 4. Averaged temperature profiles

☐**Page 7, Line 1.** Change this sentence "*temperature radial profile*" by the following "*radial temperature profile*".

Done.

☐**Page 7, Line 13.** Change this sentence.

Done.

☐**Page 7, Line 17.** How do you calculate the mean of Θ in the section of the plume at the 1-meter altitude because figure 3b does not exist.

Thanks for pointing to the wrong reference, which should be Fig. 14b. Corrected.

☐**Page 7, Line 25.** Eliminate the word "*Remark:*"

Done.

☐**Page 7, Lines 25 to the end of the section 4.** I think that this paragraph could be placed at the beginning of the section as an objective and to clarify the development of the section 4.

Thanks. Following the reviewer's suggestion the paragraph is moved to the beginning of Section 4.

Section 5. Some global characteristics of the plume dynamics

☐**Page 8, Lines 13-18.** You do not write the values of the sub-index j. For me, it is not clear the meaning of the subscript: does i represent the different sensors and j the different heights? If it is so, I do not understand equation (8). Therefore, does i and j represent the different sensors?

Yes, it does; i and j do represent different sensors. Thanks for pointing to the typos. Following the reviewer's comment we rephrased and corrected the paragraph.

☐**Page 8, Lines 13-18.** If equation (9) is an extrapolation of equation (8), you say that at every height z it verifies equation (8) and subscript i is not z. Therefore, the constant parameters a_{ij} are transformed into functions that depend on the radial coordinate. Could you explain and justify better this extrapolation?

Yes, i is not z in (9); naturally, discreet i at the height z is transformed into continuous r.

Section 6. Discussion and conclusions

☐**Page 9, Line 8.** The title of your work is related to instabilities but it is necessary to speak more about it. Could you explain better what kind of instabilities (already known or new ones) are you studying? What aspects of these instabilities are described and clarified by your experiments?

☐ Do you think there is some relationship between the instabilities you see/measure and the meandering phenomenon, which appears in geophysical situations under stable conditions?

Following the reviewer's suggestion we have clarified what kind of instability appears in the heating experiments in the preceding paragraph. We believe that the meandering phenomenon can be ruled out due to rather fast speed of the air flow one can observe in Fig. 12 representing the dynamical propagation of the heat pulses in vertical direction.

☐**Page 9, Line 30-32.** One of their major contributions is to propose a first order factorization of the spatial and temporal variations. Highlight this aspect and develop it.

Following the reviewer's suggestion, the assumption of a first order factorization in the models is highlighted.

Technical comments

☐ Use units in seconds, not minutes.

Following the reviewer's comment we supplied (where appropriate) the time measurements in minutes with the equivalent values in seconds.

Section 1. Introduction.

☐**Page 2, Lines 4 to 7.** The text is repeated, it is just the same that at the beginning of the Introduction. You have to eliminate lines 4 to 7.

Done.

Section 2.1. Vincennes quarry.

☐ It woulb be interesting to add a photograph of the quarry (in Figure 1).

We have photos of the room S15 with the heating experiment set up (e.g. the one below) and can provide it, if the editor finds it appropriate and necessary.

Section 2.2. Temperature measurements. Thermistors. Calibration.

☐ Change the name of the section (use a phrase, for example "Temperature measurements by thermistors").

Done.

☐**Page 3, Line 18.** Change "section II.3" to "section 2.3" because your notation is "2.3 Configuration of the measurement…..".

Done.

☐**Page 3, Line 16**. Rewrite the expressión because the superindex of *T* is not clear.

Done.

Section 3. Results: Temperature fluctuations in the plume.

☐**Page 4, Line 18.** Eliminate the notation "ch1, ch2, … ,ch10" because you do not use it again. Write "by 10 sensors" and add a reference to a figure.

Done.

☐**Page 4, Line 18.** Why do not you order the names of the experiments: A5a, A5b, A6a, A6b, A7a and A7b? Why do not you mention experiment A4?

Unlike the experiments A5, A6, and A7, the heat source was not surrounded by the screen.

Section 3.1. The horizontal recordings at 1.00 m.

☐**Page 4, Line 27.** You mention that "Figure 3 shows the …temperature …..from 12:00…to 16:00.." but, really, is 14:00.

Thanks. Changed to the correct interval "…from 11:00 … to 14:00…".

Section 3.2. The horizontal recordings at 1.50 m.

☐ Change "section III.1" to "section 3.1" because your notation is "3.1 The horizontal recordings at 1.00 m".

Done.

Section 3.4. AIII device maintained vertically.

☐**Page 6, Line 10-11.** Eliminate the definition of t_k ($t_k=t_0+20k$) in line 11 and write it in line 10.

Done.

Section 3.5. Joint study of the various time series.

☐**Page 6, Line 18.** Order the names of the experiments as (A5a, A6a, A7a)

The order in the text corresponds to the order by rising heights in the same sentence.

Section 4. Averaged temperature profiles.

☐**Page 7, Lines 5-6.** Are necessary the quotation marks at the following phrase: *"No velocity scale is provided by the specification of a free convection situation"*.

We believe it is necessary as being cited from (Morton et al., 1956).

☐**Page 7, Line 9.** Change the notation of the upward vertical unit vector to ***k***.

Sorry, we wish preserving the notation.

☐**Page 7, Lines 17.** Change "m_2; from" to "m_2. From".

Done.

☐**Page 7, Lines 17.** Figure 3b does not exist.

Changed for 14b.

Section 5. Some global characteristics of the plume dynamics

☐**Page 8, Line 4.** Change "section IV" to "section 4" because your notation is "4. Averaged temperature profiles".

Done.

☐**Page 8, Line 18.** Rewrite the sentence. Write "a_{ij} *being (constants) parameters*" at the beginning of the phrase. Change the sentence "*taking j = 5 of the sensor seeing the large variations*".

Done.

☐**Page 8, Line 19.** Why do you change the coefficient a_{i5} to *b*?

Done to get rid of the index 5, so that b_i represents the value of $f_z(r)$ at the position of sensor *i*.

☐**Page 8, Line 22.** Eliminate the phrase *"en bloc"* and rewrite the phrase.
Done.

Section 6 Discussion and conclusions

☐**Page 10, Line 4.** Change the reference *(Hernandez et al., 2015)* to *(Hernandez, 2015)*.
Done.

References

Revise all the bibliographic refences because the following references are not cited in the text:

☐*Carazzo, G., Girault, F., Aubry, T., Bouquerel, H., and Kaminski, E.: Laboratory experiments of forced plumes in a density stratified crossflow and implications for volcanic plumes, Geoph. Res. Lett.* ***41****: 8759–8766, 2014.*

☐*Carazzo, G., Kaminski, E., and Tait S.: The route to self-similarity in turbulent jets and plumes. J. Fluid Mech.* ***547****: 137–148, 2006.*

☐*Fischer, H. B., Imberger, J., List, E. J., Koh, R. C. Y., and Brooks N. H.: Mixing in inland and coastal waters. Academia Press, New York, United States. 483 p., 1979.*

☐*George, W. K. Jr., Alpert, R. L., and Tamanini, F.: Turbulence measurements in an axisymmetric buoyant plume. Int. J. Heat Mass Transfer* ***20****(11): 1145–1154, 1977.*

☐*Guyon, E., Hulin, J.-P., Petit, L., and Mitescu, C.D.: Physical Hydrodymanics (2nd ed.). Oxford University Press, Oxford, 536 p., 2015.*

☐ Kaminski, E., Tait, S., and Carazzo, G.: Turbulent entrainment in jets with arbitrary buoyancy.*J. Fluid Mech.* **526**: 361–376, 2005.

☐ Morat, P., Le Mouël, J.-L., Poirier, J.-P., and Kossobokov, V.: Heat and water transport by oscillatory convection in an underground cavity. *C. R. Acad. Sci. Paris* **328** (1): 1–8, 1999.

☐ Tritton, D. J.:*Physical Fluid Dynamics*. Clarendon Press, 544 p, 1988.

You mention the following reference (Crouzeix et al., 2006) in the text but you write three different papers which have the same reference:

☐*Crouzeix, C., Le Mouël, J.-L., Perrier, F., Shnirman, M. G., and Blanter E.: Long-term persistence of the spatial organization of temperature fluctuation lifetime in turbulent air avalanches. Phys. Rev. E* ***74****, 036308, 2006. Are these the right page?* Yes, this is correct reference (Phys. Rev. Journal uses the reference number of the manuscript that may have quite a bit of pages).

☐*Crouzeix, C., Le Mouël, J.-L., Perrier, F., and Richon, P.: Non-adiabatic boundaries and thermal stratification in a confined volume. Int. J. Heat Mass Transfer* ***49****: 1974-1980, 2006.*

☐*Crouzeix, C., Le Mouël, J.-L., Perrier, F., and Richon, P.: Thermal stratification induced by heating in a non-adiabatic context. Building and Environment* ***41*** *(7): 926–939, 2006.*

If you mention the three papers in the text, distinguish them with different references, something like (Carazzo et al., 2006(a), (b), (c)).

Done. We have introduced missing references into the text of the manuscript and Crouzeix et al., 2006-a, 2006-b and 2006-c.

Tables

□**Table 1.** Explain the meaning of the signs - and + related to source raised and screen in the table caption.

Done.

□**Table 2.** Express all in seconds, not in minutes, as in Table 1.

Done.

□**Table 2.** The meaning of the column "*max(□t), s*" is not explained in the table caption.

Done.

Figures

□**Figure 2.** Explain the meaning of the numbers "1, 2, 3, …,10" in the table caption. Also explain what is the screen and the meaning of AI, AII, AIII and S. The reason is that when figure 2 is mentioned, these concepts have not yet been explained.

Done. Figure caption is changed accordingly.

□**Figure 3.** Explain the meaning of "Ch1, Ch2,…Ch10" in the table caption.

Done. Figure and its caption are changed accordingly, so that T1, T2, … , T10 be the same notation in Figs. 3, 6, 8, and 9:

"T1, T2, … , T10 denote temperature series of the ten sensors on the AIII set-up."

□**Figure 6.** Explain the meaning of "T1, T2,…T10" in the table caption. Is T1 the same instrument that Ch1, and so on? If they are, use the same notation in all figures: Ch1 or T1.

Done.

□**Figure 8 and 9.** As in Figure 6.

Done.

□**Figure 9.** Rewrite the information related to dates and hours (*the periods 2003/04/21 18:54:52-2003/04/21 (upper plate) and 2003/04/22 04:12:52-2003/04/22 05:52:52*) because it is a bit confusing.

Thanks for pointing to another typo. Corrected.

□**Figure 13.** Change "*A5a, A7a, A6a and A3 experiments*" to "*A3, A5a, A6a and A7a experiments*".

Sorry, we wish preserving the order reflecting the height of the AIII set-up.

Answers to Reviewer #2

We thank the reviewer for accurate comments and valuable remarks, as well as for raising interesting points on the underlying physics. Our responses to each of the reviewer's comments are given in red through the text of his or her **Review**.

Interactive comment on "Intermittent heat instabilities in an air plume" *by* J.-L. Le Mouël et al.

Anonymous Referee #2

Received and published: 14 June 2016

The manuscript present an interesting experimental investigation of thermal plumes in a controlled environment. The most peculiar novelty of this work is the location of the experiment, which is in a naturally thermally stable room of an abandoned underground quarry. The authors performed a quite exhaustive series of measurements to characterize the properties of the thermal plumes generated by one source. The description of the experiment is quite clear and concise, and the results drawn by the authors are described in terms of temporal intermittency and its relationship with the instabilities arising in their set-up. The article is interesting and deserve publication, although a more thoughtful interpretation of the results in terms of physics of the system could be beneficial. Thanks.

I have a few minor comments, which will be listed below.

* lines 26-29 and 41-45: this sentence is repeated, please remove the second one. Done.

*** line 89: there is an extra space in the title II.2: "C alibration"** Following the R#1 suggestion the title has been changed to "**2.2 Temperature measurements by calibrated thermistors**"

* page 5: the authors should probably describe the stability of the source in terms of temperature variation, and presence of possible periodicity, which could affect their results. This is perhaps a major point that should be described with care in the text, and possibly tested in the lab. Dedicated heating experiments were performed in the last stage of the experiments in 2005 with thermistors attached to the source. Temperature of the source does not show any periodic variations in the frequency range of the instabilities mentioned in this paper. This point is now explicitly mentioned in the text at the end of section 2.3 of the revised version.

* Table 1, the entry in the lower-right case is missing the unit of measure. Done.

* lines 122-123: this description perhaps belongs to previous section? Yes, the description of thermistors in the room at distance from the entrance to the quarry may go to the previous rather general section on calibrated thermistors. However, we prefer placing it into the section describing the specifics of installation of the set-ups in the room of heating experiments.

* line 130: what is the set-up S? It only appears here and should be commented. We have changed this part of description of the set-ups: "…while the sensors of set-up S used for the same purpose were placed at about 1.5 cm inside the rock…"

* line 134: the experiments last for 24 hours. Did the authors test at least in one case what happens for longer measurements? No. Each of the 24-hour heating experiments demonstrates a persistent behavior of the temperature measurements after just a few hours at the very beginning; therefore we believe that the observed behavior would not change in case of an experiment extended for a few hours more.

* lines 145-147: the lists of experiments should be sorted in alpha-numerical order (in the present version, A7 comes before A6), unless there is a reason for this order, and in this case it should be clearly stated. Yes, there is a reason (i.e. the order by the height of the AIII set-up in horizontal position) which is clearly stated in the revision.

* line 159: Do the authors have any explaination for the difference between probes 4, 5 and 6? Is it depending on the position? Why? Yes, an obvious one would be the distance from the sensor to the axis of the plume that originates in a heating experiment. Yes, it must depend on the position of a sensor relative to the plume axis, which may and as evident from Fig. 4 does move in time, perhaps, due to natural variability of the environment.

* line 204: there are two periods at the end of the sentence: "..". Corrected.

* page 15, section III.4: could the authors comment about their findings in this configuration? As suggested by the reviewer, we added the following comments to the end of section 3.4:

As is evident from Fig.11, in the first 4 minutes after switching on the heat source at 12:00, the temperature T10, i.e. the nearest to the source, is rising slower, while the temperatures T6-T8 grow faster than at any of the other thermistors. At 12:09, the temperature T9 surpasses T6 and T7-T9 rise to their maximal values about 17-18°C. At this moment of time T10 continues to grow steadily, while temperatures T7-T9 start falling down. At 12:16 T10 rise above all the others and by 12:20 it is 1.4-2.6°C higher than any of T1-T9. It appears that at about 12:30 the formation of a plume proceeds to its final stage lasting for about 30 minutes followed by rather regular dynamics with domination of T10 ~16.5-17°C and T9 ~15.4-16°C. From 13:00 on, and till the end of heating experiment, the average values of T10 and T9 are 16.9°C with σ = 0.2°C and 15.8°C with σ = 0.7°C, respectively. The difference in σ's allows for sporadic rise of T9 above T10, with cases are exemplified in Fig. 12. In particular, one can clearly observe rather quick propagation of the heat pulse through the entire plume from the floor to the ceiling of the room S15 (Fig. 12b).

* line 259: the authors show the cumulative distribution. Yes, we do. The attribute "cumulative" is added in the revision (although assumed by default and is evident from the figure).

* line 304: the parameter UL/nu is the Reynolds number. The auhtors should acknowledge that and perhaps comment in terms of laminarity/turbulence of the flow, as resulting from their estimate 10ˆ4? As suggested by the reviewer, one sentence has been added to acknowledge the value of UL/v.

* line 317: What is the consequence of the satisfactory agreement between F and F_0? Could the authors comment on that more explicitly in the text? As suggested by the reviewer, we have added in the revised version a comment elaborating on the agreement between the two values.

* lines 332-336: did the authors look at the log-log plot of the spectra' does it present a power-law? This could be an interesting information to add to the article, even to describe the turbulence properties of the system (and given the high

Reynolds number, I suspect it should be a power-law)... Of course, we did have a look at the log-log plot of the spectra, which indeed display a complex set of power-law segments in the low frequency domain. We believe that providing this information would distract the reader from the main aim of over article, i.e. intermittent pattern in dynamics in the frequency domain from 120 to 1000 s. You may guess that we plan returning to it in a different paper.

* page 7: the authors speak about instabilities, but they do not really refer or describe what particular type of instability is relevant here. Could they please spend some words on this? Following the reviewer's suggestion we have clarified what kind of instability appears in the heating experiments in our study.

Interactive comment on Nonlin. Processes Geophys. Discuss., doi:10.5194/npg-2016-23, 2016.

Intermittent heat instabilities in an air plume

Jean-Louis Le Mouël[1], Vladimir G. Kossobokov[1,2], Frederic Perrier[1], and Pierre Morat[1]

[1]Geomagnetism, Institut de Physique du Globe de Paris, 1 rue Jussieu, 75238 Paris, Cedex 05, France
[2]Institute of Earthquake Prediction Theory and Mathematical Geophysics, Russian Academy of Sciences, 84/32 Profsoyuznaya Street, 117997 Moscow, Russian Federation

Correspondence to: Vladimir G. Kossobokov (volodya@mitp.ru)

Abstract. We report the results of heating experiments carried in an abandoned limestone quarry close to Paris, in an isolated room of a volume of about 400 m^3. A heat source made of a metallic resistor of power 100 W was installed on the floor of the room, at distance from the walls. High quality temperature sensors, with a response time of 20 s, were fixed on a 2-m long bar. In a series of 24-hour heating experiments the bar had been set up horizontally at different heights or vertically along the axis of the plume to record changes in temperature distribution with a sampling time varying from 20 ~~s~~ to ~~2 min~~120 s. When taken in averages over 24 hours, the temperatures present the classical shape of steady state plumes, as described by classical models. On the contrary, the temperature time series show a rich dynamic plume flow with intermittent trains of oscillations, spatially coherent, of large ~~amplitudes~~amplitude and a period around 400 s, separated by intervals of relative quiescence whose duration can reach several hours. To our knowledge, no specific theory is available to explain this behavior, which appears to be chaotic interaction between a turbulent plume and a stratified environment. The observed behavior, with first order factorization of a smooth spatial function with a global temporal intermittent function, could be a universal feature of some turbulent plumes in geophysical environments.

1 Introduction

Thermal plumes, columns of hot fluid that rise above a localized heat source, have received, like jets, a lot of attention (e.g., Turner, 1973). Numerous processes in the Earth and in small-scale environmental sites require the description of the effect of injecting heat or matter from natural and/or industrial sources into a stationary organized system, such as the ocean, ~~the~~a lake, or the atmosphere (Woods, 2010).

Models of plumes (and jets) have existed for decades. Models rely on a turbulent entrainment of ambient fluid in a shear layer within the edges of the plume, and a hypothesis of complete similarity along the downstream axis OZ of the plume. In these contributions, the entrainment rate of ambient fluid is proportional to the vertical velocity w (along OZ), with the same entrainment constant α_e along Z. Such is the case ~~of~~in the classical model of Morton et al. (1956) who used three conservation equations (for fluxes of mass, momentum and buoyancy) to get the expressions of the temperature difference, plume radius, and mean velocity along Z, $w(z)$. ~~Fisher~~Fischer et al. (1979) got the same expressions using essentially dimensional analysis. In fact, this hypothesis of complete similarity is strong and debated, not supported by all experiments. Recently, Crouzeix et al. (2003) resumed the study of the similarity, using available experimental data and concluded in favor of local states of partial self-similarity, in accordance with the theoretical analysis by analyses (George (et al., 1977; George, 1989), and evolving along the Zz coordinate according to a universal route. Thermal plumes, columns of hot fluid that rise above a localized heat source have received, like jets, a lot of attention (Turner, 1973). Numerous processes in the Earth and in small-scale environmental sites require the description of the effect of injecting heat or matter from natural and/or industrial sources into a stationary organized system, such as the ocean, the lake, or the atmosphere (Woods, 2010).

All those models are for stationary, time independent jets or plumes. In the present paper,While we will still consider the stationary states of plumes in confined environments, we will now turn to the spatio-temporal fluctuations withinstructures, inside the plumeplumes, and in itstheir immediate vicinity, and reveal a dynamically chaotic plume. Thus, our main interest in the present paper is the fluctuations around the mean values representing the stationary states. Our sampling in time and space, however limited, allows us to describe the main features of this dynamic flow, whose observation, to our knowledge, is unprecedented.

To demonstrate how the temperature time series disclose rich dynamics of a plume in an enclosed stratified environment we first describe the setup of the heating experiments in an isolated room of the abandoned limestone quarry in section 2, then the results of a series of the experiments with different configuration of the measurement device in section 3, which show up the development of the plume flow with a clear presence of systematic instabilities, expressed with temperature pulses of high amplitude, interspersed with long periods of stability. We check that the observed average temperatures are in a satisfactory agreement with classical models of stationary plumes (section 4), as well as with some features of self-similarity (section 5). The discussion and conclusion are given in section 6 that compares plume dynamics observed in other geophysical conditions and environment.

2 The heating experiments in the Vincennes quarry

2.1 The Vincennes quarry

Various thermodynamic experiments have been carried out from February 2002 to April 2005 in an abandoned quarry located in Vincennes, close to Paris (Crouzeix et al., 2003). The Vincennes quarry has a surface of 32,000 m^2, its ceiling is at a depth varying from 14 to 20 m. The walls show a section of the different tabular layers that have been exploited in a Lutetian formation, mostly limestone beds. The quarry consists of corridors and rooms separated by pillars of different sizes, most of them supporting the roof. Room shapes are roughly rectangular; the height of their ceiling varies between 1.5 and 7 m (the distance from the ceiling to the surface of fillings, about 2 m thick covering the rock floor). The total air volume in the quarry, difficult to evaluate precisely because of unexplored and collapsed sections, is estimated to be around 80 000 m^3. The quarry is connected to the ground surface by a single large access pit with 4.56 m diameter (Perrier et al., 2002; Perrier et al., 2005; Perrier and Le Mouël, 2016).

Temperature had been measured in the quarry since 2001, giving ~~a mean value of 12°C~~ in 2003~~ and afterwards~~ 2005 an ~~increase of about 0.1°C per year. An~~ annual mean temperature in range from 12°C to 12.2°C with a seasonal variation of the order of 0.8°C~~ is~~ related to natural ventilation through the access pit (Perrier et al., 2004; Perrier and Richon, 2010~~), which is active in winter times.~~). At times smaller than a day, temperature variations are mostly due to variations of atmospheric pressure (Perrier et al., 2001), and do not exceed 0.03°C peak to peak in the absence of perturbations (visits, heating experiments). As in most underground systems, relative humidity in the atmosphere of the quarry is high (99.2 – 99.8 %).

Among various observations of temperature, we took advantage of the exceptional conditions of stability offered by such a large quarry to conduct, among other types of experiments, a long series of measurements of temperature on a plume set up in an isolated room of a volume of about 400 m^3. This set of long duration heating experiments is the subject of the present paper.

The room S15 selected for the heating experiments has a surface of about 24 m by 9 m (Fig. 1) with an average height of about 2 m (Fig. 2). Air exchanges with the rest of the quarry proceed through two entrances of about 3 and 3.5 m wide (Fig. 1). In order to reduce ventilation effects, the experiments were performed in the inner part of the room at distance from the entrances. On July 2nd, 2003, this part of about 12 m by 9 m in surface had been insulated with a wall made of Styrofoam. However, most experiments reported in this paper were performed before the installation of the partition wall. Nevertheless, the natural ventilation of the section of room S15 used for the experiments is small, with a ventilation rate estimated to be of the order of 2×10^{-6} s^{-1} (Perrier and Richon, 2010). We presume that the air exchanges in room S15 with such a low ventilation rate are negligible in relation to the natural stratification of the air in its volume of about 400 m3. Having in mind the location and dimensions of a resulting plume in our heating experiments we may also consider negligible the effect of the distant walls, while the ceiling is acting as the limiting boundary in the system. Naturally, the ceiling, walls, and the floor act as cooling elements of the system where hot air rising from the heat source is spreading through the volume of the room.

2.2 Temperature measurements~~. Thermistors. Calibration.~~ by calibrated thermistors

We will consider space and time variations of the temperature with an amplitude as small as 0.01°C, even a few 0.001°C; so we need very sensitive sensors. For this reason, and because the experiment relies on temperature data, we will briefly describe the sensors and their calibration. The three types of temperature sensors commonly used are thermocouples, resistance temperature detectors (RTD), and thermistors. Thermistors are very sensitive, cheap (one can buy and use many of them), and present a weak noise. However, their response time can be somewhat long, and must be known; they are not very stable on long term, but we are considering relatively short time constant relative variations (see below). A thermistor is made of semi-conductor materials whose electric resistance *R* decreases monotonously when the temperature increases. The relation between temperature *T* and *R* is strongly non-linear, often written in the form, $T^{-1} = A + B\ lnR + C\ (lnR)^2$, where *A*, *B*, and *C* are coefficients to be determined. In the present study, we measure temperature space and time variations smaller than a few degrees, simultaneously at ten or twelve locations (see section ~~II~~2.3). What we need is an accurate inter-calibration of n thermistors, or *n* thermistors plus a unique reference one. In other words, the relative calibration of a series of n thermistors consists in reducing the value of the resistance R_i (i = 1, 2, … , n) of thermistor to the value R_{ref} of the reference thermistor at the same temperature. For that all the thermistors are plunged in a bath of uniform temperature, controlled by a thermometer with 0.001°C accuracy. From a number of measurements in the bath, we determine the coefficients of the simplified relationship:

$$R_{ref} = a_i + b_i R_i , \; i = 1, 2, \dots , n \qquad (1)$$

As a result, the temperature variations measured in the experiments, at all locations i, after using relation (1) are the same as if measured by the reference thermistor within 0.005°C (Crouzeix et al., 2003). The response time of the thermistors is in the range of 15-20 s, depending on the type. The sampling interval of the records is 20, or 40, or 120 s (Table 1).

2.3 Configuration of the measurement device of the experiment

Four set-ups instrumented with ten thermistors each were installed in a part of the room at distance from entrances. The sensors, 30 mm long and about 5 mm in diameter, had an intrinsic response time of about 20 s. The precision of relative temperature measurements was found to be about 0.005 °C (Crouzeix et al., 2003). One of the set-ups, AIII, was placed just above the heat source and, unlike the other three, which remained at the same positions, was configured differently in thirteen heating experiments from March 10 to June 9. Specifically, the 2-m bar with thermistors was placed vertically in experiments A1-A3 to evaluate the effect of the source at different heights, and that of the screen, then horizontally in experiments A4-A7 successively at a height of 1, 2, and 1.5 m (see Fig.2 and Table 1). To study the possible contribution of sideway radiations, a screen was placed around the source in experiments A3, A5-A7 (Table 1). Moreover, the sampling rate of measurements in AIII varied from once in 20 s in the first four experiments to once in 120 s in the last two. The set-ups AI and AII were used to measure the temperature in vertical air columns away from the walls, while the sensors of set-up S used for the same purpose were placed at about 1.5 cm inside the rock of the ceiling and wall and in the filling of the floor. These laterlatter experiments, dedicated to studying the reaction of the room to the heating, are outside the scope of the present paper, where we focus on the experiments studying the plume itself.

Most of the heating experiments (including all those considered in the present study) lasted for 24 hours, from Monday 12 a.m. to Tuesday 12 a.m.., when the heat source was switched on, and were separated from the previous one by six days, when the heat source was switched off. Thus, the heat source is continuously on during the whole duration of the heating period. The heat source was a metallic resistor of power 100 W with a rectangular surface of 5 by 7 cm and height of 15 cm. Measurements in the laboratory have shown that the source reaches its maximum temperature within 600 s (i.e. 10 minutes.). During the experiments, it was located about 3.4 m from the nearest back wall of the room (Fig.1). Except for one experiment (A2, see Table 1), the source was put directly on the floor as indicated in Fig.2. The thermal stability of the source was studied during dedicated experiments with thermistors directly attached to the source. The source did not show any significant periodic variations and none of the effects reported below can be attributed to the source itself.To study the possible contribution of sideway radiations, a screen was placed around the source in experiments A3, A5-A7 (Table 1).

3 Results: Temperature fluctuations in the plume

We now present the data which are at the core of the present paper. The temperature variations are measured along the two meters long bar AIII, by 10 sensors ~~ch1, ch2, … , ch10.~~(Fig. 3). In experiments A5a, A5b, A7a, A7b, A6a, and A6b the bar is maintained horizontally, centred above the heating source, at a height of 1 m for A5, 1.5 m for A7, and 2 m for A6 above the floor, respectively (Table 1). In experiment A3 the bar is maintained along the vertical of the source. These experiments were all performed with a screen around the source, in order to cancel or reduce radiative heating.

A previous study of the thermal stratification induced in the same room S15 by the heating (Crouzeix et al., 2006) had shown that temperature variations in the environment outside the plume were small compared to temperature variations in the plume itself; we will consider that the plume is in an environment with a uniform temperature T_0. In the following graphs the temperatures are reckoned from the reference temperature of the environment T_0, $\Delta T(t) = T(t) - T_0$.

3.1 The horizontal recordings at 1.00 m

Fig. 3 shows the recordings of temperature at a height of 1 m, made from ~~12~~11:00 on April 7 to ~~16~~14:00 on April 8, 2003, one hour before, during, and ~~4~~two hours after the heating experiment A5a, using a sampling interval of 40 seconds. After a transient phase of about an hour from switching on the heating source, the curves take the form of regular spikes of high amplitude at sensor 5 (up to 1.5°C), smaller but still high on sensors 4 and 6. Note that the curves 4 and 6 are not always exactly affine one of each other, which is presumably an effect of shifts of the plume, and~~, in fact,~~ that the spikes are present with smaller and smaller amplitudes on all the curves.

The duration of the temperature peaks of instability is close to ~~six~~360 s (i.e. 6 minutes~~.~~). They appear either isolated, or in pairs, or in trains; when a peak is isolated, or is the last of a train, the declining phase of instability is longer than ~~6 minutes~~360 s. Between these temperature instabilities phases of stability are present, sometimes longer than 5 hours~~.~~ (i.e. 18000 s).

Fig. 4 displays the temperature data from the same experiment in the form of a color-coded contour space-time map (level lines) over the time interval from 2003/04/07 9:00 to 2003/04/08 15:00. The colour scale indicates the amplitude of the measured temperatures. We observe more vividly the trains of nearly regular strong heat pulses along with their spread along the horizontal device. These heat pulses of instability should not be taken as physical drops of air observed at a given time.

Let us zoom on the train of instabilities of April 7, from 18:00 to 20:00 (Fig. 5, upper plate). The peaks take the form of localized pulses, each about 380 seconds. Look at the abrupt shift of the plume at about 18:30. Another illustration is coming from the same experiment A5a from 4:00 to at 6:00 on April 8 (Fig. 5, lower plate). One can see six isolated pulses with peak to peak inter-event times of 420, 480, 840, 960, and 1360 s (which are suggestive of a likely “doubling of period”) followed by a train of at least six of apparently connected pulses whose mean duration is about 320 seconds.

3.2 The horizontal recordings at 1.50 m

A similar analysis of temperatures collected at the height of 1.50 m has been performed (experiments A7a on May 26-27 and A7b on June 2-3, 2003). Fig. 6 shows the recordings from 11:00 on May 26 to 17:00 on May 27. Clearly, the general behavior of the recording is the same as at the height of 1.00 m (section ~~III~~3.1), although the larger sampling rate of one per 120 seconds provides coarser curves. Nevertheless, the contrast between active and quiet segments ~~(as well as duration of the phases of stability)~~ is smaller than in the case of temperatures at 1 m height.

A zoom on a train of the temperature peaks, in space-time representation, is illustrated by Fig. 7. The mean peak to peak time for the eight pulses of the train starting just before midnight (at about 23:58) is ~~8 minutes (±~~480 ± 40 s~~)~~. However, the individual durations of pulses range from 360 up to about 600 seconds, which might be considered as a mixture of single and double periods; or the first and the last heat pulses might be considered as isolated ones. We point out again that in 2003 we were not able to make simultaneous recordings, i.e. to perform a direct comparison of several temperature recordings made at the same time at several positions above the source.

3.3 The horizontal recordings at 2.00 m

Fig. 8 shows the results of experiment A6a made on April 21-22 at the height of 2 m. Again the recording presents periods with and without peaks, with the largest amplitude at sensors 4 and 5 (in fact, very similar). One observes a slow temperature increase from 13:00 to 19:53 on April 21, then a descent till 22:13, followed by a flat behavior till the end of the heating phase at 12:00 on April 22. At this 2-meter height, the interaction of the plume with the ceiling makes the situation somewhat more complex. Fig. 9 shows two zooms on the time intervals 18:53 – 20:33 on April 21 and 4:11 – 5:51 on April 22. Despite the 120-second sampling, it is seen that, when the oscillations are large enough, they are practically in phase at all sensors, i.e. the temperature varies in the same way in the whole plume. In the first interval we observe a train of ten temperature pulses with duration of about 410 s each, while in the second interval we observe two trains of five and four pulses, respectively, with durations of about 440 and 425 s respectively. Fig. 10 gives a representation of a long train of ten pulses from 19:12 to 20:20 on April 21; their mean duration is ~~6.8 minutes (±~~408 ± 34 s~~)~~ with a larger variability (from 240 to 600 s). Moreover, we observe a companion series of instability pulses of heat separated from the main one.

3.4 AIII device maintained vertically

In experiments A1, A2, and A3 (Table 1), the device AIII is held vertically, with sensor ~~ch10~~T10 close to the heating source (placed on the floor). Results of experiment A3 are displayed in Fig. 11, in the form of a space-time presentation of the temperature level lines (as in Figs. 4, 5, 7, and 10). At each moment of time t_k ($t_k = t_0 + 20k$ in seconds) we report the value of temperature $T(h_i, t_k)$, h_i being the height at location of the i-th sensor (i=1, 2, …, 10~~); $t_k = t_0 + 20k$ in seconds.~~). A series of conspicuous dilatations or contractions of the T sections appear all along the graph; in general, the dilatations are sharp, the following contractions much slower. Unfortunately, no simultaneous horizontal recording exists (a single AIII device was available). Fig. 12 shows 3 hours (a~~-~~) and 30 minutes (b) of zoom of Fig. 11~~,~~.

As is evident from Fig.11, in the first 4 minutes after switching on the heat source at 12:00, the temperature T10, i.e. the nearest to the source, is rising slower, while the temperatures T6-T8 grow faster than at any of the other thermistors. At 12:09, the temperature T9 surpasses T6 and T7-T9 rise to their maximal values about 17-18°C. At this moment of time T10 continues to grow steadily, while temperatures T7-T9 start falling down. At 12:16 T10 rise above all the others and by 12:20 it is 1~~ hour 23 minutes long.~~.4-2.6°C higher than any of T1-T9. It appears that at about 12:30 the formation of a plume proceeds to its final stage lasting for about 30 minutes followed by rather regular dynamics with domination of T10 ~16.5-17°C and T9 ~15.4-16°C. From 13:00 on, and till the end of heating experiment, the average values of T10 and T9 are 16.9°C with σ = 0.2°C and 15.8°C with σ = 0.7°C, respectively. The difference in σ's allows for sporadic rise of T9 above T10, with cases are exemplified in Fig. 12. In particular, one can clearly observe rather quick propagation of the heat pulse through the entire plume from the floor to the ceiling of the room S15 (Fig. 12b).

3.5 Joint study of the various time series

The intermittent nature of the various temperature signals is further studied in Fig. 13. On the left side of the four plates in Fig. 13, the times of the 50 largest local maxima of the average temperature of all the sensors on the AIII bar are shown for each of the three experiments performed at height 1, 1.5, and 2 m (corresponding to experiments A5a, A7a, and A6a, respectively) in horizontal position and the experiment (A3) in vertical position. The empirical cumulative distribution function of the obtained 49 inter-event times, expressed in fractions of a day, is plotted on the right side of each plate. Table 2 summaries a few statistics of these inter-event times, when split into two classes of short and long intervals by the unique threshold of ~~12 minutes~~720 s. Except for the bar in vertical position (first line), the mean of the short times ranges from about ~~6~~360 to ~~8¼ minutes~~495 s, while the mean of the long times is about 5 or more times larger, with the largest ones lasting for a few hours. Overall, the statistics of the inter-event times is remarkably similar in all experiments.

4 Averaged temperature profiles

Assuming a Gaussian shape for the horizontal profiles of temperature difference $\Delta T(r,z) \sim \exp(-r^2/b^2(z))$, r being the radial distance from the maximum of $\Delta T(z)$ in the planes z = 1, 1.5, and 2 m, the "radius" $b(z)$ can be estimated from the measurements; it is found that this radius $b(z)$ is larger and the temperature difference $\Delta T(z)$ is several times lower than the values predicted by the Morton et al. (1956) model. Horizontal profiles show that the mean plume is deviated along the bar from the vertical of the source; it is likely that it also deviates in the perpendicular horizontal direction (no data). Measured temperatures should then be corrected before being compared with model predictions. Phase changes of water can also be a cause for temperature deviations being lower than predicted by the model, as well as some possible inadequacy of the model.

Let us consider now in brief the average temperatures T_h at height h taken over the 24 hours of each heating experiment. Vertical profiles (Fig. 14a) present a negative gradient $\Delta T_h = T_h - T_0$ in the lower part of the room, which turns positive in a layer about 50 cm thick below the ceiling. On the horizontal profiles (Fig. 14b), maximal averaged temperatures are observed on sensors 4 and 5, although the heat source is located below sensor 6. As expected, the width of the plume is getting wider when the AIII bar is placed higher, and the temperature profile presents the classical bell-shape form observed in thermal plumes generated by a point source. A Gaussian form of the radial temperature ~~radial~~ profile $T(r)$ in the plume ~~(where *r* is the radial coordinate)~~ is often presupposed in stationary plume models, which focus on the variation of mean width, velocity, temperature, versus the vertical coordinate (Morton et al., 1956; Landau and Lifshitz, 1987; Tritton, 1988; Guyon et al., 2015).

We will just make a few comments on our observations in the light of stationary models. Plumes belong to the class of free convection flows, maintained by temperature differences. ~~"~~Here we consequently follow the qualitative rule of thumb proposed by numerous authors: "No velocity scale is ~~provided~~generated by the specification of a free convection ~~situation".~~ parameter" (Tritton, 1988). Nevertheless, an estimate of the order of magnitude U of the velocity can be obtained, with some caution, from the Navier-Stokes equation for the steady state:

$$\vec{u}\overrightarrow{\nabla u} = -\frac{1}{\rho}\overrightarrow{\nabla \rho} + \nu\nabla^2\vec{u} - g\alpha\,\Delta T\vec{z} \qquad (2)$$

where $\vec{u}$ is the velocity, $\vec{z}$ the upward vertical unit vector, ρ is the air density, ν its kinematic viscosity (0.15 10^{-4} m^2s^{-1}), g the gravity acceleration (~10 ms^{-2}), α the expansion coefficient ($\alpha \sim T^{-1} \sim 3\ 10^{-3}$ K^{-1}), ΔT the temperature anomaly ~~taken~~. Taking the value of ΔT from Fig. 14b as 0.3 °C, ~~the buoyancy~~we get $g\alpha\,\Delta T \sim 10^{-2}$ ms^{-1}~~.~~ (the buoyancy). From $\vec{u}\overrightarrow{\nabla u} \sim U^2/L \sim g\alpha\,\Delta T$~~,~~ it comes $U \sim (g\alpha\,\Delta TL)^{½}$, which gives $U \sim 10^{-1}$ ms^{-1}.

For this estimate to be valid, we have to check *a posteriori* that the viscous force is weak compared to the inertial one: $\vec{u}\overrightarrow{\nabla u}$ / $\nu\nabla^2\vec{u} \sim UL / \nu \sim (g\alpha\,\Delta T\,L^3 / \nu^2)^{½} = Gr^{½} \sim 2^{-½}\,10^4$; Gr is the Grashof number, which ~~for~~ in ~~our~~the case of air has a large value. Note that the large value of the ratio UL / ν (i.e. the Reynolds number) found here also suggests turbulent flow in the plume (Turner, 1973).

The flux F of the buoyancy $B = g\Theta = g\alpha\,\Delta T$ at height z is:

$$F(z) = g\int_{S(z)} w(z)\,\Theta\,(z)\,ds \qquad (3)$$

w is the vertical mean velocity, S the area of the section of the plume. Let us take z = 1 m, $w \approx U \approx 10^{-1}$ ms^{-1}, S(1 m) ≈ 10^{-2} m^2~~; from~~. From Fig. ~~3b~~14b the mean of Θ in the section of the plume at the 1-meter altitude is $\int_S \Theta\,(1\text{ m})\,ds \approx 1.43\ 10^{-3}$ m^2.

Then,

$$F_{z = 1\text{ m}} \approx 1.4\ 10^{-3}\ m^4\ s^{-3} \qquad (4)$$

Let us compare this estimate of F with the flow of buoyancy delivered by the source:

$$F_0 = g\, \alpha\, P\, (\rho\, C_p)^{-1} \qquad (5)$$

P is the power of the source (100 W), ρ the air density at 12.5°C (1.236 kg m^{-3}), C_p the specific heat of air at constant pressure (C_p = 1006 J kg^{-1} K^{-1}). It comes

$$F_0 = 2.4\ 10^{-3}\ m^4 s^{-3} \qquad (6)$$

The comparison between F_0 and our estimate of F can be judged satisfactory. This agreement suggests that the measured energy flux in the plume itself corresponds to the energy delivered by the source; thus thermal losses, such as large radiation losses or interactions with the walls (Crouzeix et al., 2006), can be neglected at the level of the plume.

~~*Remark:* Assuming a Gaussian shape for the horizontal profiles of temperature difference Δ$T(r,z)$ ~ exp($-r^2/b^2(z)$), r being the radial distance from the maximum of Δ$T(z)$ in the planes z = 1, 1.5, and 2 m, the "radius" $b(z)$ can be estimated from the measurements; it is found that this radius $b(z)$ is larger and the temperature difference Δ$T(z)$ is several times lower than the values predicted by the Morton et al. (1956) model. Horizontal profiles show that the mean plume is deviated from the vertical of the source; it is likely that it also deviates in the perpendicular horizontal direction (no data). Measured temperatures should then be corrected before being compared with model predictions. Phase changes of water can also be a cause for temperature being lower than predicted by the model, as well as some inadequacy of the model.~~

5 Some global characteristics of the plume dynamics

We presented above (section ~~IV~~4) the average temperature profiles obtained from our heating experiments as a representation of stationary plume models, which raises some interesting questions (which will be touched upon below). The interest and novelty of our study, however, relies in the higher frequency content of our time series of temperatures in the plume (Figs. 3-13). Let us thus come back to the plume dynamics.

Consider $\bar{T}(t)$ being the average temperature recorded over the ten sensors on the bar. Fig. 15 shows the energy spectra of the series of the empirical first derivative of the average temperature, $(\Delta\bar{T}(t))/\Delta t$, in experiments A6a and A6c at 2 m height (top), A7a and A7b both at 1.5 m height (middle), and A5a and A5b both at 1 m height (bottom). The maximum peaks appear at periods of about 478 and 467, 474 and 388, 395 and 467 seconds respectively; the average is 445 seconds and the standard deviation 42 seconds.

From the comparison of the temperature variations ΔT(t) registered along the horizontal bar AIII disposed at the three heights of 1, 1.5, and 2 meters, it appears that (as already pointed out above) the curves $\Delta T_i(t)$ relative to the different sensors (i = 1, 2, … , 10), to a first approximation, are affine to each other:

$$\Delta T_i(t) = a_{ij}\, \Delta T_j(t) \qquad (7)$$

a_{ij} being (constants) parameters. For example, taking j = 5 (i.e., of the sensor ~~seeing~~which according to Fig. 14b is detecting the ~~large~~largest variations, ~~a_{ij} being (constants) parameters~~presumably, next to the plume axis),

$$\Delta T_i(t) \approx a_{i5}\, \Delta T_5(t) = b_i\, \Delta T_5(t) \qquad (8)$$

This observation is not trivial. First, it clearly confirms the significance of variations of a few hundredths of a degree and the quality of the calibration. Second, and more important, it demonstrates that the plume varies in time grossly “en bloc” in time.as a block. In other words, extrapolating a bit boldly and going from discreet local measurement to a continuous spatial function, we have:

$$\Delta T_z(r,t) \approx f_z(r)\ \theta(t) \qquad (9)$$

ΔT_z is, at each z, the product of a space function $f_z(r)$ by a time function $\theta(t)$. Making a step further, we assimilate $f_z(r)$ to exp(-r^2/b^2/r^2), b), b_i depending on z according to a self-similar law. Note again that we have available only three altitudes z (1.0, 1.5, and 2 m, respectively), and no simultaneous recording at two altitudes.

The causes of the observed instabilities remain unclear. The mean axis of the plume could be affected by unstable motions and distortions, especially given the fact that external influences cannot be completely ruled out before the construction of the partition wall (Fig. 1). Complementary experiments performed after the completion of the wall, however, indicated that the mean barycenter of the plume can indeed move, but that this effect is not dominating, and that the observed instabilities of the plume are not a consequence of slight plume motion, but large and intrinsic instabilities of the plume itself.

6 Discussion and conclusions

In this paper, we report on the temporal behavior of turbulent plumes in geophysical conditions, which still remains poorly known and rarely studied. The instabilities observed in our heating experimentsOur objective of studying these temporal fluctuations from the quasi-stationary states revealed well justified, as we indeed observed a rich set of temporal behaviours for temperatures in the plume itself and in the stratified environment in its vicinity as well. The instabilities observed in our heating experiments as pulses of high amplitude in air temperature time series, nevertheless, seem to be a universal and familiar feature. For example, in experiments simulating plumes with saline solutions in large tanks, (Kaminski et al., 2005; Carazzo et al., 2006; Carazzo et al., 2014), the recordings reveal the peculiar temporal instabilities of the plumes, with the occurrence of transient large voids, even close to the plume axis, and also rather high above the plume source (Fig. 16).

Our experiments and our data sets, while able to reveal important aspects of the instabilities, nevertheless, suffer from a number of limitations. First, we made only temperature measurements. Second, the ten sensors were attached every 20 cm on a 2-m long bar. Because we had only one moveable bar, no simultaneous recordings for different arrangements are available. Third, air velocity was not simultaneously measured and our temperature measurements could not be transferred into estimates of velocity. Fourth, the response time of our sensors (20 s) did not allow us to access the probably important higher frequency part of the temporal effects. Finally, the experimental room was subject to a small level of natural ventilation during our experiments, and an influence on the dynamical regimes of the plumes cannot be completely ruled out.

Despite of that, our experiments indicate that, in a first approximation, the temperatures $\Delta T(x,t)$ recorded versus time t along the horizontal bar, at various positions x above the source, suggest essentially spatially coherent trains of pulses arranged in a quasi-periodic manner, with durations of 360-400 s, separated by intervals of stability, which can last up to several hours. The local response function $\Delta T(x,t)$ thus appears as the product of a smooth spatial function ~~$S(x$~~$f_z(r)$ by a non-linear mechanism ~~F~~$\theta(t)$, generating a chaotic regime (note e.g. that doubling of period are observed). A Markovian process appears as an adequate description of the function $\theta(t)$ (Iosifescu, 1980; Blanter et al., 2006). It would be interesting to explain the value of the periods observed during quasi-periodic regimes, and that of the intermittent intervals of stability (up to several hours). Clearly, the observed factorization of $\Delta T(x,t)$ function is reminiscent of chaotic solutions of a system of non-linear differential equations mimicking the behavior of, sometimes complex actual dynamic systems~~.~~ (e.g., Morat et al., 1999). As an illustration, one may think of one coordinate of the celebrated system of the Lorenz equations (Lorenz, 1963). Such an exercise however cannot really be attempted for the dynamical plume, due to the limitations of our observations and additional important aspects of the problem. Indeed, the dynamic plume is the major acting ingredient of a filling box with non-adiabatic boundaries (Linden, 1990; Crouzeix et al., 2006~~).~~ b; Crouzeix et al., 2006-c). During a 24 hours experiment, heat is accumulated at the ceiling and exchanged with the ceiling and side walls, causing probably evaporation and condensation, and significant associated heat transport by phase changes of water. The hot air, thus cooled at the ceiling is then fed again into the plume, with a circulation time which is probably an important characteristic time of the plume dynamics, and contributing to the intermittent quasi-periodicity. Nevertheless, the plume integrates the complexity of the various heat relaxation scheme and feedback into an overall simple organization, with a first order factorization of the spatial and temporal variations. While numerical simulations that propose such a first order factorization have started to shed light on these mechanisms (Hernandez, 2015), experiments remain necessary to establish important properties.

Some aspects of this dynamics could be captured in the experiments performed in water tanks alluded to above (Fig. 16), and also point to the intermittent behavior of the reversals of the mean wind in Rayleigh-Bénard convection (Sreenivasan et al., 2002; Sugiyama et al., 2010). In the case of Rayleigh-Bénard convection, chaotic temporal variations arise despite the constant boundary conditions, in the absence of a source of motion, for a non-localized source of buoyancy. In the case of plumes in confined environments, the plume or jet itself is a source of velocity in addition to buoyancy (Hernandez ~~et al.~~, 2015; Lopez and Marques, 2013). Despite the variability of conditions, the observed dynamical behavior seems to be remarkably similar to the behavior of the flickering candle (Maxworthy, 1999), and could be considered, tentatively, as universal. These temporal fluctuations bear also astonishing similarities to the dynamics of smoke above a bonfire, or the structure of clouds. In more viscous media and geological time scales, the episodic temporal structure of deep mantle plumes, which bear important consequences in terms of the time structure of hot spot volcanism (Kumagai et al., 2008), could also reflect similar fluctuations around the stationary state. However, the apparent similarity of the situations may be due to the limited spatial sampling in our experiment. More elaborated and dedicated experiments are needed to study the temporal variations inside a turbulent plume and also in its environment. In confined situations, indeed, the plume dynamics might result from the interactions of the plume with its environment and the various relaxation times that it can provide.

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Underground environments offer a promising context where these poorly known aspects of fundamental physics could be studied fruitfully, potentially providing useful insights for situations of geophysical or industrial relevance.

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Tables

Table 1: Configurations of the experiments carried out in March-June 2003. Each was performed with a heat source of 100 W and lasted 24 hours. AIII position indicates the device orientation: V for vertical and H_z for horizontal at altitude z.

Name	Date	AIII position	Source raised	Screen	Sampling time
A1	03/10	V	-	-	20 s
A2	03/17	V	+	-	20 s
A3	03/24	V	-	+	20 s
A4	03/31	H_1	-	-	20 s
A5	04/07, 04/14	H_1	-	+	40 s
A6	04/21, 04/28, 05/05, 05/12, 05/19	H_2	-	+	120 s
A7	05/26, 06/02	$H_{1.5}$	-	+	~~120~~ 120 s

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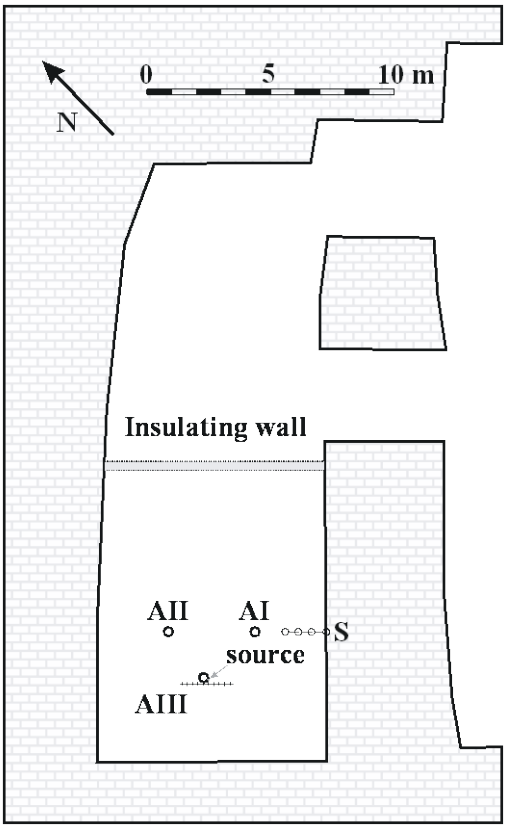
Table 2. Peak to peak inter-event time statistics: ID identifies the 24-hour heating experiment; AIII indicates position of the 2-m bar: V for vertical and H_z for horizontal at height z; N_s is the number of short (Δt < 12 minutes) intervals; N_l is the number of long (Δt > 12 minutes) intervals; E(Δt_s) is the average duration of the short intervals, in *s*; E(Δt_l) is the average duration of the long intervals, in *s*; columns n1, n2, and n3+ give the number of single, double, and multiple pulses, correspondingly.

ID	AIII	N_s	N_l	E(Δt_s), *s*	E(Δt_l), *s*	max(Δt), *s*	n1	n2	n3+
A3	V	26	23	227	3421	18840	15	3	6
A5a	H_1	29	20	357	3748	17560	12	5	7
A5b	H_1	22	27	395	2801	20840	17	10	4
A7a	$H_{1.5}$	24	25	495	2400	7680	20	10	2
A7b	$H_{1.5}$	25	24	432	2815	11280	19	4	6
A6a	H_2	30	19	432	2185	6360	10	5	7
A6c	H_2	31	18	449	2473	7560	13	4	6

Figures



5 **Figure 1: The Sketch of the experiment room S15 in the Vincennes quarry showing the location of temperature set-ups AI, AII, AIII, and S, and of the insulating wall installed in July 2003.**

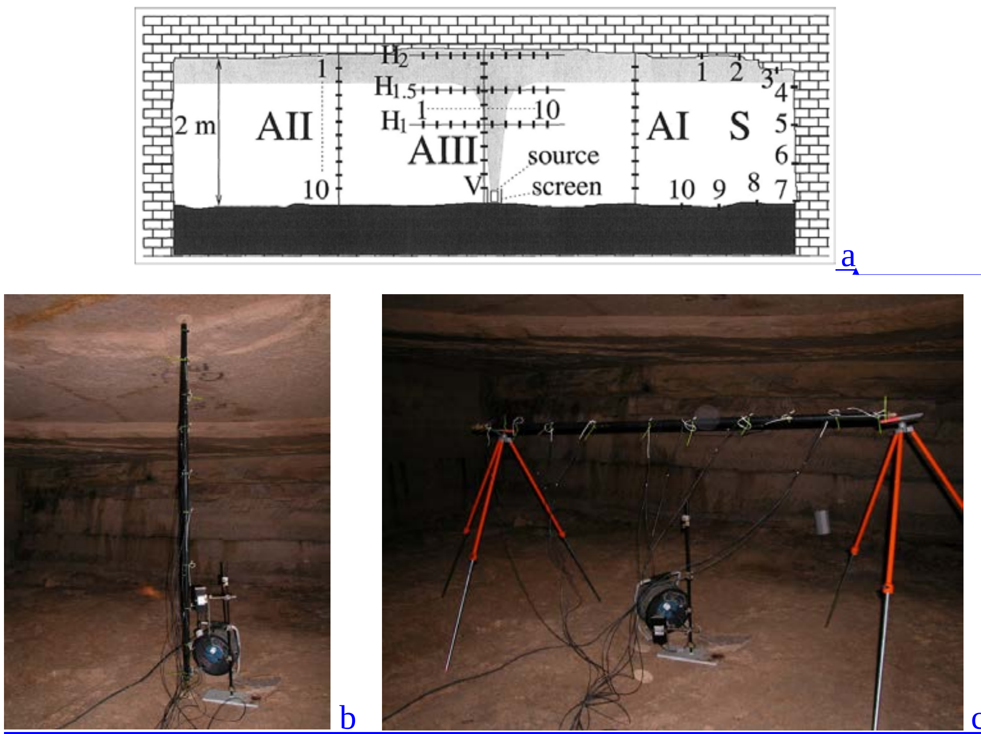


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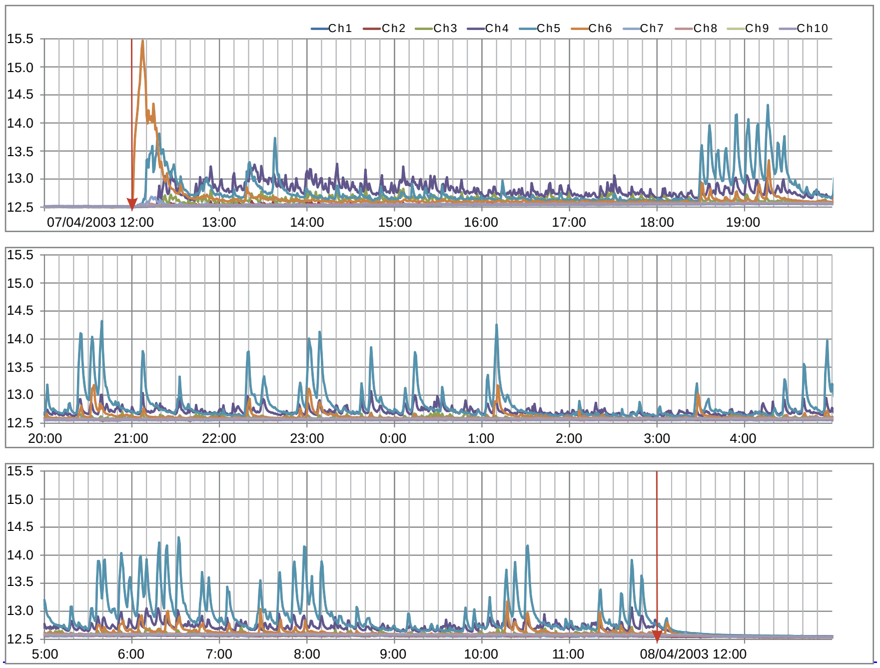
Figure 2: (a) Schematic cross-section of the experimental room S15 showing the four set-ups (AI, AII, AIII, and S) along with the positions of the temperature sensors. (1-10 for each set-up); (b, c) photos of the set-up AIII in advance the heating experiments A2 and A4 (Table 1).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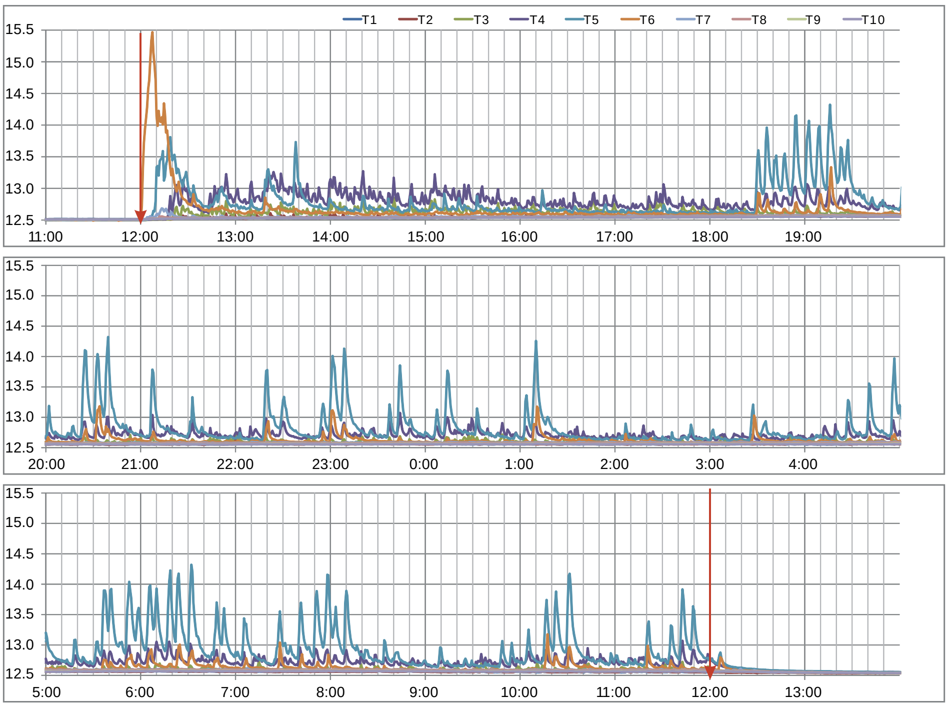

Figure 3: The temperatures in C° at 1-meter height 1 hour before, during, and 2 hours after the A5a experiment. T1, T2, … , T10 denote temperature series of the ten sensors on the AIII set-up.

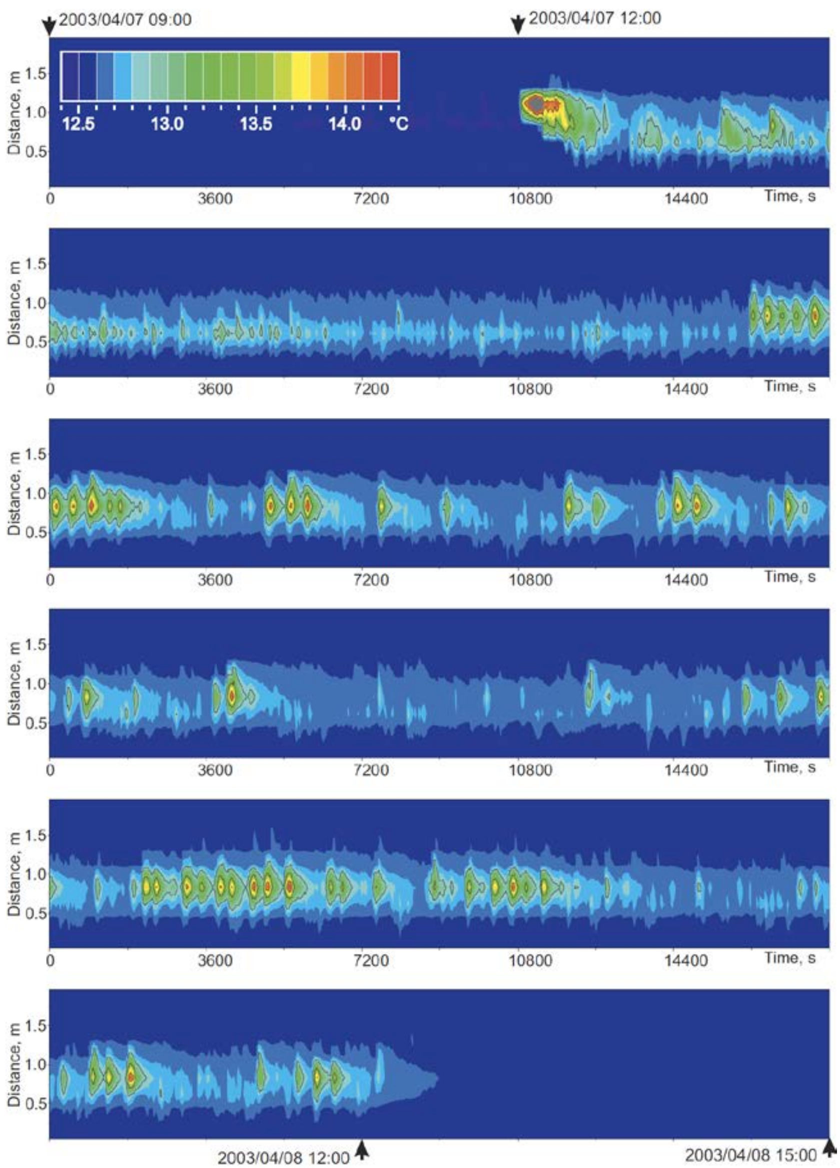

Figure 4: The temperatures 3 hours before, during, and 3 hours after the A5a heating experiment in space-time domain: temperature color-coded in C°; on the vertical axis are shown the location of the sensors on the horizontal 2-m bar; temporal tick marks on horizontal axis correspond to 3600 s = 1 hour.

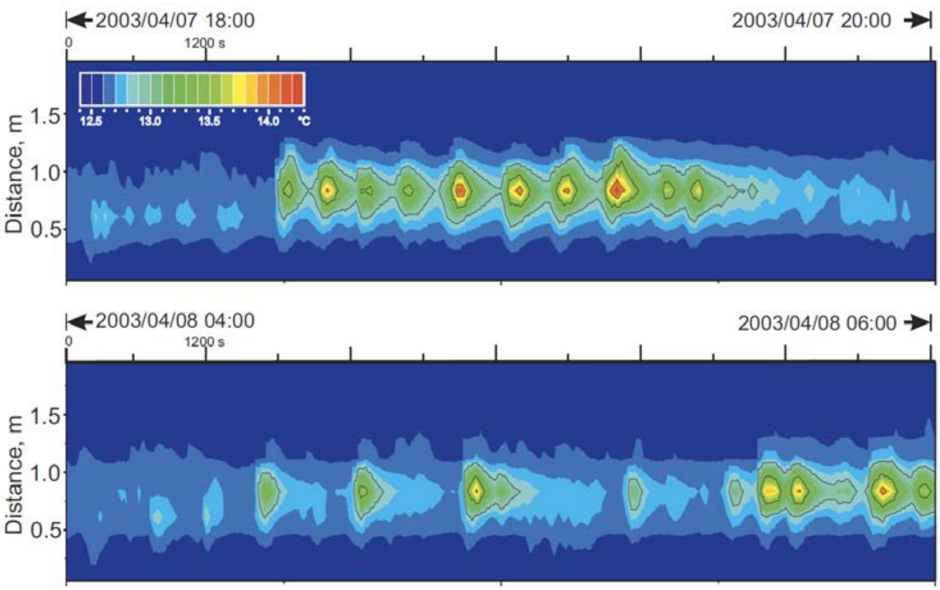

Figure 5: The temperatures in the space-time domain during two hours of the A5a heating experiment when a long train (upper plate) and a likely "doubling of period" (first half of the lower plate) of strong heat pulses are observed. Times of the beginning and ending are indicated for each plate.

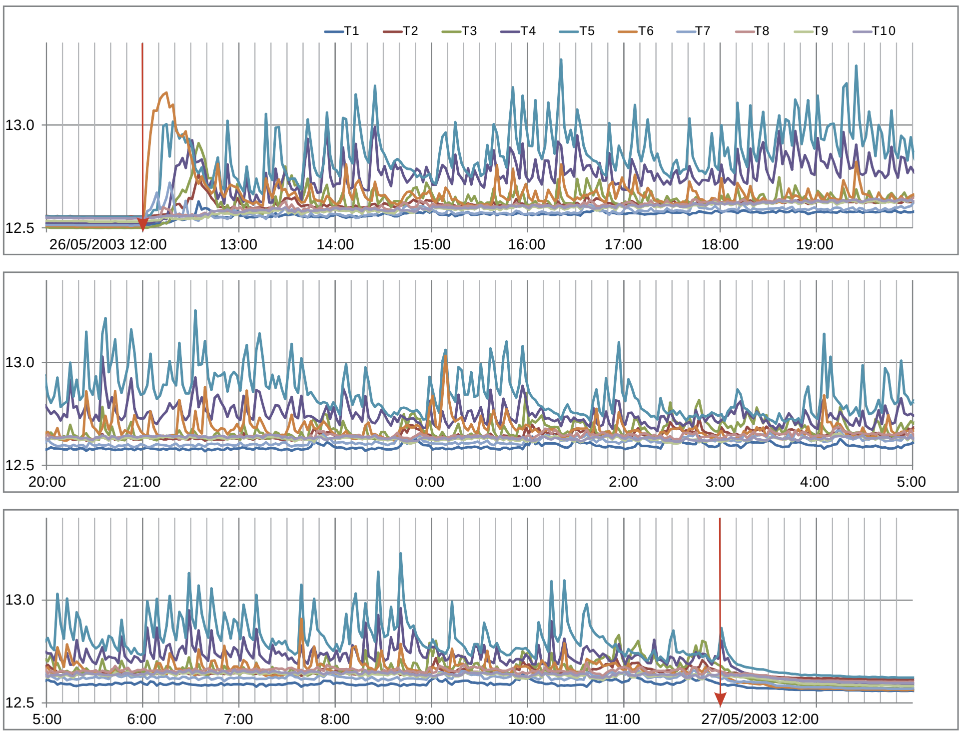

Figure 6: The temperatures in C° at 1.5-meter height 1 hour before, during, and 2 hours after the A7a experiment. **T1, T2, … , T10 denote temperature series of the ten sensors on the AIII set-up.**

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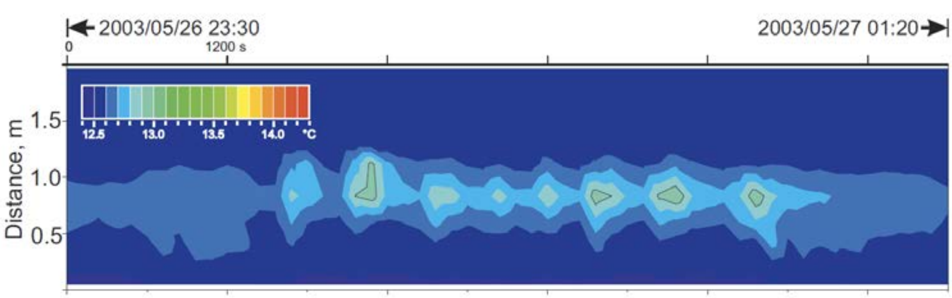

Figure 7: The temperatures in space-time domain during 110 minutes of the A7a heating experiment where a long "train" of strong heat pulses is observed. The color-coding is the same as in Figs. 4 and 5.

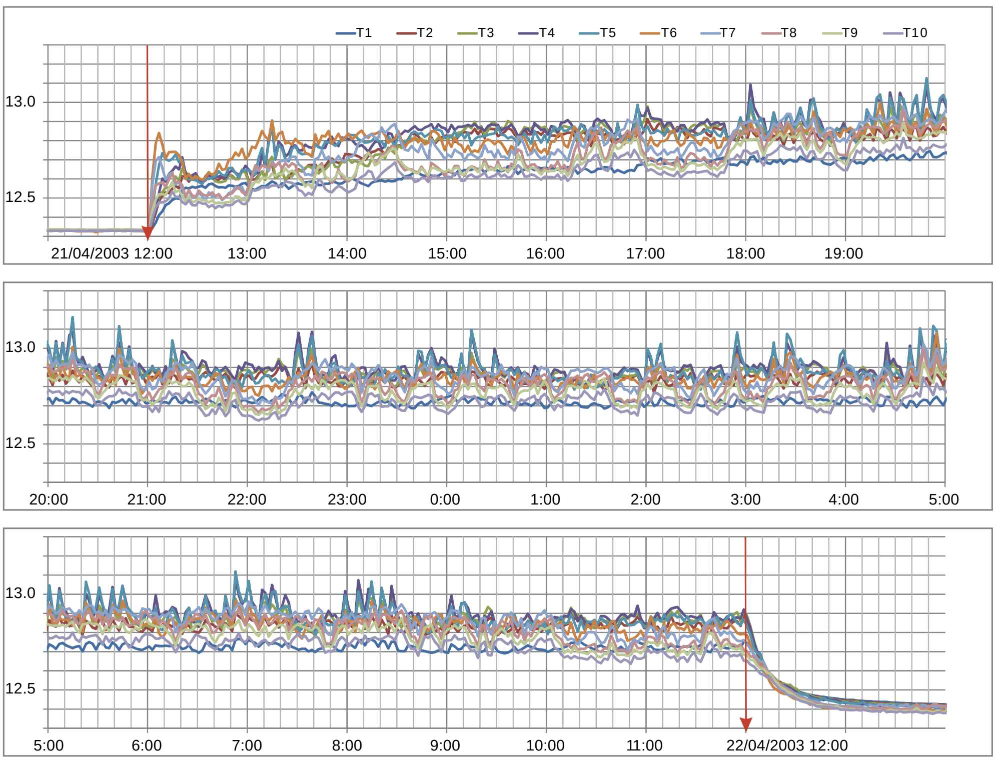

Figure 8: The temperatures in C° at 2-meter height 1hour before, during, and 3 hours after the A6a experiment. T1, T2, … , T10 denote temperature series of the ten sensors on the AIII set-up.

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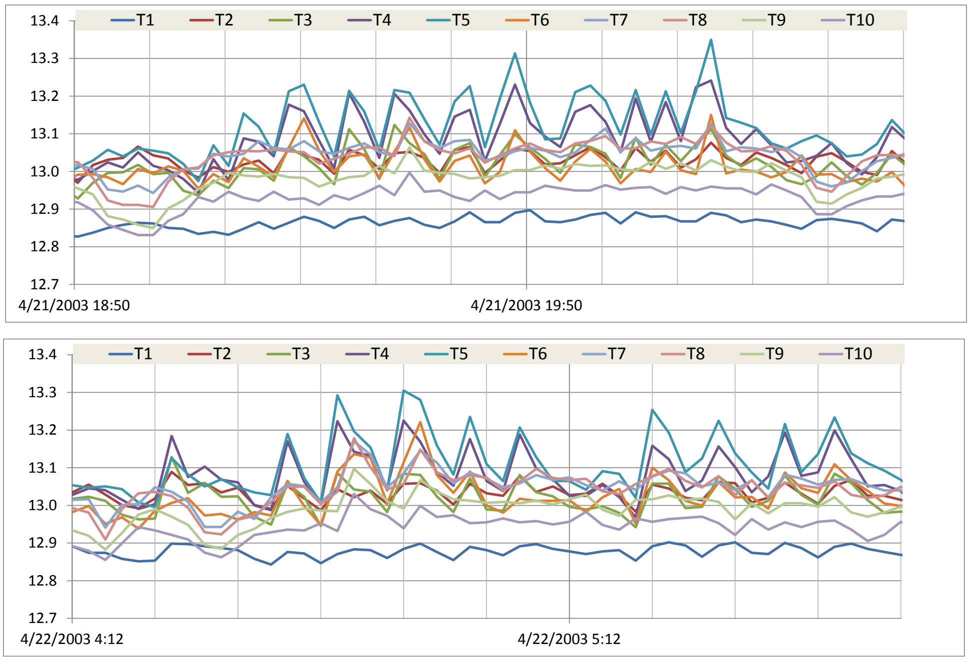

Figure 9: The temperatures during the A6a experiment heating in the periods 2003/04/21 18:~~54:52~~50-2003/04/21 20:40 (upper plate) and 2003/04/22 04:12~~:52~~-2003/04/22 05:52~~:52~~ (lower plate): Temperature is given in C°. T1, T2, … , T10 denote temperature series of the ten sensors on the AIII set-up.

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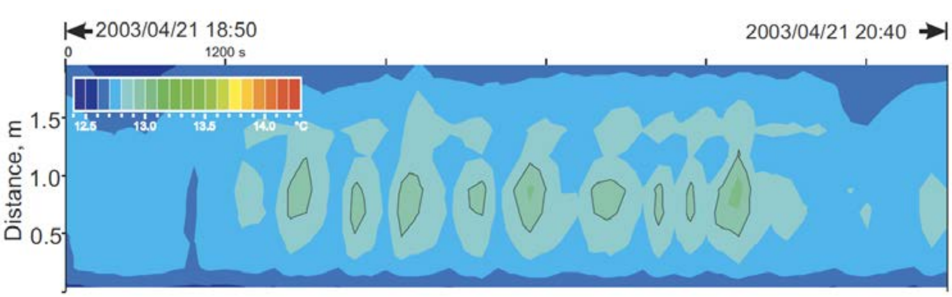


Figure 10: Temperatures in space-time domain during 110 minutes of the A6a heating experiment where a long "train" of strong heat pulses is observed. The colour coding is the same as in Figs. 4 and 5. Note the presence of concomitant pulses aside of the main series.

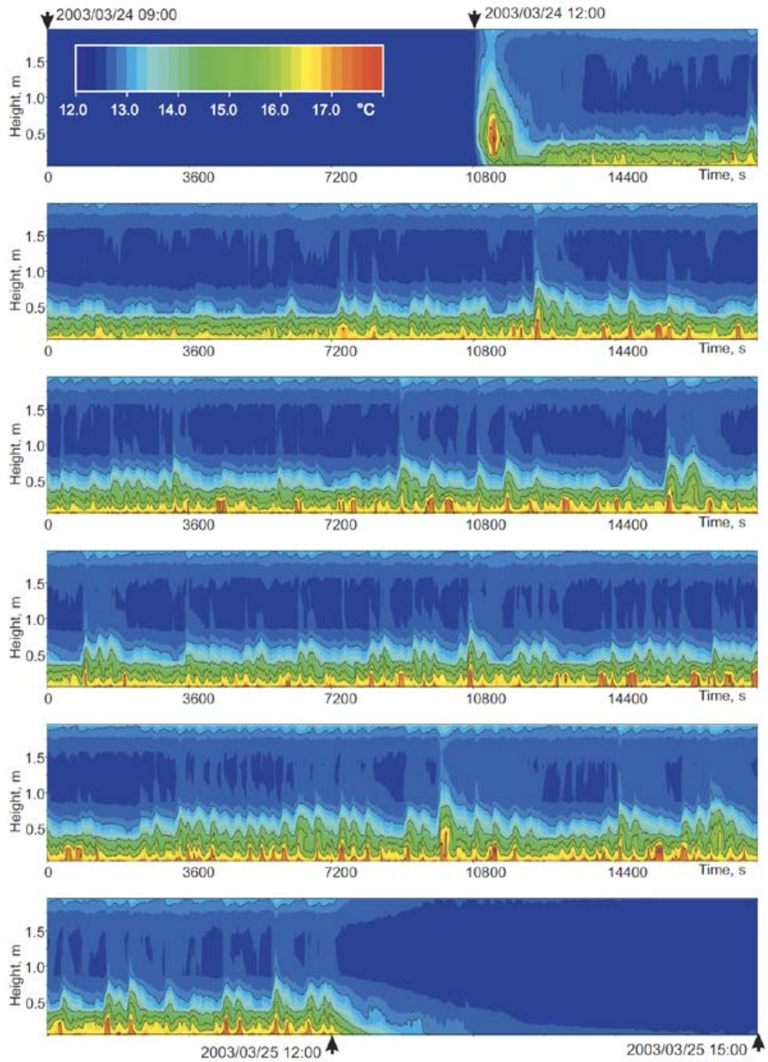
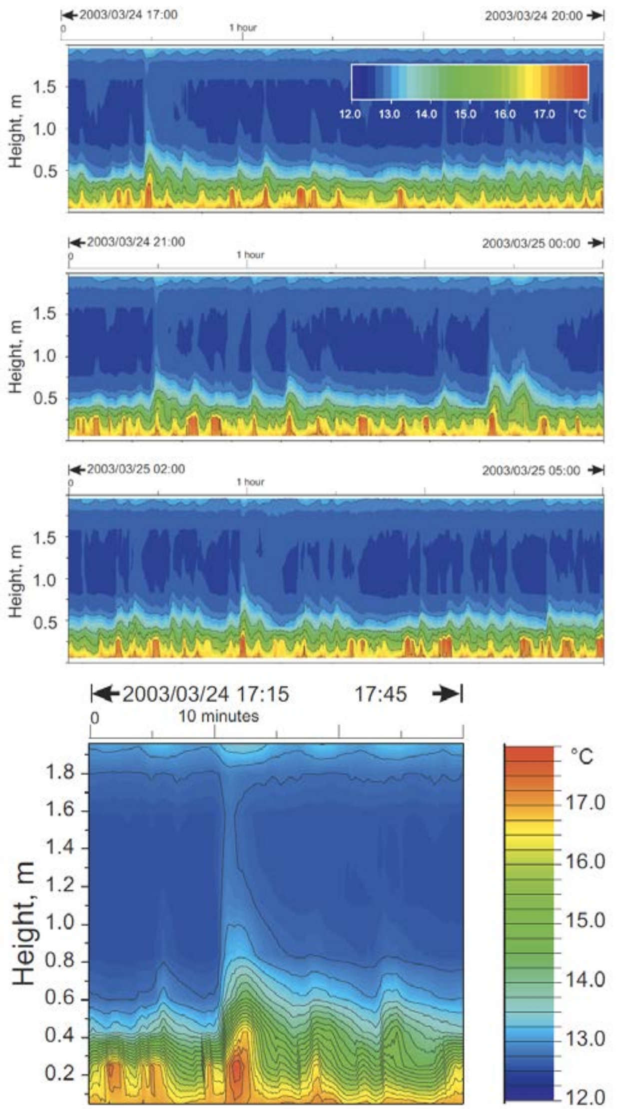


Figure 11: Temperatures before, during, and after the A3 heating experiment in space-time domain: Temperature color-coded in °C; on the vertical axis is represented the position of the sensors on the vertical bar (from 10 at the bottom to 1 on the top).



a

b

Figure 12: Temperatures in space-time domain during the three 3-hour intervals (a) and 30 minutes (b) of the A3 heating experiment.

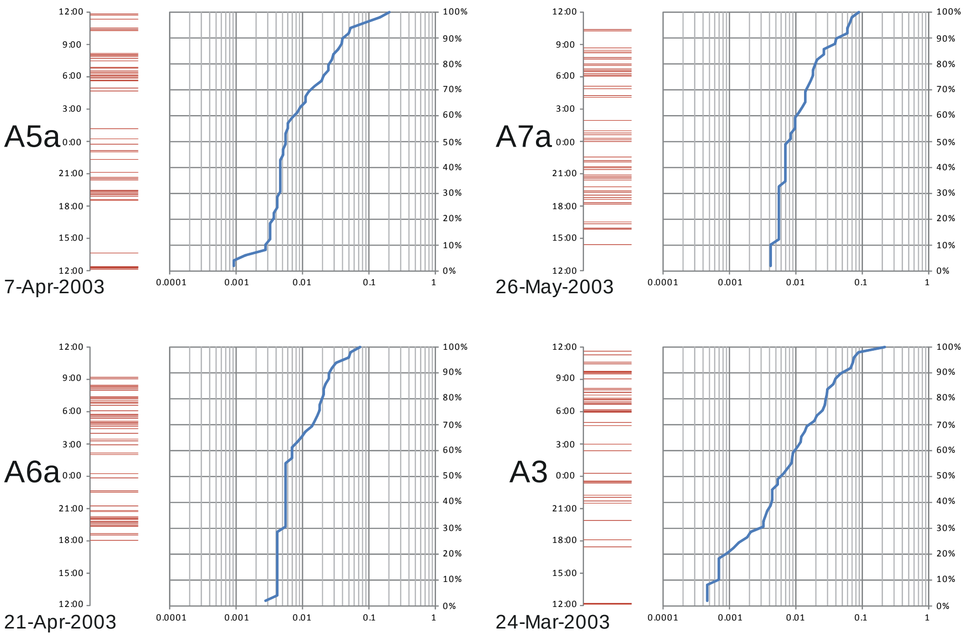
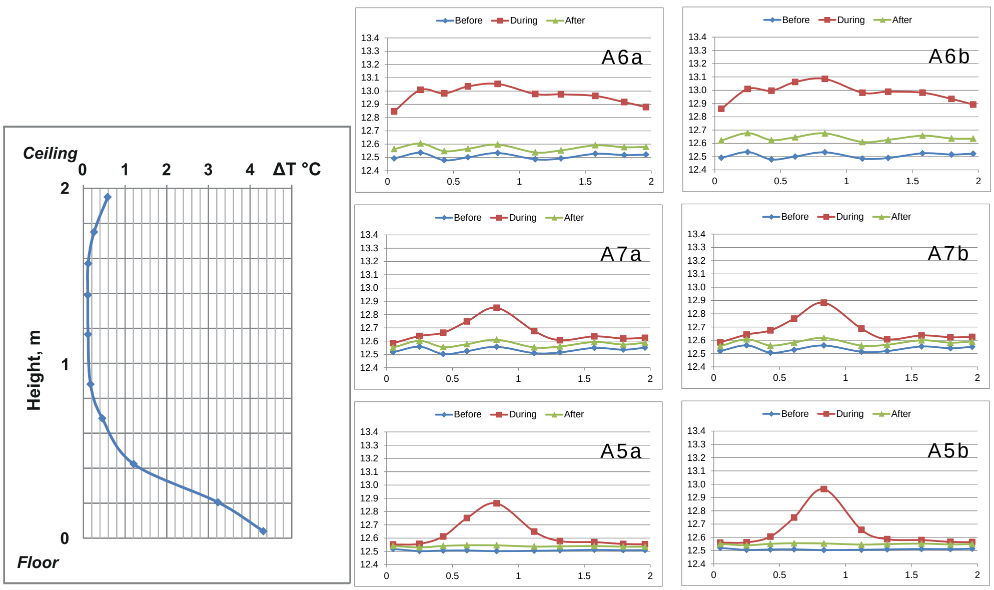


Figure 13: Times of the 50 largest local maxima of the average temperature of all the sensors on AIII bar (left), and the empirical cumulative distribution function of their inter-event times, in units of fractions of a day (right) observed in the A5a, A7a, A6a, and A3 experiments. Time increases when going up.



a b

Figure 14: (a) The difference ΔT = T_h – T_0 of the average temperatures in 24 hours during (T_h) and 12 hours before (T_0) a heating experiment with a vertical bar AIII (experiment, A3). (b) The average temperatures on a horizontal bar AIII in 12 hours before (blue), 24 hours during (red), and 12 hours after a heating experiment at 2-m (top), 1.5-m (middle), and 1-m (bottom) heights (experiments A6a, A6b, A7a, A7b, A5a, and A5b, correspondingly).

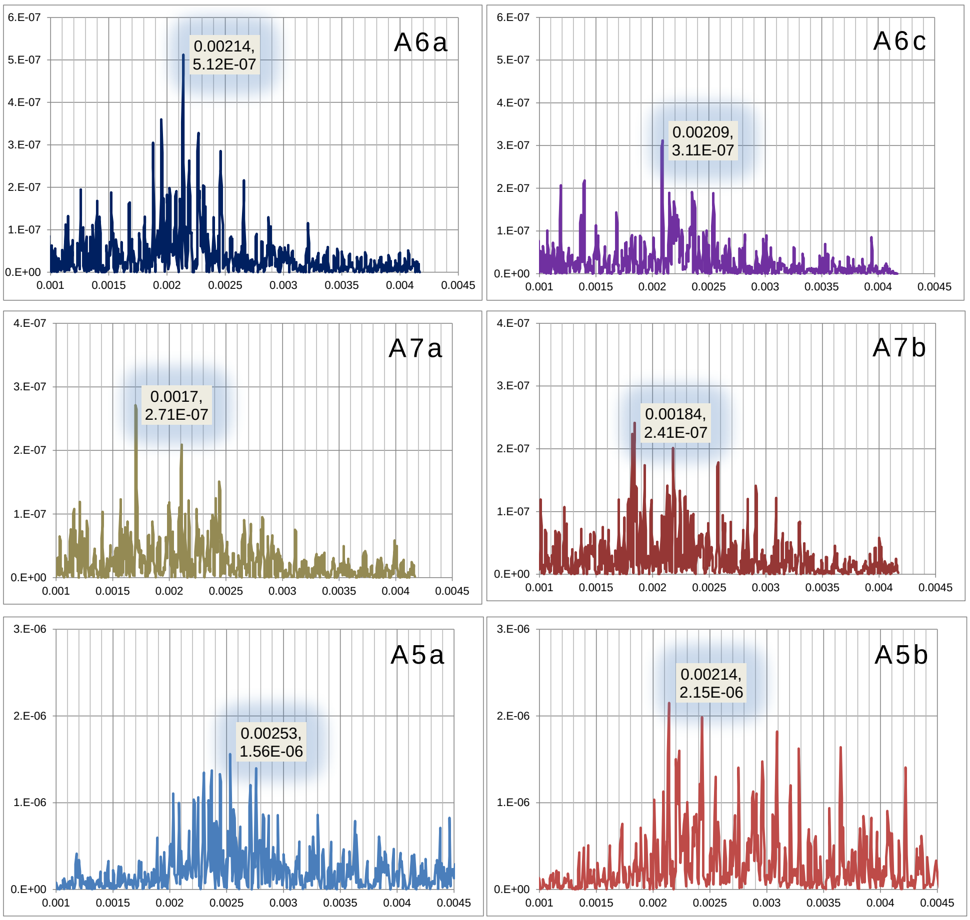


Figure 15: The power spectra, as a function of frequency in Hz, of the first derivative of the average temperature during A6a, A6c (both with the bar at 2 meters, top), A7a, A7b (both with the bar at 1.5 meters, middle), A5a, and A5b (both with the bar at 1 meters, bottom). Each maximum is supplied with the frequency and the power.

Figure 16: A snapshot from a movie (~~Carrozo~~Carazzo et al., 2014, Supplementary Material S3), recording an experiment simulating a volcanic vent in a stratified water tank.