Abstract The numerical simulations of pyroclastic flow propagation along the Vesuvius slopes, described in a companion paper (Todesco et al. 2002, this volume), are herein analyzed in terms of the local variables of the flow with the aim of assessing quantitatively pyroclastic flow hazard in the Vesuvian area. The analysis was carried out by determining the timewise behavior of selected hazard variables of the flow – such as density, velocity, temperature, dynamic pressure, and pressure perturbation – at various distances from the crater and in the proximity of ground level. Density, velocity, temperature, and pressure of the flow were directly computed by the model during a period of about 15 min. These variables were then used to estimate two additional variables: the dynamic pressure of the flow and the isotropic pressure variation with respect to the undisturbed atmospheric pressure. These two variables may be both critical for the assessment of damage produced by the flow on engulfed buildings and people indoors. Dynamic pressure is associated with the motion of the flow, whereas the isotropic pressure variation accounts for the large-scale dynamics of the process, including the effect of the weight of the flow and the propagation of pressure waves into the atmosphere. A post-processing of the time series produced led to the definition of peak curves of the main hazard variables as a function of distance from the vent. The results indicate that pyroclastic flow propagation is an unsteady process producing strongly transient stresses on the structures encountered. Mass flow-rate per unit angle of propagation of the flow is confirmed as the main parameter controlling the flow dispersal and, therefore, the intensity of dynamic pressure and isotropic pressure variation. For the worst case considered, i.e., a mass flow-rate of $5 \times 10^7$ kg s$^{-1}$ spreading over a sector of 90°, the two contributions have a similar magnitude, with typical values ranging between 3 and 1 kPa in the medium (4 km) and distal (7.5 km) regions of the flow, respectively. For this case, no significant variations are predicted between the southern and northern axisymmetric profiles assumed. Production of missiles transported by the flow is expected to represent an additional significant hazard associated with the flows.

Keywords Dynamic pressure · Hazard assessment · Pyroclastic flows · Temperature · Vesuvius

Introduction

Pyroclastic flows are one of the most destructive phenomena produced by explosive volcanoes. The term pyroclastic flow is used here in a general sense to mean a pyroclastic density current, irrespective of particle concentration. Historical eruptions at Vesuvius, such as the famous 79 and 1631 eruptions, provide clear evidence of the disastrous pyroclastic flow impact on urbanized areas (Sigurdsson et al. 1985; Rosi et al. 1993; Cioni et al. 2000). Starting with the eruption of Mt. Pelée, Martinique, in 1902, which completely destroyed the city of Saint Pierre, killing about 28,000 people (Lacroix 1904), the last century also saw many disasters produced by the occurrence of pyroclastic flows. Eruptions at La Soufrière (1902), Taal (1911), and Lamington (1958) all produced more than 1,000 deaths each and large areas of complete
devastation all around the eruptive center (Taylor 1958; Baxter et al. 1998, and references therein). More recently, the destructive effects of pyroclastic flows were observed at Mount St. Helens (1980), Unzen (1991), Merapi (1994), and Soufrière Hills Volcano, Montserrat (from 1995 onward), where, fortunately, the damage and number of fatalities was much more limited (Nakada 2000). Such recent events also showed that pyroclastic flows, although unsurvivable in the more proximal regions, may not be lethal in the more distal regions affected by the flow, especially if some protection is provided by resistant buildings (Baxter 1990; Baxter et al. 1998). Therefore, it is interesting and useful to study pyroclastic flow hazard through the analysis of those variables that are more significant for the quantification of the impact that this phenomenon produces on the structures and people present within the hazard areas. This analysis is even more critical for the Vesuvian area, and for several other large cities and conurbation areas threatened by explosive volcanoes (Naples and Campi Flegrei, Italy; Mexico City, Mexico; Seattle, USA; Kagoshima, Japan), where several hundreds of thousands people live along the volcano’s flanks (Tilling and Lipman 1993; Pyle 1995) and, therefore, even in the event of a partial failure of the evacuation plan, there would still be a very high risk for several thousands of people (Baxter 2000).

The impact on people and buildings as they are engulfed by a pyroclastic flow is difficult to evaluate, and it is only recently that an attempt has been made to quantify and analyze the type of stresses associated with pyroclastic flow. Valentine and Wohletz (1989a) were the first to investigate the destructive potential of pyroclastic flows by using numerical models. By means of a two-phase gas-particle flow model (Valentine and Wohletz 1989b), they described the radial and temporal evolution of a number of pyroclastic flows produced by collapsing columns with mass flow-rate in the range of $4 \times 10^{8} - 10^{9}$ kg s$^{-1}$, and analyzed their hazards in terms of velocity, temperature, and dynamic pressure. Similarly, Baxter et al. (1998) analyzed the pyroclastic flow simulations of Dobran et al. (1994) at Vesuvius, in order to quantify more precisely the possible effects on people outdoors engulfed by the flow. In that work, special emphasis was given to the definition of two critical isolines (i.e., 0.1 kg m$^{-3}$ for particle concentration in the air and 200 °C for temperature) corresponding to unsurvivable conditions for humans. The study clearly indicated the different propagation of the two isolines, and suggested that respiratory problems would represent the main risk factor for people outdoors in the more distal portion of the flow.

An estimation of damage produced by typical stresses associated with pyroclastic flows was also made. Blong (1984) briefly outlined the damage that pyroclastic flows cause to the structures involved. Valentine (1998) tried to evaluate more precisely the impact of pyroclastic density currents on structures by reviewing the observations of damage from nuclear explosions and comparing the main effects of the two phenomena. More recently, Spence et al. (2000) and Zuccaro et al. (2000) carried out structural vulnerability surveys in the Vesuvian area with the aim of assessing the integrity and resistance of several building components to pyroclastic flow actions.

In this paper we analyze the numerical simulations of pyroclastic flow propagation presented in the companion paper (Todesco et al. 2002), which describe the role of important system parameters on flow evolution (including mass flow-rate per unit angle of propagation of the flow, topographic profile, duration of the flow feeding, and initial magma properties). In particular, we now focus on the local properties of the flow, in order to obtain the necessary data for evaluating the impact of pyroclastic flows on people and structures engulfed by them. The analysis was performed by determining the temporal evolution of selected hazard variables of the flow, sampled at around ground level and at various distances from the crater. The local behavior of the flow variables is clearly related to the large-scale evolution described in the companion paper and also makes possible a better understanding of the emplacement dynamics of the flow. A post-processing of the time series produced led to the definition of peak curves of the main variables analyzed as a function of distance from the eruptive center. Finally, an estimation of the additional hazard associated with the production of missiles carried by the flow was performed. The information derived from this work and the results of human survival and structural vulnerability studies were then integrated in order to obtain quantitative risk scenarios for a pyroclastic flow event in the Vesuvian region (Baxter 2000).

**Description of the flow variables analyzed**

In order to obtain useful information that could be combined with human and structural vulnerability studies, a set of specific flow variables was analyzed. Some of them derive directly from the output data of the numerical model, whereas some others were computed as a function of the output variables after simple manipulations. The volumetric fraction of particles in the air and the gas temperature of the flow (as described in several figures of the companion paper) belong to the first group, whereas the dynamic pressure of the flow as well as the pressure variation between the local isotropic pressure of the flow (computed by the model) and the pressure of the undisturbed standard atmosphere (representing the initial condition imposed on the computational domain) belong to the second group.

As far particle in-air concentration is concerned, it is well established that a minimum density of $0.1$ kg m$^{-3}$ of inhalable dust ($<100$ µm) can cause asphyxia (Baxter 1990; Baxter et al. 1998). Such a concentration of particles corresponds approximately to a volumetric particle fraction of $3 \times 10^{-5}$, which, in all simulations performed, is observed very close to the pyroclastic flow head. In other words, as already predicted by Baxter et al. (1998), unrespirable conditions exist for people outdoors all over...