

# Drivers of severe air pollution events in a deep valley during wintertime: A study case from the Arve River Valley, France.

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## ABSTRACT

The Arve river valley airshed in the French Alps experiences particularly severe air pollution during wintertime stable atmospheric conditions associated with persistent cold-air pools. PM<sub>10</sub> data recorded in the region indicate that the urbanized area of the central basin-shape section of the valley is generally the most polluted, with a harmful impact on the health of inhabitants. In the present work, we examine the air pollution transport potential of the Arve river valley airshed using results from high-resolution numerical simulations of a cold-air pool documented as part of the Passy-2015 field campaign. Passive tracers were used to model PM<sub>10</sub> with emissions provided by a detailed inventory developed by the local air-quality agency. The observed differential in PM<sub>10</sub> levels between valley sections was well captured by the numerical model and could not be explained solely by the differential in emissions. The stagnation, recirculation and ventilation potential of the airshed was evaluated spatially and temporally using integral quantities. The analysis indicated that the central basin-shape section of the valley is poorly ventilated and hence air pollution there would originate mostly from local emission sources. This stagnation zone appears to be almost decoupled from the rest of the airshed. The airshed was decomposed in separate valley sections so as to quantify the fate of the pollutants emitted within each section. Air pollution apportioned according to the contribution of emissions from the different valley sections shows that indeed the central basin-shape section is dominated by local sources. The situation was found more complex in the valley sections further downstream, where the contribution from the sum of the non-local sources can be as large as that from local sources. This study allows to identify the origin of the strong pollution in the Arve river valley, through the link between the local topography, emission sources and pollutant transport.

## 1. Introduction

During the winter season, mountainous areas are affected by episodes of severe air pollution. This occurs when atmospheric stability increases due to the formation of a temperature inversion that suppresses vertical mixing in the lower atmosphere (Chazette et al., 2005). Particulate pollution is of particular concern as it has a strong effect on human health, from asthma to increased risk of heart attack (Anderson et al., 2012), and as early as the pregnancy (Guxens et al., 2014).

The relationship between meteorology and high concentration of particulate matter (PM) in the atmosphere has been explored extensively in the literature. Smith et al. (2001) used computer-calculated trajectories of air masses together with relevant meteorological data to interpret a three-year-long data set (1995-1997) of PM<sub>10</sub> (particles with an aerodynamic diameter less than 10 μm) collected in London in

the United Kingdom (UK). The model proved to be able to describe well 60 to 65 % of the observed variation of PM<sub>10</sub> in this time period. It was concluded from this study that the local climate is not the main driver of concentration peaks; in fact, an advection of PM<sub>10</sub> from external sources was shown to play an important role by adding in some cases up to 20 μg m<sup>-3</sup> to the concentration recorded in the city. Vardoulakis and Kassomenos (2008) analyzed a three-year-long data set (2001-2003) to explore the relationship between concentrations of PM<sub>10</sub>, other pollutants (such as carbon monoxide and nitrogen oxides) and meteorological variables in two European cities (Athens, Greece and Birmingham, UK). The authors found a positive correlation during the cold season between PM<sub>10</sub> concentration, low wind speed and solar radiation, which are normally associated with stable boundary layers.

The impact of stable layers on air quality in complex terrain is well known to be more significant than over flat regions. Topographic effects lead to stronger and deeper temperature inversions that block vertical ventilation and prevent mixing of pollutants which is known as cold air pools. The later may results in long periods of poor air quality and fog, depending on the sources of pollution and the amount of air humidity, respectively. In the urbanized Salt Lake valley (Utah, USA) for example, Whiteman et al. (2014) studied

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the relationship between local weather conditions and particulate air pollution in the winter season using a 40-year-long data set (1973-2003).  $PM_{10}$  concentrations in the area were found to be highly correlated with the valley heat deficit, a measure of atmospheric stability, especially on days with snow-covered surface, low clouds and fog, which are often associated with persistent (long-lasting) pollution episodes. Neemann et al. (2015) investigated the relationship between the development of a cold air pool and high concentrations of pollutants in the Uintah Basin, Utah, USA, for a one-week long pollution episode in February 2013. Numerical model results showed a high sensitivity of boundary-layer development and ozone concentrations to snow cover. By increasing surface albedo and reducing short-wave radiation absorbed by the surface, snow cover leads to a colder air near the surface and a more stable boundary layer, leading to higher concentrations of pollutants. Largeron and Staquet (2016) investigated the relationship between the dynamics of persistent cold air pools (PCAPs) and episodes of high particulate pollution during the winter of 2006-2007 in the Grenoble valley in the northern French Alps using data from ground-based weather and air quality stations (the acronym AQS will be used when more convenient). A criterion based solely on the temperature difference between the valley floor and the valley top was developed to detect episodes associated with persistent temperature inversions in this deep valley. Nine episodes were identified during the winter, all being associated with high particulate pollution mainly due to local emissions. Only one pollution episode during that winter was not related to a temperature inversion, pollution concentration being due to long-range transport.

All previous studies indicate that the strength and duration of wintertime temperature inversions in complex terrain control the local concentration of pollutants. The determination of the resulting spatial and temporal distribution also requires the knowledge of the rate and location of local emission sources (as well as atmospheric chemistry). In the present study we focus our attention on the Arve river valley located in the northern French Alps (see Fig. 1). This valley has experienced high levels of particulate air pollution during PCAPs events in the winter season since  $PM_{10}$  concentration is recorded (Piot, 2011), in the sense that European standards set by the Directive 2008/50/EU are exceeded (that is, more than 35 days a year display a daily average value of  $PM_{10}$  concentration greater than  $50 \mu\text{gr m}^{-3}$ ). The small town of Passy in the Arve river valley, with about 11 000 inhabitants, is one of the main concerns of local authorities (Atmo-Auvergne-Rhône-Alpes, 2018).

During the winter of 2014-2015, a field campaign was conducted around the town of Passy (Staquet et al., 2015; Paci et al., 2017). The main objective of this field campaign named Passy-2015, was to characterize the atmospheric dynamics in this section of the Arve river valley and to relate these dynamics to pollution episodes. A strongly polluted PCAP event occurred between 6 and 13 February, which was associated with the first intensive observation period (IOP1) of the field campaign. Using data of this IOP1, Chemel

et al. (2016) explored the relationship between the temporal variability of  $PM_{10}$  concentration and that of the valley heat deficit. When daily-averaged values are considered, the authors found that the determination coefficient (square of the correlation coefficient) between the valley heat deficit and the  $PM_{10}$  concentration was high and equal to 0.69. However, the hourly evolution of the  $PM_{10}$  concentration was found to be relatively complex and could not be explained simply by the hourly variability of the heat deficit of the valley. The concentration of  $PM_{10}$  in the lower atmosphere is affected by variables such as local emissions of  $PM_{10}$  and local dynamics at the position where the measurement is made. An analysis of local atmospheric circulation was performed by Sabatier et al. (2018) for a section of the Arve river valley using data from a Doppler Lidar during IOP1. The authors attempted to explain the high levels of  $PM_{10}$  recorded and the rather special spatial distribution of pollutants along the valley during this episode. As expected, the atmospheric dynamics during the episode were characterized by a strong temperature inversion together with calm winds that prevented the ventilation of pollution out of the valley. In fact, light winds favored the formation of hot spots of high  $PM_{10}$  concentration, highlighting the important role of local wind dynamics in the valley. Both studies provided important insights in the understanding of the severe pollution episodes recorded in this section of the valley but also pointed out the need for numerical simulations to better understand this complex situation.

Arduini et al. (2020) used results from high-resolution numerical simulations to explore the local and non-local meteorological drivers of the PCAP event associated with IOP1. The authors analyzed the different stages of the event and pointed out the importance of the tributary valleys during the persistent stage of the PCAP, which together with the advection of air from above determine the height of the inversion layer. Throughout the episode, local and non-local interactions took place between the dynamics in the valley, the flows in and out of its main tributaries and the synoptic flow. This work provided a detailed account of the atmospheric dynamics during the PCAP event, which as shown in other studies (e.g., Silcox et al. 2012, Green et al. 2015, Baasandorj et al. 2017), have a determinant role in the accumulation of pollutants in complex terrain. However, the origin of the pollution episodes and the horizontal heterogeneity in the distribution of pollution in the valley remain outstanding issues.

The present work relies on numerical simulations of IOP1 of the Passy-2015 field campaign to study the drivers of particulate air pollution in the section of the Arve river valley near Passy. For this purpose a configuration similar to that presented in Arduini et al. (2020) is used, in which the emission inventory developed by the local air quality agency is implemented. The numerical model and the emission inventory are described in Sect. 2. In Sect. 3 the temperature and velocity fields and the  $PM_{10}$  concentration in the valley atmosphere as computed by the model are compared to data from the field campaign and recorded at the air quality

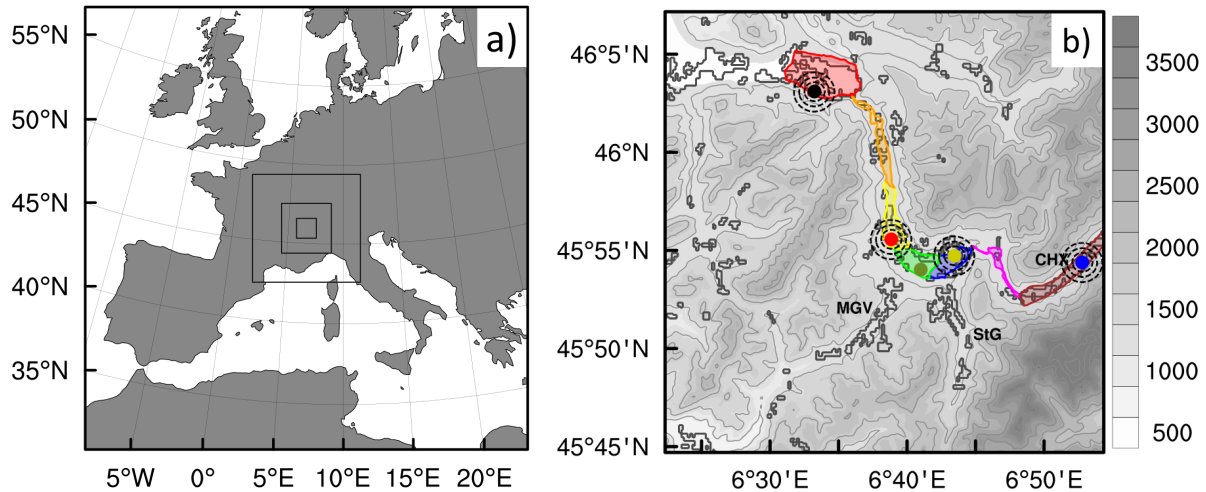


Figure 1: Domains d01, d02, d03 and d04 used in the numerical modelling of the Arve river valley (domains d02 to d04 are indicated with boxes). b) Topographical representation of the innermost domain d05. Black contours indicate urban areas in the domain. The locations of the air quality stations in the zone are marked with color dots: Chamonix (blue), Passy (yellow), Sallanches (red) and Marnaz (black). The exact locations of the stations are documented in Table 3. The location of the main measurement site in the Passy-15 field campaign is denoted with the green dot. The black letters indicate the main tributaries leading to the cities of Megève (MGV) and Saint-Gervais-les-Bains (StG). The Passy valley defined in the text is decomposed here into seven color areas, to facilitate the analysis (see section 4).

156 stations, respectively. The spatial distribution of  $PM_{10}$  con-186  
 157 centration in the valley predicted by the numerical model is re-187  
 158 presented in Sect. 4. The origin of this distribution is re-188  
 159 lated to stagnation and ventilation zones computed in Sect.189  
 160 5. The local and non local contributions to pollution in each190  
 161 air quality station are analyzed in Sect. 6. Finally, conclu-191  
 162 sions along with a discussion are presented in Sect. 7.

## 163 2. The numerical model

### 164 2.1. The Passy valley

165 The Arve valley is located in the north of the French197  
 166 Alps, near the French-Swiss border (see Fig. 1). In the198  
 167 present paper, we focus on the section of the valley near199  
 168 Passy, named the Passy valley as in Arduini et al. (2020) (see200  
 169 Fig. 1b). This valley section involves three other cities, Sal-201  
 170 lanches (16,700 inhabitants) and Marnaz (5,500 inhabitants),202  
 171 located downstream of Passy, and Chamonix (8,900 inhab-203  
 172 itants) located upstream. The altitude of the valley floor in204  
 173 Passy is about 560 m above sea level (a.s.l.). It decreases205  
 174 downstream along the 24 km length of the valley to 475 m206  
 175 a.s.l. in Marnaz and increases upstream through a steep sill207  
 176 with slope about  $10^\circ$ , to Chamonix, which is distant from208  
 177 Passy by 20 km and of altitude 1035 m. The Passy valley is209  
 178 surrounded by high mountains that reach up to 2,700 m a.s.l.210  
 179 in the western and northern parts of the valley. The highest211  
 180 peak in the area is Mont Blanc (4808 m a.s.l.), located right212  
 181 above and south of the town of Chamonix. The Passy valley213  
 182 has two main tributaries leading to the cities of Megève and214  
 183 Saint-Gervais-les-Bains (see Fig. 1b). In the winter season215  
 184 the local time (LT) is UTC+1 (Coordinated Universal Time216  
 185 plus one hour). All times below are expressed in local time.

### 192 2.2. Configuration of the meteorological model

193 The Weather Research and Forecasting (WRF) model  
 194 (Skamarock et al., 2005), version 3.5.1, was used to perform  
 195 the numerical simulations, and customized as described be-  
 196 low. The model was coupled to a chemical module (WRF-  
 197 Chem) to model the diffusion and transport processes of pas-  
 198 sive tracers emulating the behavior of  $PM_{10}$  in the atmo-  
 199 sphere. In this work, we assume indeed that  $PM_{10}$  has a low  
 200 chemical reactivity during wintertime conditions and can be  
 201 modelled as a passive tracer. Elemental carbon (EC), which  
 202 represents a significant fraction of the total mass of  $PM_{10}$  in  
 203 winter (up to 15%, Aymoz et al. 2007) is actually well known  
 204 for its low chemical reactivity in the atmosphere.

The simulation was performed using five nested domains  
 centered in the airport of Sallanches ( $45.935^\circ N$ ,  $6.636^\circ E$ )  
 and was carried out in three steps. The first three domains  
 (d01, d02 and d03) were run in a one-way online nested con-  
 figuration, covering the continental scales (see Fig. 1a). Re-  
 analysed data from the European Centre for Medium-Range  
 Meteorological Forecasts (ECMWF) were used to initialize  
 the model and provide the lateral boundary conditions for  
 the outermost domain with a 6-hour update. The simulation  
 started on 7 February 2015 at 1300 LT and was run for 7 days  
 until 14 February 2015 at 1300 LT. The size, horizontal and  
 vertical resolutions and time step for each domain are listed  
 in Table 1.

In a second step, the results obtained for domain d03  
 were used as initial and lateral boundary conditions for do-  
 main d04 through a down-scaling process. The lateral bound-  
 aries of domain d04 were updated every 10 minutes. This  
 simulation for domain d04 was run for six days, from 8 Febru-

ary at 1300 LT to 14 February at 1300 LT.

Finally, the same downscaling method was applied to produce the initial and lateral boundary conditions for domain d05, in which the horizontal resolution of the grid is 111 m in the horizontal and 92 grid points are used in the vertical direction. The vertical coordinate was stretched as to refine the resolution near the ground, with the first grid point located at 9.2 m above ground (implying that the first mass point is at 4.6 m). The simulation for domain d05 was run from 9 February at 1300 LT to 13 February at 1300 LT.

Domain	$nx, ny, nz$	$\Delta x = \Delta y$	$\Delta z_{min}$	$\Delta t$
d01	202, 202, 46	15 km	42 m	30 s
d02	246, 246, 46	3 km	42 m	6 s
d03	340, 340, 46	1 km	42 m	2 s
d04	406, 406, 92	333 m	21 m	0.6 s
d05	382, 382, 92	111 m	9.2 m	0.06 s

Table 1: Main parameters used in the simulations. The number of grid points  $nx, ny, nz$  correspond to the east-west, north-south and vertical directions, respectively. The vertical coordinate is stretched with height and  $\Delta z_{min}$  represents the height above the ground of the first grid point, the first mass point being located at  $\Delta z_{min}/2$ .

The planetary boundary layer (PBL) was parameterized in the first online run (for d01, d02 and d03) using the Yonsei University (YSU) scheme (Hong, 2010). For the two innermost domains (d04 and d05), the PBL was explicitly resolved using a turbulent kinetic energy (TKE) 1.5 order closure employing a Smagorinsky coefficient  $C_s$  equal to 0.1. The other physical and dynamical options were the same in all domains. The temporal discretization of the model equations is based on a Runge-Kutta scheme of third order and a time-splitting technique is implemented for the acoustic modes. The advection terms were discretized using a fifth-order Weighted Essentially Non-Oscillatory (WENO) scheme with positive definite filter. The scheme developed by Morrison et al. (2005) was used to parametrize the microphysics in the model with the inclusion of the modifications on the treatment of ice fog proposed by Neemann et al. (2015). Shortwave and longwave radiation were parameterized with the Rapid Radiative Transfer Model (Mlawer et al. 1997). Land-surface processes were modelled with the Noah land surface model with four soil layers (Chen and Dudhia 2001) and the ground thermal conductivity and the latent heat flux as computed in the WRF model version 3.7 were implemented. The surface layer physics was modelled by the revised MM5 Monin-Obukhov scheme (Jiménez et al. 2012).

### 2.3. Terrain representation in the numerical model

Data from the Shuttle Radar Topography Mission (Farr et al., 2007) at a resolution of about 90 m were used to create the topography, which was interpolated to the horizontal resolution of the d01 to d05 domains. For a horizontal resolution of 3 km (d02), the maximum slope angle of the terrain

is about  $25^\circ$  but for a 100 m resolution (d05), this maximum slope can reach values close to  $75^\circ$ . Such a steep slope generates numerical instability and a filter was implemented in the model to reduce the maximum slope angle to  $42^\circ$  to overcome this problem. The general shape of the topography is retained while maintaining the main small-scale characteristics of the topography.

Due to the importance of snow cover in surface-atmosphere interactions (Tomasi et al. 2014; Neemann et al. 2015), a method was developed for the initialization of snow cover in the model. Indeed, the resolution of currently available numerical model reanalysis products is about 15 km, a too coarse resolution for an adequate representation of the snow layer during the simulated days in the d05 domain. In the present work, MODIS/Terra (MOD10\_L2) satellite products for snow cover at a spatial resolution of 500 m were averaged between 5 and 10 February 2015 and interpolated at the horizontal resolution of the innermost domain to initialize the snow fields. The initialization of the snow albedo and snow depth is described in Arduini et al. (2020).

### 2.4. Emission Input

The emission input used in the simulations is based on an emission inventory developed by the local air quality agency of the Auvergne Rhône-Alpes region (Atmo-Aura) for the year 2015 (Atmo-Auvergne-Rhône-Alpes, 2017). The inventory is available at a resolution of 100 m in the whole region and was implemented in domain d05 of the simulations only. The inventory involves several pollutants, such as nitrogen oxides, non-metallic volatile organic compounds, polycyclic aromatic hydrocarbons, heavy metals and suspended particles such as  $PM_{10}$  which are the focus of the present work.

The different emission sectors are categorised using the classification proposed by the European Topic Centre on Atmospheric Emissions (ETC/AE), which classifies the activities generating an emission of pollutants into the atmosphere using the Selected Nomenclature of Air Pollution Sources (SNAP). The eleven SNAP categories, or sectors as commonly named, have been considered and their contribution to the total emission of  $PM_{10}$  in domain d05 is presented in Table 2. The table shows that in this area three main contributors account for about 90% of the total emissions: residential heating (SNAP 2), production processes (SNAP 4) and road transport (SNAP 7), contributing 61.24%, 9.55% and 19.42%, respectively. The former value is consistent with the finding of Chevrier (2016) that biomass burning averaged over the winter of 2013-2014 contributes between 62% and 73% to  $PM_{10}$  concentration when recorded at the air quality stations of the Passy valley. Note that emissions from SNAP 7 sector in Table 2 are limited to the valley core, from Marnaz to Passy, due to missing data in the original emission inventory. Estimating these missing data yields a corrected mass contribution of 23.5%, which is close to the value reported in Table 2.

Because the emission inventory is provided as the total mass emitted for the whole year, a disaggregation of the to-

SNAP	Classification	% in mass
1	Combustion in energy and transformation industries	1,28
2	Non-industrial combustion plants (Residential heating)	61,24
3	Combustion in manufacturing industry	2,56
4	Production processes	9,55
5	Extraction and distribution of fossil fuels and geothermal energy	0,00
6	Solvent and other product use	0,75
7	Road transport	19,42
8	Other mobile sources	3,03
9	Waste treatment and disposal	0,97
10	Agriculture	1,20
11	Other sources and sinks	0,00

Table 2: The relative mass contribution of each SNAP sector to the total  $PM_{10}$  emission in the innermost numerical domain d05 as provided by the emission inventory supplied by Atmo-Aura for the year 2015. Note that emission from SNAP sector 7 is limited to the central part of the Passy valley, from Marnaz to Passy. (An estimate of the missing emissions, which are mainly contributed by the Chamonix area and Megève valley, yields a relative contribution of the total mass in SNAP sector 7 of about 23.5%.)

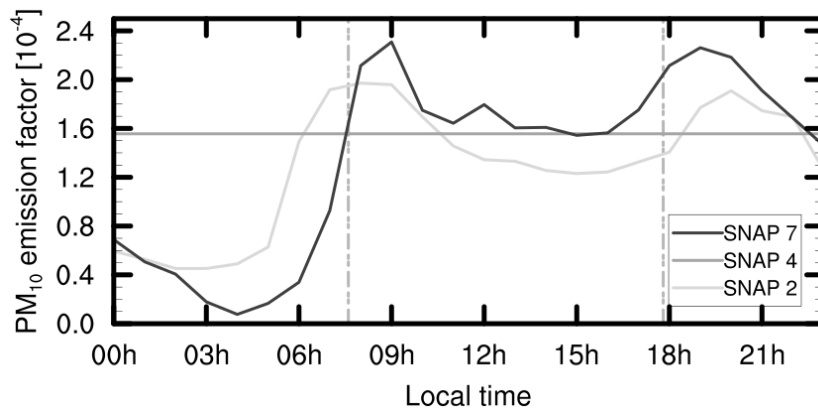


Figure 2: First level disaggregation in time of total year emission for a complete daily cycle during the first week of February 2015 for the three main SNAP sectors emitting in the area, SNAP 2 (residential heating, light grey line), SNAP 4 (production processes, dark grey line) and SNAP 7 (route transport, black line). Vertical dashed lines stands for the average sunrise and sunset times during the simulation period.

tal value must be made for each simulated day. For this purpose, a daily temporal profile of emission factors is used which depends upon the SNAP sector (among other factors see [Atmo-Auvergne-Rhône-Alpes, 2017](#)). Figure 2 displays the daily profiles we implemented for the three main SNAP sectors represented in this area (SNAP 2, SNAP4 and SNAP 7), based upon the recommendations of Atmo-Aura ([Atmo-Auvergne-Rhône-Alpes, 2017](#)) and of the Netherlands Organization for Applied Scientific Research, TNO ([Schaap et al., 2005](#)). The profiles for SNAP 2 and SNAP 7 display two emission peaks which correspond to the morning and late afternoon rush hours. The morning peak of SNAP 2, due to residential heating, occurs slightly before that for SNAP 7, due to road transport, the order of occurrence of these two peaks reversing for the late afternoon rush hour. SNAP sector 4 is represented by a constant emission factor.

In the numerical model, the emission input file was created with all  $PM_{10}$  emissions available in domain d05, which is the area of interest. The WRF-Chem model read the emis-

sion inputs every hour, all emissions being released at ground level. Two simulations were performed. In the first numerical experiment, serving as reference, the tracer field was forced with  $PM_{10}$  emissions in the whole d05 domain. In the second numerical experiment, the Arve river valley between Marnaz and Chamonix was divided into seven subsections, represented by color areas in Fig. 1b. Four areas among the seven were defined around the air quality stations

Location	Latitude	Longitude	H [m .a.s.l.]
Chamonix	45.93° N	6.87° E	1038
Passy	45.92° N	6.71° E	588
Sallanches	45.94° N	6.64° E	542
Marnaz	46.06° N	6.53° E	504

Table 3: Location of the four air-quality stations in the innermost domain d05. These locations are indicated with color dots in Fig. 3.

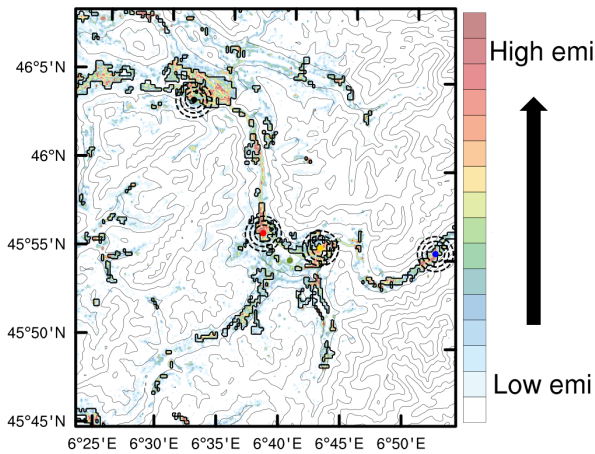


Figure 3: Horizontal distribution of the emission input in the domain for a complete day (9th February 2015) overlaid with contours of the terrain height (grey contours). Black contours indicate urban areas in the domain. The locations of the air quality stations in the zone are marked with colour dots: Chamonix (blue), Passy (yellow), Sallanches (red) and Marnaz (black). In addition, the location of the main measurement site in the Passy-15 field campaign is denoted with a green dot. No scale is provided for confidentiality reasons.

located in this valley section (in Marnaz, Sallanches, Passy and Chamonix, see Table 3); one area is located around the main measurement site of the Passy-2015 campaign; and two areas correspond to junctions between areas (between Chamonix and Passy AQS areas, and between Sallanches and Marnaz AQS areas). In this second numerical experiment, eight tracer fields were defined simultaneously. One tracer field was defined per color area, being forced by the emissions of that area only (leading to seven tracer fields). A last tracer field was forced by all emissions in the d05 domain not contained in the color areas. The latter field is mainly contributed by emissions from the tributary valleys of Megève and Saint-Gervais.

### 3. Atmospheric dynamics in the Passy valley and $PM_{10}$ concentration: numerical predictions versus observations

#### 3.1. Atmospheric dynamics in the Passy Valley

The first objective of this section is to provide a brief account of the atmospheric dynamics in the Arve river valley during IOP1 of the PASSY-15 campaign by comparison with field data from that campaign. The second objective is to compare the results of the present numerical simulations with those obtained by Arduini et al. (2020), to check the relevance of modifications introduced in the present model.

The PCAP event associated with IOP1 resulted from the passage of an upper-level ridge over the region. This synoptic flow pattern led to the advection of warmer air above the western Alps, setting the conditions for the PCAP to develop in the Passy Valley (see Arduini et al., 2020). The

PCAP formed in the evening on 9 February 2015, when the upper-level ridge moved over Northwest Europe, until the 14th February 2015 (see Fig. 4a). The PCAP event triggered a severe particulate air pollution episode in the valley as discussed in section 3.2 below.

Figure 4 displays the time evolution of vertical potential temperature profiles during IOP1 recorded during the campaign by radiosoundings (Vaisala Radiosonde RS92-SGP, RS) launched from the ground at the main measurement site (Fig. 4a) and simulated by WRF (Fig. 4b). A quantitative assessment of the ability of the simulations to reproduce the field data is provided by the vertical profile of the Mean Absolute Error (MAE) and of the bias. The MAE is largest at the ground, equal to about 3 K. It decays to a value of 1.5 K in about 100 m above the ground, keeping this value up to 2500 m. The MAE is associated with a negative bias of 1.8 K close to the ground. These values should be related to the accuracy of temperature measurements by radiosoundings, which is equal 0.5 K. Overall, except for the first 100 meters above the ground, we can conclude that a good agreement is observed between the simulation results and the field data.

The numerical simulations presented in this paper rely on previous work by Arduini et al. (2020), as mentioned above, in which two main changes were brought. The vertical resolution was increased by almost a factor of two in the first 200 m above the ground level, with 15 grid points in the current configuration versus 8 in the model of Arduini et al. (2020). This aims at a better representation of the lower atmosphere, where pollutants are transported. A second difference is that in the present case the model was run continuously over the five-day period, as opposed to a reinitialization every 24 hours in the simulations by Arduini et al. (2020) (the reason being that the latter simulations were compared with idealized simulations run over successive 24-hour periods).

The results of the two models are compared in Fig. 5 which displays the vertical profiles of the potential temperature (Fig. 5a and 5b) and of the wind speed (Fig. 5c and 5d) versus time during IOP1 at the main measurement site. The vertical profile of the MAE with respect to the field data is also displayed for each model. The wind field data have been obtained by a Lidar Windcube 8 from a height of 40 m above the ground (this instrument being blind below this height). Potential temperature field data have been obtained from radiosoundings, as noted above. Figure 5 displays a focus on the region close to the ground, up to 1000 m a.s.l., where we expect the differences between the two models, if any, to be the largest. (Figure 5a is therefore a zoom of Fig. 4b from the ground to 1000 m).

When the potential temperature profiles are considered (Fig. 5a and 5b), the vertical profiles of the MAE of the two simulations differ by at most 0.7 K, and this occurs close to the ground. This difference is of the same order as the accuracy of the measurements by the radiosoundings (equal to 0.5 K, as noted above) and is therefore not significant. Considering now the wind speed profiles, the MAE profiles for

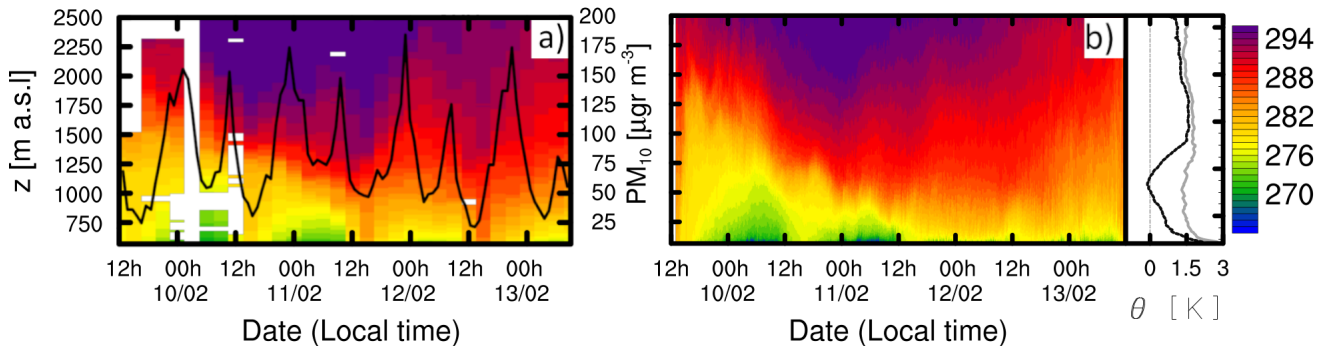


Figure 4: a) Temporal evolution of the vertical structure of the cold-air pool obtained by compiling potential temperature profiles from the radio sounding ascents performed during the Passy-15 field campaign at the location of the main measurement (IOP site) overlaid with the  $\text{PM}_{10}$  concentration registered over the same time period by the air quality station at Passy (black line). b) Temporal evolution of the vertical structure of the cold-air pool by computing the potential temperature vertical profiles with the WRF model at the same location.

the two models are very similar over a height of 100 m above the ground, the difference below that height being of at most  $0.26 \text{ m.s}^{-1}$ . Since the accuracy of the LIDAR is equal to  $0.2 \text{ m.s}^{-1}$ , this difference between the two models can again be considered as non significant. We can therefore conclude that the increase of the grid resolution close to the ground and the continuous running of the simulation over five days do not bring any improvement in the comparison with the field data.

The fact that the increase of the grid resolution close to the ground does not bring any improvement calls for other interpretations of the differences between the numerical model and the field data. Both numerical simulations display warmer air temperature near the ground when compared to the field data (the bias in absolute value being at most 2 K and an overestimation of the wind speed (close to the ground the bias is positive and equal to  $0.3 \text{ m.s}^{-1}$  at most). This suggests that the heat and moist fluxes from the soil to the atmosphere may not be well represented, as well as surface roughness elements such as forests (Chow et al., 2006, De Meij and Vinuesa, 2014, Foster et al., 2017, Wagner et al., 2019). It should also be pointed out that the effect of the  $\text{PM}_{10}$  polluted air on radiative transfer is not taken into account in the model, while this effect has been shown to reduce the local air temperature and the wind speed (Nair et al., 2017).

### 3.2. Numerical predictions versus measurements at air-quality stations

The PCAP event observed during IOP1 was associated with a strongly polluted episode. This is attested in Fig. 4a where the temporal evolution of the hourly-averaged  $\text{PM}_{10}$  concentration recorded at the AQS in Passy is superposed on the potential temperature profiles. The  $\text{PM}_{10}$  concentration exhibits two peaks per day, in the morning and at night, consistent with the emission profile used in the simulation (see Fig. 2).  $\text{PM}_{10}$  being mainly contributed by wood burning (see Table 2 for SNAP2), peak values at nighttime are higher than in the morning, reaching values up to  $180 \mu\text{gr m}^{-3}$ .

the 11 February. The lowest values of the concentration, still comprised between  $25$  and  $50 \mu\text{gr m}^{-3}$ , occur around 1300 LT, as a shallow convective layer develops above the ground due to the insolation of the ground surface. In the morning of 13 February, the peak values of the previous mornings drop from a value above  $120 \mu\text{gr m}^{-3}$  to  $80 \mu\text{gr m}^{-3}$  due to the change in the synoptic regime and the progressive destruction of the CAP.

The purpose of this section is to assess the validity of  $\text{PM}_{10}$  concentration predicted by the model with respect to measurements of that concentration at the four air-quality stations located in the innermost domain. Figure 6 presents a comparison between the predicted and recorded values between 9 and 13 February 2015.

The values of the  $\text{PM}_{10}$  concentration recorded at the AQS display two marked peaks in the morning and at night, the morning peak being sharper and most often of lower intensity than at night. The average over the period of these recorded values is higher at the AQS in Passy, equal to  $72.6 \mu\text{gr m}^{-3}$ , than at the AQS in Sallanches and in Chamonix, located downstream and upstream of Passy, respectively.  $\text{PM}_{10}$  concentrations recorded at the AQS in Marnaz, located outside the valley in a less confined area, are much lower with an average during the episode of about  $30 \mu\text{gr m}^{-3}$ .

In the upstream section of the valley in Chamonix, the model captures the temporal variation of the  $\text{PM}_{10}$  concentration, but it underestimates the magnitude of that concentration throughout the simulated time period (see Fig. 6a). We recall that the emission inventory in Chamonix does not include emissions of SNAP sector 7, which may contribute to the underestimation of  $\text{PM}_{10}$  by the numerical model in this valley section. In Passy, the magnitude and temporal variation of the  $\text{PM}_{10}$  concentration during the mornings are well represented (see Fig. 6b). However, the model does not capture adequately the nocturnal peaks occurring at around 0100 LT, the concentration reaching a maximum value about 4 hours too early. This point is further discussed below, in light of Fig. 7. In Sallanches, the model simulates well the  $\text{PM}_{10}$  concentration observed at the monitoring site, al-

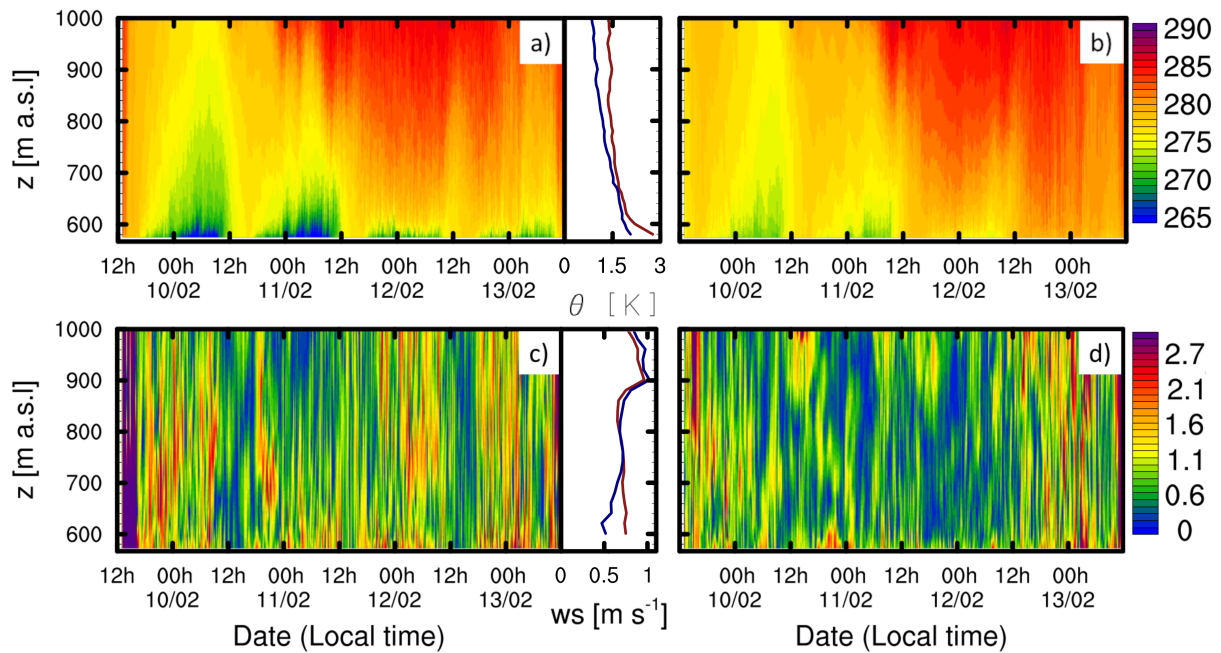


Figure 5: Temporal evolution of the vertical profile of the potential temperature (upper row) and wind speed (bottom row) computed by the present numerical simulation (left column) and by the simulation of Arduini et al. (2020) (right column) over a height of 440 m a.g.l. The computations were done at the location of the main measurement site of the Passy-15 field campaign. Vertical profiles of the mean-absolute-error (MAE) between the numerical result and the field data are displayed, with red lines for the present simulation and blue lines for the simulation by Arduini et al. (2020).

505 though during the night a small overestimation of the con-534  
 506 centration is visible (see Fig. 6c). In Marnaz, the AQS was535  
 507 unfortunately not functioning during the first half of the IOP536  
 508 However, the model shows a good agreement with the data537  
 509 available for the second part of the IOP (see Fig. 6d). 538

510 In light of these results, the performance of the model in539  
 511 the downstream section of the valley (Sallanches and Mar-540  
 512 naz) appears better than in the upstream section (Passy and541  
 513 Chamonix). Since the same emission inventory and emis-542  
 514 sion profile were used for the entire domain, we may con-543  
 515 clude that the atmospheric boundary layer is better repre-544  
 516 sented in the downstream section of the valley. 545

517 In order to analyse the origin of the discrepancies be-546  
 518 tween the numerically predicted and the recorded concen-547  
 519 trations, the wind speed predicted by the numerical mode548  
 520 and the emission profile used in that model are plotted with549  
 521 the predicted  $PM_{10}$  concentration in Fig. 7, in Passy (Fig.  
 522 7a) and Sallanches (Fig. 7b). We first analyse the results ob-  
 523 tained in Sallanches, which were shown to agree better with550  
 524 the AQS data. The concentration follows the emission cycle,551  
 525 with peaks reached at about the same time. This behavior552  
 526 is consistent with concentration building up from emission553  
 527 when the wind speed is weak. The wind speed displays554  
 528 daily cycle as expected, with a very weak speed indeed, at555  
 529 most  $2.5 \text{ m s}^{-1}$ , which nearly vanishes around midday when556  
 530 it reverses between up- and down-valley directions (see Ar-557  
 531 duini et al., 2020). 558

532 In Passy, the time series of  $PM_{10}$  concentration follows  
 533 that of the emission profile in the morning (except on 12

February). By contrast, as already stressed above, the evening  
 peak occurs too early, by about 4 hours with respect to the  
 concentration at the AQS. The model predicts a nearly van-  
 ishing wind speed in the afternoon, during at least 6 hours,  
 the wind increasing from about 1900 LT while remaining  
 weak, less than  $2 \text{ m s}^{-1}$ . The duration of the quasi-vanishing  
 wind regime in the afternoon is surprisingly long. If not re-  
 alistic, it would account for the too early peak of  $PM_{10}$ , emis-  
 sions accumulating without dispersion during the whole af-  
 ternoon and early night.

Overall this detailed comparison shows a good agree-  
 ment between the predictions of the numerical simulations  
 and the measurements. The main difficulty is the numerical  
 prediction of the wind speed in Passy during the day. This  
 is challenging as this wind speed is very weak all day long  
 at this location, less than  $2 \text{ m s}^{-1}$ .

#### 4. Spatial distribution of the $PM_{10}$ Concentration

The present section analyses the spatial distribution of  
 $PM_{10}$  concentration in the Passy valley, as simulated by the  
 model. The vertical distribution at the locations of the AQS  
 is first considered, before analysing the horizontal distribu-  
 tion of the  $PM_{10}$  concentration in the Passy valley. The spa-  
 tial distribution of the  $PM_{10}$  emissions is first computed and  
 discussed.

The Passy valley was divided into seven subsections, rep-  
 resented as color areas in Fig. 1b. The relative importance



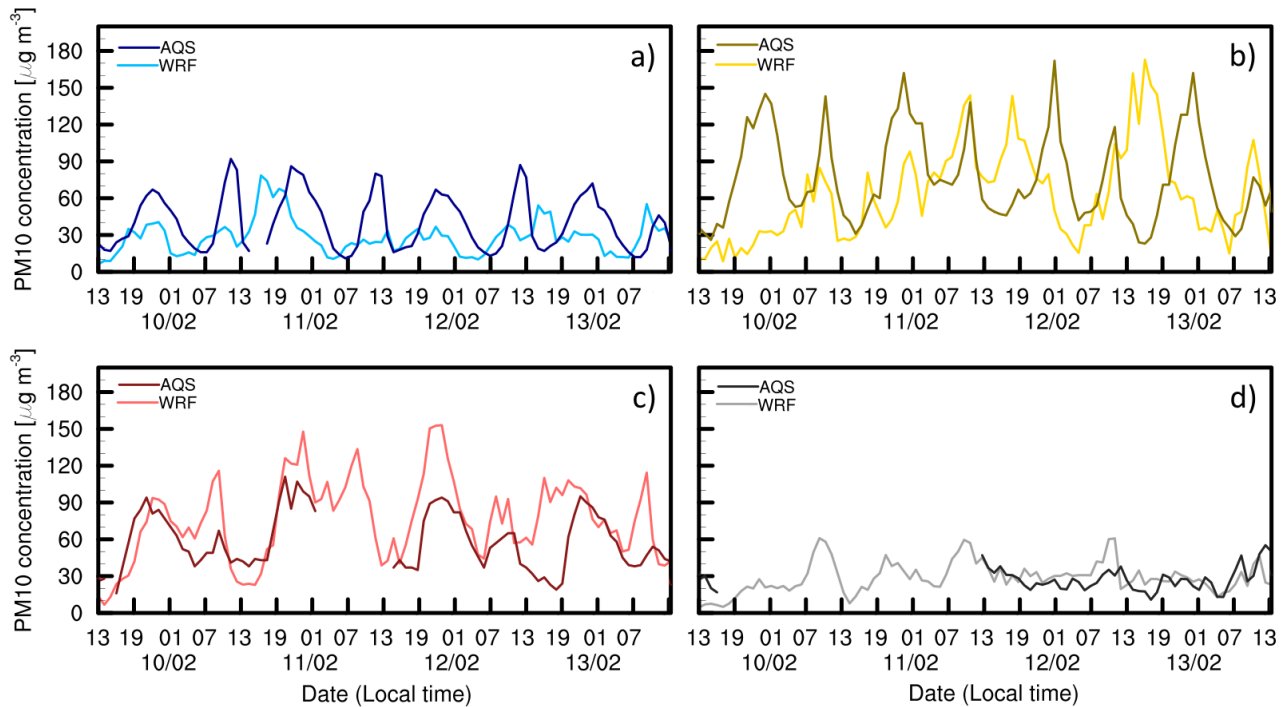


Figure 6: Hourly-averaged time series of the concentration of  $PM_{10}$  in  $\mu\text{gr m}^{-3}$  in Chamonix (a), Passy (b), Sallanches (c) and Marnaz (d) using data collected at the AQS (dark lines), and results from WRF at those locations (light lines). The results of the model have also been averaged horizontally over a square of side 1/3 km centred about each AQS location and vertically over 10 m from ground level.

of emissions in the valley was estimated by computing, for each area, the emission averaged over that area divided by the total emission averaged over the total color area, namely

$$R_{QQ_i} = \frac{\langle Q \rangle_{A_i}}{\langle Q \rangle_{\sum_{i=1}^7 A_i}}, \quad (1)$$

where  $A_i$  is one of the seven areas ( $1 \leq i \leq 7$ ) and  $\sum_{i=1}^7 A_i$  is the total color area displayed in Fig. 1a (the emission rate  $Q$  is integrated over one hour). Time series of  $R_{QQ_i}$  for each subsection are displayed in Fig. 8 for the simulated time period. As expected, all curves follow the emission profile imposed in the numerical model (displayed in Fig. 2). However emissions are larger by a factor about two in the subsection involving the town of Passy due to sources associated with domestic heating and with industrial activities in this valley subsection. The second largest emission area is the subsection involving the town of Sallanches. Emissions are similar in all other subsections, except in the one located between Passy and Sallanches where emission is smallest because the landcover mainly consists in fields.

Fig. 9 displays the vertical profiles versus time of the  $PM_{10}$  concentrations predicted by the model at the AQS locations. These profiles extend over a height of 400 m a.g.l. The figure displays several striking points. First the AQS locations can be divided into two distinct groups, those located inside the valley core, in Passy and Sallanches, and those located outside that core, in Marnaz and Chamonix.

This distinction is already present in the emission profiles (see Fig. 8) but not so clearly. Since the concentration field results from the combined effect of emission and transport of these emissions by the wind, the wind field should be considered to fully account for the behavior observed in Fig. 9. The latter point is investigated in section 5.

The  $PM_{10}$  concentration profiles in Passy and Sallanches display a similar distribution (see Fig. 9b and 9c): the highest concentration levels, up to  $130 \mu\text{gr m}^{-3}$  are found at these locations and the values larger than  $100 \mu\text{gr m}^{-3}$  remain concentrated in a layer of about 50 m a.g.l.. These results are consistent with concentration measurements reported during stable wintertime conditions in the Inn valley by Gohm et al. (2009). The whole concentration field does not extend beyond 400 m, except for a convective plume around noon on the 10 February that reaches 500 m or so. A mixed layer is actually observed in Sallanches and Passy in the early afternoon during that day, temporally decreasing the concentration at the ground. The concentration also decreases in the early morning of 12 February, due to the acceleration in the wind speed (up to  $2.5 \text{ m s}^{-1}$ ) observed in Sallanches, and to a lesser extent in Passy, at that time (see Fig. 7). This down-valley wind transports pollution further down, thereby cleaning the valley core but increasing the  $PM_{10}$  concentration in Marnaz during the same time period (see Fig. 9d).

Numerical predictions at the AQS locations in Chamonix and Marnaz display similar concentration fields, both in amplitude and height, but the concentration values are much

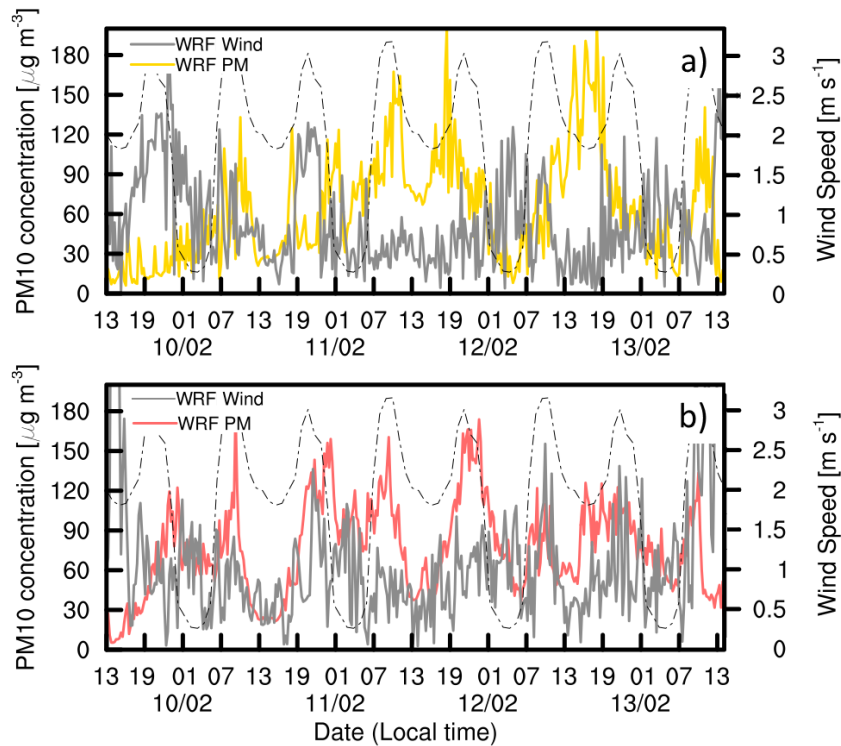


Figure 7: Time series of the concentration of  $\text{PM}_{10}$  in  $\mu\text{g m}^{-3}$  (color lines) and the horizontal wind speed (grey lines) using results of the simulations. The results of the model have been averaged in time over 15 minutes, over a horizontal square of side 1/3 km centered about each AQS and vertically over 10 m from ground level. The emission profile has been added (dashed line) as a reference (with no unit). The calculations have been done for the positions of the AQS at Passy (a) and Sallanches (b).

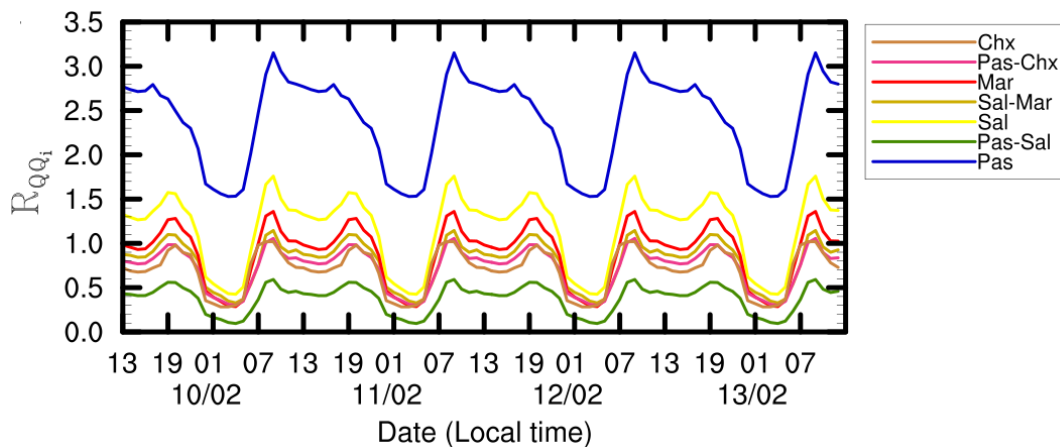


Figure 8: Emissions released in each of the subsections defined in Fig. 1a, averaged over that subsection, normalized by the total emission over the Passy valley domain, averaged over that domain (see Eq. (1) for a mathematical definition of  $R_{QQ_i}$ ).

608 lower than in the valley core (see Fig. 9a and 9d). This is 616  
 609 is consistent with the emission levels reported in Fig. 8 617  
 610 However those levels are relatively close in Marnaz and Sal 618  
 611 lanches, suggesting a marked impact of the wind field. Quite 619  
 612 remarkably, the concentration field remains trapped in a shal 620  
 613 low layer of height 50 m above the ground, implying a strong 621  
 614 stratification of the air layer. Exceptions are the afternoon of 622  
 615 the 10 February in Chamonix, probably because of convective 623

activity, and in the early morning of the 12 February in Marnaz as discussed above.

Figure 10 presents  $\text{PM}_{10}$  horizontal concentration averaged over six hours (so as to smooth out discrepancies due to shifts in time in the model results) for a 24-h period during the core of the PCAP episode. Urban areas, indicated as black contours in Fig. 10, appear as hotspots of pollution. More precisely the central part of the valley, where the cities

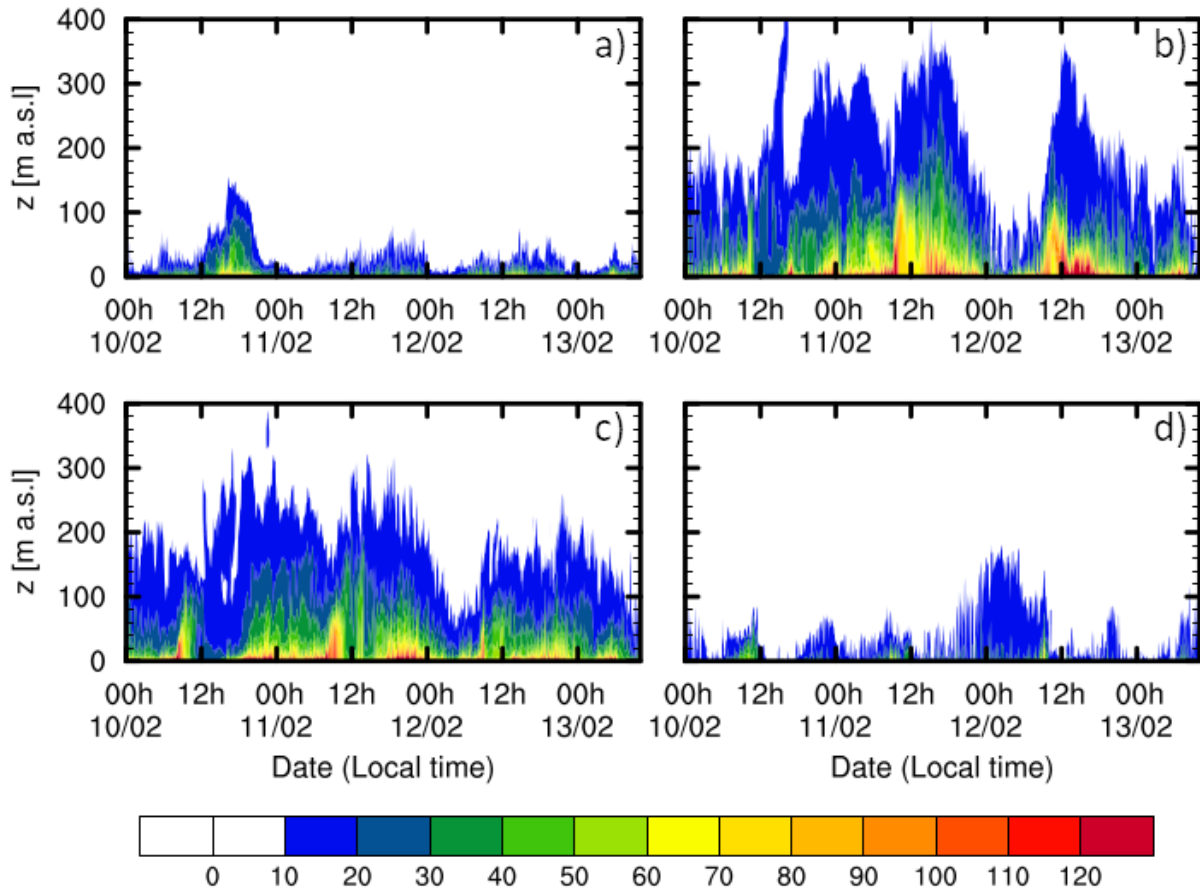


Figure 9: Temporal evolution of the vertical profiles of the PM<sub>10</sub> concentration in  $\mu\text{gr m}^{-3}$  at the locations representing the AQS in the domain (Chamonix (a), Passy (b), Sallanches (c) and Marnaz (d)). The results of the model have been averaged over a horizontal square of side  $1/3$  km centered about each AQS.

of Passy and Sallanches are located, display important accumulations of PM<sub>10</sub>: average values are above  $50 \mu\text{gr m}^{-3}$  and peak concentrations up to about  $150 \mu\text{gr m}^{-3}$  are found in larger areas in the morning and evening rush hours. Pollution is also found in the town of Chamonix, though at a less striking level, with localized areas where the concentration is higher than  $55 \mu\text{gr m}^{-3}$  in the morning and early afternoon. By contrast, the tributary valleys of Megève and St-Gervais do not experience high levels of PM<sub>10</sub>: the concentration is always below  $30 \mu\text{gr m}^{-3}$ . Fig. 10 shows that four pollution hotspots can be identified: in the town of Passy, downstream of the monitoring station in Sallanches, upstream of the valley exit (near Magland) and on the west side of Marnaz. The analysis of the wind field in the next section helps to clarify this behavior.

## 5. Stagnation and ventilation zones in the Arve river valley

The objective of this section is to estimate the transport potential of pollution by the flow field. For this purpose, the method proposed by Allwine and Whiteman (1994) is used to compute stagnation, recirculation and ventilation zones. This method was originally designed when measurements at

a single station are available (a synthetic account is provided by Cook et al., 2011). In the present work, the method is applied to each grid point of the innermost domain allowing for a complete picture of the transport properties of the flow over time in the Passy valley.

### 5.1. Principle of the method

The method proposed by Allwine and Whiteman (1994) relies on time series of the horizontal velocity components at a fixed height in the atmosphere. Let  $T$  be the length of the time series, sampled into  $n$  intervals of length  $\tau$  over which the data are averaged (for instance  $T = 24\text{h}$ ,  $\tau = 10$  min). The speed and direction of the horizontal velocity field are next computed over each  $i^{\text{th}}$  interval,  $1 \leq i \leq n$ . Allwine and Whiteman (1994) introduced two parameters:

- The wind run  $S_i$ , defined as the virtual distance that an air parcel would travel during the  $i^{\text{th}}$  time interval, assuming that it does not experience any change in speed or direction. At the end of the time period  $T$ , a parcel has travelled the virtual distance  $S = \sum_{i=1}^n S_i$ .
- the recirculation index  $R$  defined by  $R = 1 - \frac{L}{S}$ , where

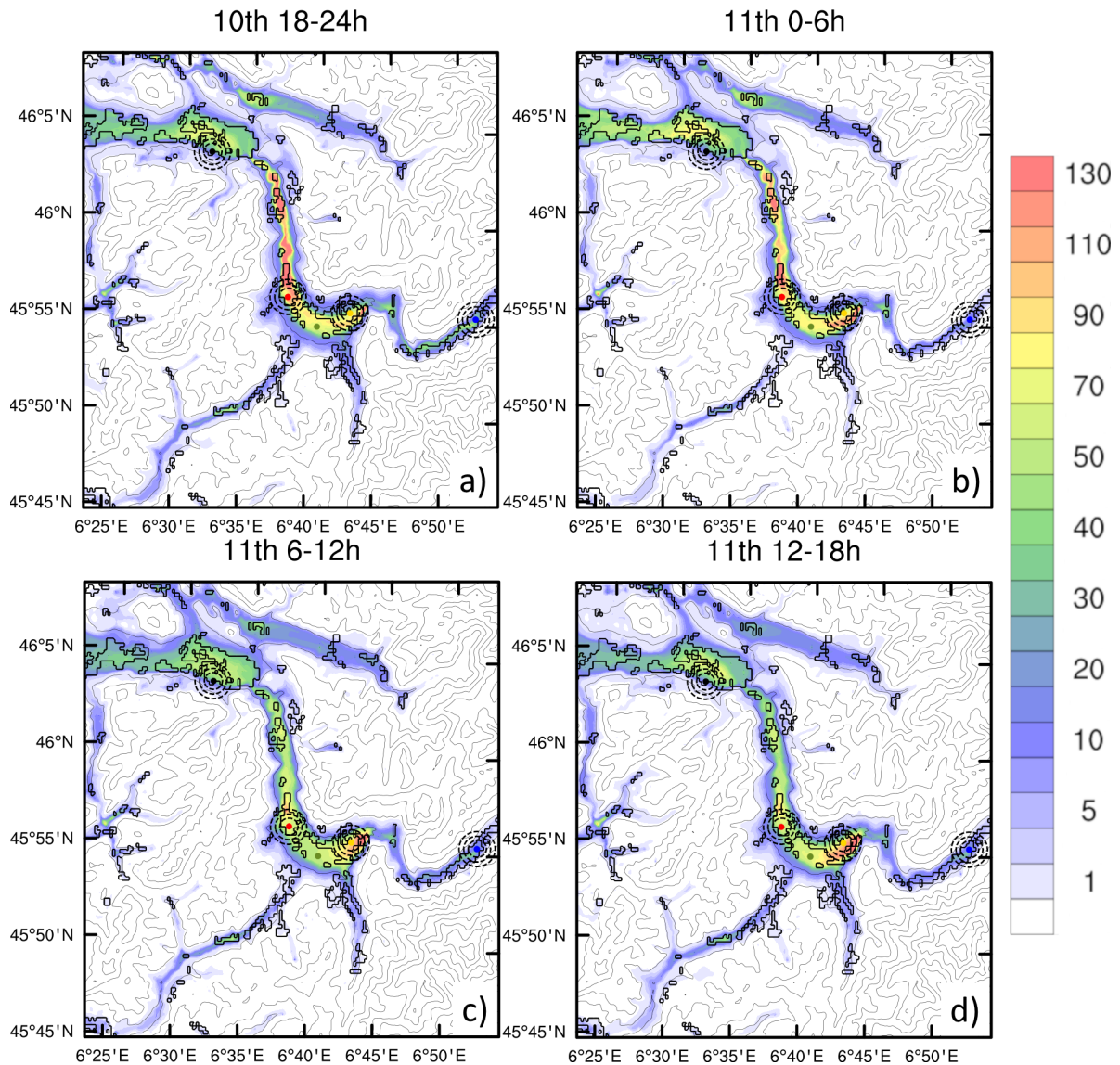


Figure 10: Contour plots of six-hour average of  $PM_{10}$  concentration [ $\mu\text{gr m}^{-3}$ ] averaged along the vertical in the first 10 m above the ground overlaid with contour lines of the terrain height. Black contours indicate urban areas in the domain. The locations of the air quality stations in the zone are marked with coloured dots; Chamonix (blue), Passy (yellow), Salanches (red) and Marnaz (black). The exact locations of the stations are documented in Table 3. The location of the main measurement site in Passy-15 is denoted with the green dot.

666  $L$  is the effective distance travelled by the fluid particle  
 667 over time  $T$  (see Figure 11).

668 When  $S$  is much larger than  $L$ ,  $R$  tends to 1. This means  
 669 that an air parcel following the flow has travelled some distance,  
 670 but its final position remains close to its initial position:  
 671 the parcel has experienced recirculation.

672 When  $S$  is of order  $L$ ,  $R$  tends to 0. If  $S$  is large enough,  
 673 this means that the air parcel has travelled far away from its  
 674 initial position: it has experienced ventilation.

675 Finally, if  $S$  is small enough (whatever  $R$ ), the parcel is  
 676 trapped in a stagnation zone.

677 For practical application, the notions of recirculation, stag-  
 678 nation and ventilation therefore require the definition of thresh-  
 679 old values, also referred to as critical values. These critical

values are denoted  $S_c$ ,  $S_{cv}$ ,  $R_c$  and  $R_{cv}$  and are defined as follows:

- if  $S \leq S_c$  in a given zone, this zone is defined as a stagnation zone;
- if  $R \geq R_c$  in a given zone, this zone is defined as a recirculation zone;
- if  $R \leq R_{cv}$  and  $S \geq S_{cv}$  in a given zone, this zone is defined as a ventilation zone.

## 5.2. Choice of the values of the critical parameters

The computation of these different zones requires to assign values to the critical parameters and to choose the length

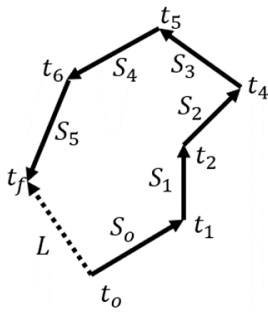


Figure 11: Sketch of the definitions of the wind run ( $S_i$ ) and of the transport distance ( $L$ ). Note that the end of each arrow in the figure corresponds to a time, not a point in space. Adapted from Allwine and Whiteman (1994).

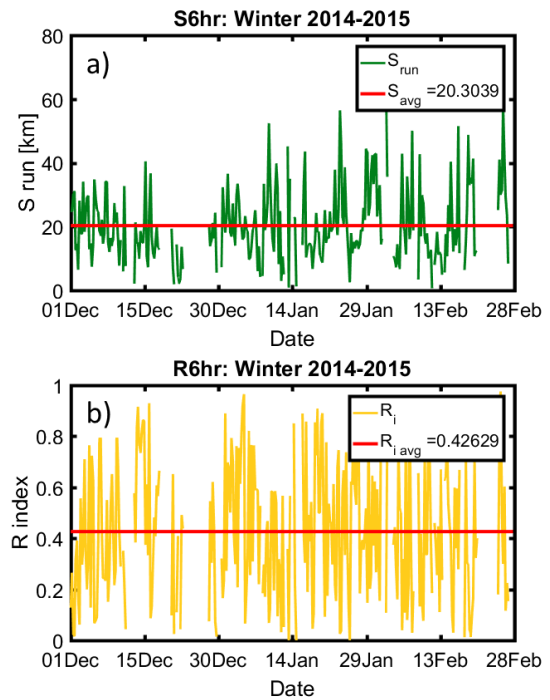


Figure 12: Timeseries of the wind run  $S$  (a) and the recirculation index  $R$  (b) for the winter of 2014-2015 (1st December 2015 to the 28th February 2015). The horizontal velocity components of the wind recorded at the first level of the LiDAR (40 m a.g.l.) have been used to compute  $S$  and  $R$ , for  $T = 6$  h and  $\tau = 10$  min.

of about 0.5 found for  $R$  already implies a general trend for recirculation and stagnation in the Passy valley.

### 5.3. Stagnation, recirculation and ventilation zones in the Passy valley

Largeron (2010) improved the classification by including two additional categories (critical stagnation and low ventilation) based on Allwine and Whiteman (1994) method. This classification is indicated in Table 4, with the present values for the critical parameters. These categories are designed to cover all possible conditions for pollutant transport from the worst condition (critical stagnation), for which pollutants remain trapped and accumulate, to the best condition (ventilation) for which pollutants are transported away from the measurement site. In the present work we merge Low ventilation and Ventilation in a single category.

When the innermost domain is mapped using these categories, regions ranging from critically-stagnant zones to ventilated zones are identified (see Fig. 13). The tributary valleys of Megève and Saint-Gervais, on the south part of the domain, and the section of the valley between Passy and Chamonix are ventilated zones in all frames of Fig. 13, being associated with valley flows. Yet, the bottom part of these sections, namely the core of the Passy valley, is not ventilated: the section around Sallanches lies in a stagnation zone in all frames, that around Passy lies most of the time in a critically stagnant zone and the section between

of the time series  $T$ . This length is usually set to 24 h in complex terrain. There is no method to choose the critical values (see Cook et al., 2011, for a discussion). In Allwine and Whiteman (1994) for instance, these values are defined from the average values of  $R$  and  $S$  over a three-month winter period, computed separately for two sites in the Colorado Plateau basin, USA.

In the present case, the critical values are determined from the data recorded at the main measurement site of the Passy-15 field campaign. These data are the horizontal velocity components of the wind recorded at the first level of the LiDAR (40 m a.g.l.), and over three months of the 2014-2015 winter. Once the critical values have been chosen, we apply the method of Allwine and Whiteman (1994) to all grid points of the innermost domain (see section 5.3).

The wind run  $S$  and the index  $R$  have first been computed for  $\tau = 10$  min and for different values of  $T$ , equal to 6 h, 12 h and 24 h (see Fig. 12). If we define the critical value of  $S$  from its average value over the three-month winter period, then  $T = 6$  h is preferable. Indeed, this average value is equal to 20 km for  $T = 6$  h, 34 km for  $T = 12$  h and 64 km for  $T = 24$  h. These values correspond to a wind of  $0.9 \text{ m s}^{-1}$  which is a light wind speed in line with the recorded values. If we were choosing  $T = 24$  h and set  $S_c$  to 64 km then the whole valley would be a stagnation zone because the length of the valley is 25 km from Passy to Marnaz (the conclusion is the same for  $T = 12$  h). We therefore choose  $T = 6$  h and set  $S_c$  to 20 km. The critical value for ventilation  $S_{cv}$  is set to 32 km, corresponding to an average wind speed of about  $1.5 \text{ m s}^{-1}$ , which can flush the whole valley during  $T = 6$  h. Fig. 12a shows that  $S$  has values below  $S_c$  about 60% of the time and above  $S_{cv}$  about 15% of the time.

The time series of  $R$  over the three-month period is displayed in Fig. 12b. The average value of  $R$  is equal to 0.43 for  $T = 6$  h (0.5 for  $T = 12$  h and 0.56 for  $T = 24$ h). Allwine and Whiteman (1994) set  $R_c = 0.6$ , corresponding to the resultant distance  $L$  being equal to 40% of the total wind run over the time  $T$ . In the same way, they set  $R_{cv} = 0.2$ , corresponding to the resultant distance being equal to 80% of the wind run over the same time. The same values are used here for  $R_c$  and  $R_{cv}$ . With these choices, the average value

Category	Criterion	Thresholds
<b>Critical stagnation (SC)</b>	$S \leq S_c$ and $R \geq R_c$	$S_c = 20$ km, $R_c = 0.6$
<b>Stagnation (S)</b>	$S \leq S_c$ and $R \leq R_c$	$S_c = 20$ km, $R_c = 0.6$
<b>Recirculation (R)</b>	$R \geq R_c$	$S_c = 20$ km, $R_c = 0.6$
<b>Low ventilation (V)</b>	$S_c \leq S \leq S_{cv}$ and $R \leq R_c$ or $S \geq S_{cv}$ and $R_{cv} \leq R \leq R_c$	$S_c = 20$ km, $R_c = 0.6$ $S_{cv} = 32$ km, $R_{cv} = 0.2$
<b>Ventilation (LV)</b>	$S \geq S_{cv}$ and $R \leq R_{cv}$	$S_c = 20$ km, $R_c = 0.6$ $S_{cv} = 32$ km, $R_{cv} = 0.2$

Table 4: Definition of the five categories to characterize the transport properties of the flow based on [Largeron \(2010\)](#). The critical values for the wind run have been modified to better describe the wind structure in the Arve River Valley at the main measurement site (represented by a green dot in Fig. 1b). The critical values have been computed for  $T = 6$  h. In Fig. 13, the last two categories have been merged.

758 these two zones, which contains the main measurement site, 759  
759 is a recirculation zone. This behavior is explained in [Arduini et al. \(2020\)](#): the flows along the Megève, Saint-Gervais and 760  
760 Chamonix valleys are down-valley for the most part of the 761  
761 day and they detrain at their level of neutral buoyancy over 762  
762 the strongly stratified air layer at the valley bottom, leaving 763  
763 that layer unventilated. Figure 13d shows that the air flowing 764  
764 along the Megève valley in the afternoon of 11 February is 765  
765 still able to flow down toward Sallanches. Yet this ventila- 766  
766 tion process does not affect the section containing the town 767  
767 of Passy, which remains decoupled from the rest of the val- 768  
768 ley at all times. The critical stagnation zone in this valley 769  
769 section together with the high emission level (see Fig. 8) 770  
770 accounts for the high PM<sub>10</sub> concentration values recorded 771  
771 there. For the same reasons, though with a lesser intensity, 772  
772 the fact that Sallanches lies in a stagnation zone most of time 773  
773 with an important emission level accounts for the high val- 774  
774 ues of the concentration found at that location (see Figs. 6c, 775  
775 and 9c). 776

777 The central part of the valley on the North of Sallanches 778  
778 is a ventilation zone, associated with a valley flow along the 779  
779 Arve river. A jet-like structure (not shown) forms at the val- 780  
780 ley exit by mass conservation (the Passy valley gets very nar- 781  
781 row just before Marnaz) creating a ventilation zone down- 782  
782 stream of the valley exit. The major part of the emissions 783  
783 near Marnaz (see Fig. 3) is located inside this ventilation 784  
784 zone, accounting for the low level of PM<sub>10</sub> concentration 785  
785 recorded at the AQS in Marnaz (see Fig. 6d). 786

## 786 6. Local and Non-local Contributions 787

788 The relative contributions of the PM<sub>10</sub> emissions of each 789  
789 of the seven subsections of the valley to the total PM<sub>10</sub> con- 790  
790 centration at the location of the air quality monitoring sites 791  
791 (Chamonix, Passy, Sallanches and Marnaz) are presented in 792  
792 Fig. 14. More precisely, Fig. 14 displays the ratios 793  
793

$$794 \frac{\langle C_i \rangle_{AQS_j}}{\langle \sum_{i=1}^7 C_i + Rest \rangle_{AQS_j}}, \quad (2) 795$$

796 for  $i$  comprised between 1 and 7 and  $j$ , between 1 and 4. 797  
797 Each index  $i$  is associated with a color, and the same color 798

convention as in Fig. 8 is used. "Rest" represents the tracers being emitted in the innermost domain but outside the seven subsections.

In the upstream section of the valley at Chamonix (see Fig. 14a) PM<sub>10</sub> pollution is originating almost entirely from local sources throughout the episode. This result can be accounted by the fact that no source are considered upstream of the Chamonix valley subsection and that the valley flow is down-valley in this subsection. This finding is consistent with a previous study by [Chazette et al. \(2005\)](#), which highlighted the importance of local emission sources on the concentration of wintertime pollution at this site.

The total concentration of PM<sub>10</sub> recorded in Passy is dominated by the contribution of local sources emitted at Passy, with an average of 74% throughout the episode (see Fig. 14b). This confirms the decoupled character of this section of the valley during the persistent stage of the episode (10 - 13 February) pointed out in Sect. 5. It is worth noting that the contributions from the downstream sections are almost zero, suggesting that no up-valley flow is present there during the episode. Relatively small contributions originate from Chamonix and from the tributary of St-Gervais (see the brown line and the black line in Fig. 14b, respectively), especially at night, suggesting that part of the flow from these tributaries is able to penetrate the CAP. This suggests that, as deduced by [Sabatier et al. \(2018\)](#), the tributaries can make a contribution (about 15% when averaged throughout the episode) to the pollution recorded at Passy.

The situation is more complex in Sallanches (see Fig. 14c), where strong interactions take place with the surroundings subsections. Although the average emissions released from this section are the second largest in the domain (see Fig. 8a), the contribution from local sources is not as high (43%) as reported for the upstream section (74%). The contribution of the subsection linking Sallanches and Marnaz is relatively small (less than 10%, see the gold line in Fig. 14c) because the valley flow is primarily down-valley. The contribution of PM<sub>10</sub> emissions sources from the subsection in Passy is very important, with an average of 25% throughout the episode. Note that a daily cycle can be identified in the timeseries, with a large contribution from Passy during the

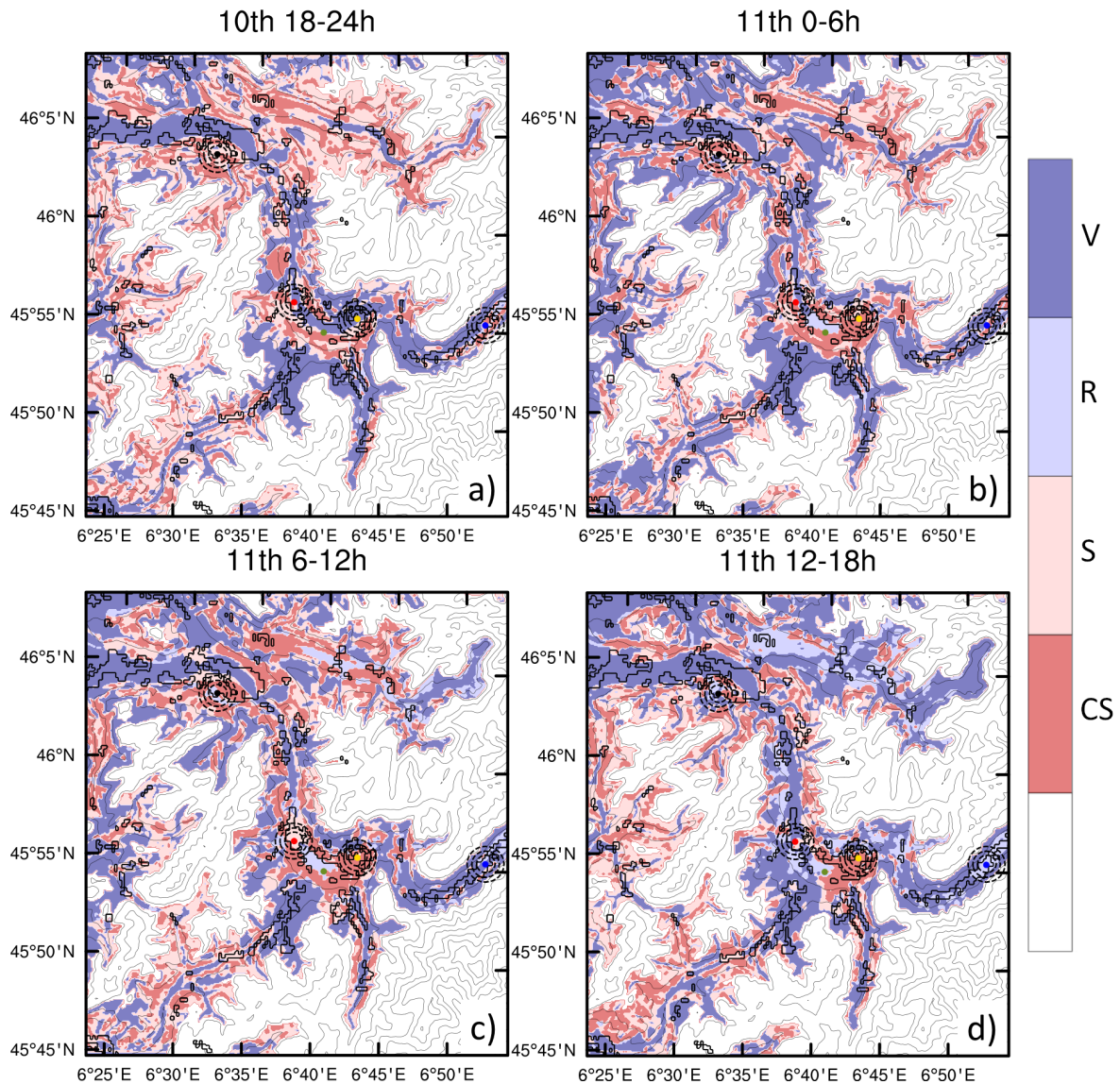


Figure 13: Maps tracking the zones prone to critical stagnation (CS), stagnation (S), recirculation (R) and ventilation (V) using a six-hour average in time and averaged along the vertical in the first 10 m above the ground. The results have been overlaid with contour lines of the terrain height. The data is masked to show the information only for terrain height lower than 1500 m a.s.l. Black contours indicate urban areas in the domain. The locations of the air quality stations in the zone are marked with coloured dots; Chamonix (blue), Passy (yellow), Sallanches (red) and Marnaz (black). The exact locations of the stations are documented in Table 3. In addition, the location of the main measurement site in Passy-15 is denoted with the green dot.

830 night, while the export of pollution ceases during the day. Fi-842  
 831 nally, the contribution from the tributary leading to Megève  
 832 (see the black line in Fig. 14c) reaches values as high as 27%  
 833 for short periods of time.

834 In Marnaz (see Fig. 14d) the contribution of local source844  
 835 to the local PM10 pollution is about 70% on average during845  
 836 the episode. A daily cycle is also visible in the timeseries846  
 837 During the night, non-local pollution increases, especially847  
 838 from sources outside the seven subsections (see the black848  
 839 line in Fig. 14d). Note that the peaks in the contribution849  
 840 of these sources match very well with the peaks for the up-850  
 841 stream sources, suggesting that these sources are located in851

the upstream part of the valley.

## 7. Discussion and conclusions

A real-case simulation of the particulate-matter transport processes in a section of the Arve river valley (northern French Alps) was performed using the Weather Research and Forecasting (WRF) model. The influence of the valley-wind system on the ventilation of pollutants and the effect of very local pollution sources on the resultant pollutant concentration in such a deep alpine valley when subject to wintertime anticyclonic conditions was quantified. The results about

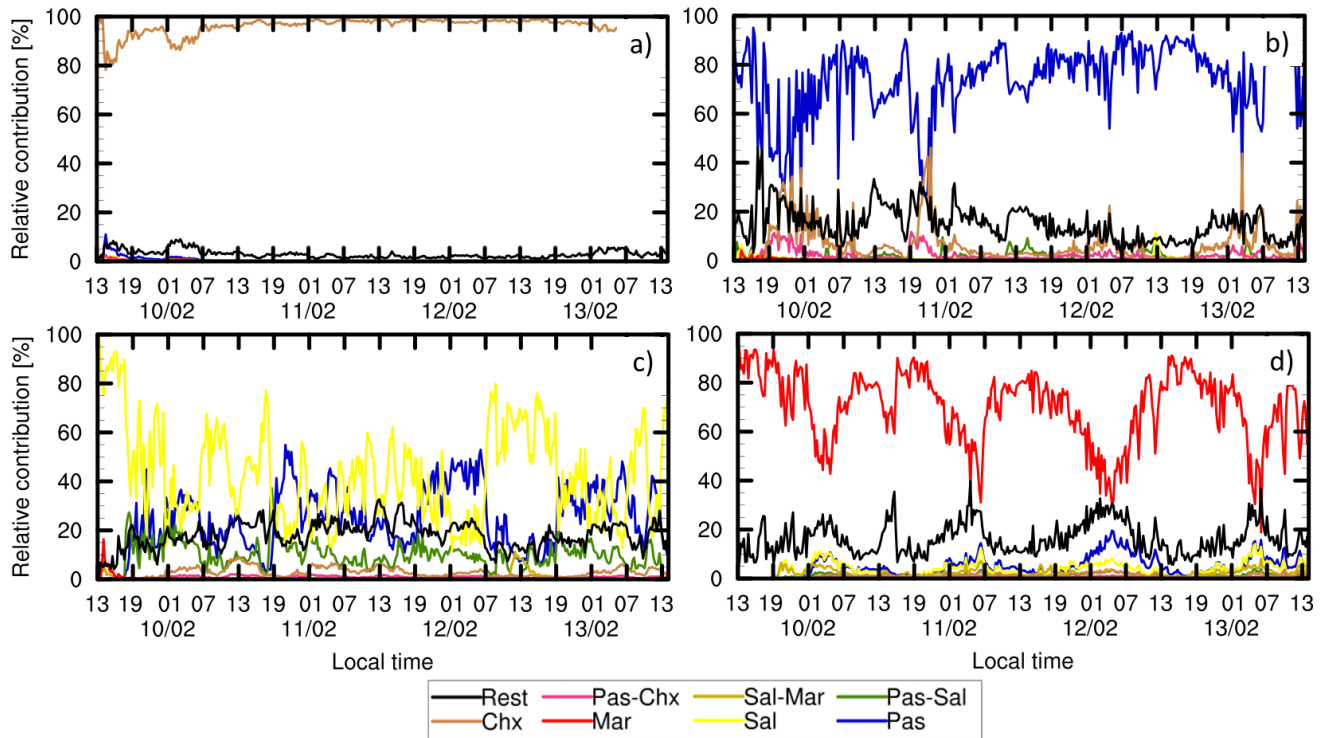


Figure 14: Time series of the relative contributions of  $PM_{10}$  emissions of each of the seven subsections of the valley previously defined (see fig. 1b) to the total  $PM_{10}$  concentration at the location of the AQS of Chamonix (a), Passy (b), Sallanches (c) and Marnaz (d) using data produced in the innermost domain d05. This relative contribution is defined by Eq. 2. The results of the model have been averaged in time every 15 minutes and in space over a horizontal square of side 1/3 km centered about the location of AQS; an average is also performed over the first 10 m above ground level.

852 the flow dynamics presented here are based on a previous 857  
 853 work developed by Arduini et al. (2020). The simulations 878  
 854 reproduce the pollution episode associated with the first in- 879  
 855 tensive observation period (IOP1) of the Passy-15 field cam- 880  
 856 paign (Staquet et al., 2015, Paci et al., 2017) which was con- 881  
 857 ducted in the surroundings of the town of Passy during the 882  
 858 second week of February 2015. The ability of the model to 883  
 859 accurately simulate the concentration of  $PM_{10}$  in the valley 884  
 860 from realistic emission sources has been tested against data 885  
 861 recorded by four air quality stations (AQS) in the area (Cha- 886  
 862 monix, Passy, Sallanches and Marnaz, see Fig. 1). An anal- 887  
 863 ysis was then developed to account for the distribution of 888  
 864 pollution in the valley from the simulated atmospheric dy- 889  
 865 namics and the emission sources. The main results of this 890  
 866 study are summarized as follows: 891

867 • A sensitivity test was conducted by running the simu- 892  
 868 lation continuously for four days of the IOP (instead of 893  
 869 being run over 24h during 4 consecutive days) and by 894  
 870 improving the vertical resolution close to the ground, 895  
 871 with the first mass point at 4.6 m above the ground 896  
 872 level (m a.g.l.) and the double of grid points in the 897  
 873 first 200 m a.g.l. (17 grid points in the first 200 m 898  
 874 a.g.l.). We found that these changes do not improve 899  
 875 comparison with the field data. Indeed, the difference 900  
 876 in the mean-absolute errors for each simulation rela- 901

852 tive to the field data is close to the accuracy of the 857  
 853 instruments. We conclude that a better representa- 878  
 854 tion of the boundary conditions, terrain characteristics 879  
 855 and surface forcing is rather required to improve the 880  
 856 representation of the heat and moist fluxes from the 881  
 857 soil to the atmosphere, and of the flow field close to 882  
 858 the ground (see f.i. Chow et al., 2006, Rasheed et al., 883  
 859 2011, De Meij and Vinuesa, 2014, Rendón et al., 2014, 884  
 860 Foster et al., 2017, Wagner et al., 2019). Taking the 885  
 861 effect of the  $PM_{10}$  particles on radiative transfer could 886  
 862 also improve the comparison as the air temperature 887  
 863 and wind speed were both found to overestimate the 888  
 864 values of the field data (see f.i. Nair et al., 2017). 889

- The model performance was evaluated by comparing the simulated concentration of  $PM_{10}$  in the domain with data recorded by the air quality stations (AQS) in the area. The correct magnitude of the concentration is well captured throughout the domain (see Fig. 6). However, the simulated concentration of  $PM_{10}$  at the Sallanches and Marnaz AQS locations show better agreement with the data collected by the AQS than the simulated concentration of  $PM_{10}$  at the Chamonix and Passy AQS locations. The main discrepancy occurs in Passy, where the simulated  $PM_{10}$  appears to peak too early in the evening compared to the AQS



data (about four hours earlier). Because of the time at which the AQS reports those peaks (around midnight) it seems that this discrepancy is not a consequence of the release of emissions in the model but should be attributed to the dynamic characteristics of the atmosphere at Passy. Indeed, the flow close to the ground in Passy nearly vanishes around noon and remains very weak (less than  $0.5 \text{ m s}^{-1}$ ) up to about 1900 LT, an unexpected behavior which may account for the too early peak of  $\text{PM}_{10}$  concentration.

- From the measurements of the AQS available across the valley, an unusual horizontal distribution of pollution was observed, with hotspots of  $\text{PM}_{10}$  concentration in localized sites throughout the central part of the Passy valley. These sites prone to high  $\text{PM}_{10}$  pollution are normally associated with urban areas (See Fig. 10). To understand the distribution of pollutants in the domain we divided the valley into seven sections (see Fig. 1b), which allowed us to track the evolution in time and space of pollutants released in each of the valley section. The section with the highest amount of released pollution is that of Passy, even so, this cannot completely explain the high concentration of pollutants there. The sections of Sallanches and Marnaz emit a similar amount of pollution during the episode, although in Sallanches there is a much higher concentration of  $\text{PM}_{10}$  than in Marnaz. As well, this difference cannot be explained only from the point of view of emissions, rising the need to estimate the ventilation potential in the domain.
- Following the method developed by Allwine and Whiteman (1994), zones prone to ventilation and stagnation in the domain were characterized (see Fig. 13). A relationship was identified between these zones, their respective emission sources and the zones liable to high pollution. In Passy, for example, critical stagnation is often found due to the fact that it remains decoupled from the rest of the central part of the Passy valley. The air from the Chamonix and St-Gervais tributaries indeed detach over the bottom layer in Passy, with the major part of the mass flux flowing over that layer and leaving it unperturbed. Only a small fraction of that flux contributes to the  $\text{PM}_{10}$  concentration in the Passy section, about 15% over the episode. On the other hand, the air from Megève can flow into the CAP but goes down-valley towards Sallanches, leaving the section in Passy uncoupled from the rest of the valley, which creates a stagnation zone. Such stagnation zone along with the fact that this area presents the highest emission of all the valley sections, results in the highest concentration of  $\text{PM}_{10}$  recorded in the area.
- The local and non-local contribution to the concentration of  $\text{PM}_{10}$  in the different sections of the valley has been identified. In Passy, which through the analysis stands out as the location with the highest emissions, showing the greatest problems of atmospheric

stagnation and particulate air pollution, the most important factor contributing to the pollution reported at the AQS site was the local sources. The decoupled character of the area and the large emissions become a dangerous combination. In Sallanches, on the other hand, the impact of external sources (such as tributaries and Passy's pollution) play an important role in the problem by reporting a very similar contribution to local sources. From this study, it is clear that there is almost no transport in the upstream direction through the episode. Indeed no section of the valley seems to be affected by pollution released in a neighbouring downstream section suggesting no up-valley transport during the episode.

As a final consideration, it is important to note that the analysis presented in this paper is based entirely on a single winter and especially on a one-week pollution episode. Although the results of the Passy-15 field campaign and the works exploring those results (including the one presented here) provide valuable information on the drivers of particulate air pollution in the valley, the need for long-term meteorological and pollutant measurements in the area to better understand what is leading to such pollution problems is clear.

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