Pollutant Dispersion

Subjects: Meteorology & Atmospheric Sciences

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This entry reviews atmospheric processes affecting pollutant transport and diffusion over complex terrain, focusing in particular on the peculiarities of processes over mountains when compared to flat terrain. In fact, pollutant dispersion processes over complex terrain are much more complicated than over flat areas, as they are affected by atmospheric interactions with the orography at different spatial scales. In particular, atmospheric flows over complex terrain are characterized by a continuous and interacting range of scales, from synoptic forcing to mesoscale circulations and turbulence fluctuations. In complex terrain, the mechanical and thermal influence of the orography can modify the large-scale flow and produce smaller-scale motions which would not exist on flat terrain, thus enhancing the spatial and temporal variability of atmospheric processes relevant for pollutant dispersion.

air pollutant
turbulence
dispersion
transport
diffusion
atmospheric boundary layer
mountain
complex terrain

The concentration of pollutants in the atmospheric boundary layer (ABL) depends not only on emissions, but also, and sometimes crucially, on atmospheric dispersion. High concentrations of pollutants therefore follow not only from strong emissions, but also from reduced dispersion, especially in the atmospheric layer adjacent to the surface, where most of the pollutants are emitted.

1. Temperature Stratification

Temperature stratification (static stability) is one of the main factors controlling turbulent mixing in the atmosphere: the most critical situations occur under wintertime anticyclonic episodes, when radiative cooling at the ground leads to the formation of a very stable air layer above the surface. This situation is usually referred to as ground-based inversion; it inhibits turbulent motions, and consequently keeps pollutants âtrappedâ in that layer [1][2][3][4][5][6]. This situation may last for several days to several weeks, and is more frequent in mountainous regions; here the reduced sky-view factor limits the penetration of solar radiation into valleys and basins, and the nocturnal drainage winds favor the accumulation of cold air at low levels.

2. Mountain Boundary Layer Height

A key parameter affecting pollutant concentration is the height of the ABL, as it determines the volume of atmosphere available for pollutant dispersion. Turbulent mixing comes again into play, since it also contributes to controlling the evolution of the ABL depth. Over flat terrain, the depth of the ABL can often be assumed to be horizontally homogeneous, whereas over complex terrain the so-called âmountain boundary layerâ (MoBL) [7] is spatially highly inhomogeneous and interacts with mesoscale flows. As a consequence, an accurate determination of the height of the

MoBL is a more difficult task than over flat areas [7]. In fact, apart from quite substantial uncertainty arising from data quality and parameter choices even over flat terrain (cf., e.g., [8]), at least well-established criteria are available in the literature. Conversely, more interacting factors contribute to the spatio-temporal variability of the MoBL height in complex terrain, as extensively discussed in a recent review paper [9]. For example, heterogeneity in the penetration of solar radiation in mountain valleys and basins can produce significant spatial variability in the surface energy budget, influencing both atmospheric stratification and the boundary layer height [10][11]. Additionally, quantities defining the reference âboundary layer heightâ based on classical (i.e., flat terrain) concepts under convective conditions, do not, in general, correspond to the height up to which mixing is effective (i.e., the MoBL height). For example, Lang et al. [12] highlighted, using idealized large eddy simulations (LES), that different definitions of the boundary layer height yield similar results over flat terrain (Figure 1a), while significant discrepancies arise when idealized topographic features are introduced into the simulation (Figure 1b). Likewise, under stable stratification, the height of the boundary (inversion) layer can be modulated by the interaction of the upper-level wind with down-valley flows of tributary valleys, as the direction of the upper-level wind varies during the stable episode [13].

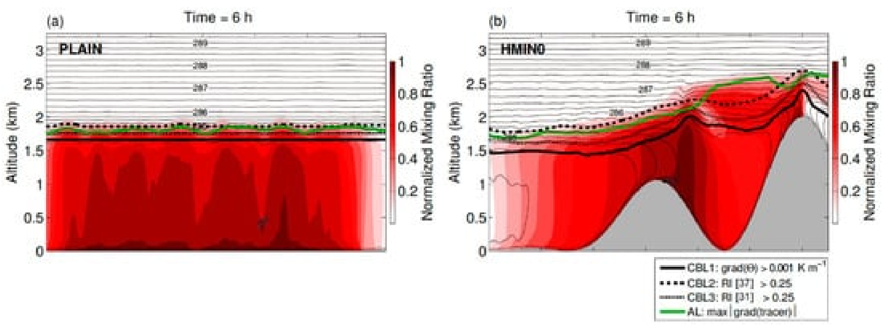

Figure 1. Cross sections of tracer concentrations (color contours) after 6 h of simulation for (**a**) flat terrain and (**b**) idealized topography, from Lang et al. [12]. The height of the convective boundary layer is plotted according to different definitions: black solid line (potential temperature gradient > 0.001 K m^{â1}), dashed line (Richardson number > 0.25, following [14]), dotted line (Richardson number > 0.25, following [8]), and green solid line (maximum gradient of the tracer). Potential temperature is shown as black contour lines (0.25 K increment). Adapted from [12].

3. Strong Synoptic Forcing

When the upper-level wind speed is considered, two main situations affecting pollutant dispersion in the lowest layers in mountainous regions can be distinguished. One situation occurs with strong upper-level wind speed, associated with a significant synoptic forcing. Over a plain, these conditions usually favor the dispersion of pollutants. However, in mountainous terrain, depending on the alignment of the upper-level wind with the valley axis [15], the valley bottom may be sheltered from downward intrusions of the wind from above. Additionally, the penetration of the upper-level wind down to the lowest levels of valleys and basins may be further prevented by underlying pre-existing and persistent stable layers, such as those associated with nighttime cooling, especially in wintertime [16]. Under these conditions, the flow inside valleys is decoupled from the airflow situation above the crest level, and the persistence of such conditions (i.e., light local flows and stable stratification) favors pollutant accumulation at the lowest levels.

4. Weak Synoptic Forcing and Thermally Driven Flows

The second situation occurs under persistent anticyclonic pressure fields, generally associated with weak synoptic forcing and clear skies. In this case, the circulation inside the valley or basin is driven by the local heating and cooling of the air layers adjacent to the ground, leading to down-slope and down-valley flows during the night and up-slope and up-valley flows during the day

[17][18]. The slope and valley flows control the transport and the diffusion of pollutants. In summer, the up-slope and up-valley flows are generally well developed, and may be associated with convective cells, which can extend very high above the valley bottom, up to a few kilometers, thus transporting pollutants to high altitudes [19]. In this case, up-slope circulations strongly enhance the mass exchange between the valley boundary layer and the free atmosphere with respect to pure turbulent exchange [20]. On the contrary, in wintertime, due to the reduced heating of the valley atmosphere, down-slope and down-valley flows dominate the valley circulation [21][22]; as shown in [23] from numerical simulations in the Grenoble Valley, this ânighttimeâ flow regime may last about 18 h (over 24 h), ceasing only for a few hours around midday, during which a weak convective activity may be observed above the valley bottom over a height of, at most, 50 m. In these situations, wind speed is generally weak (less than 1.5â2 msâ1), with frequent calm regimes (with wind speed less than 0.5 msâ1) and an inversion layer characterized by a positive temperature gradient can form in the valley up to an altitude close to the crest level. As a result, pollutant dispersion is strongly reduced during a wintertime episode [24][25]. In low wind speed conditions, pollutant dispersion is governed by meandering, a phenomenon still largely under study (see a brief review in [26]), dispersing plumes over wide angular sectors [27].

The inversion layer, typical of these wintertime episodes, along with topographic effects, leads to the formation of stagnation and ventilation zones [28][29]. In the sections of the valley displaying a nearly basin-like structure, stagnation zones develop in which pollutants travel over short distances from their emission points [30][31]. In these stagnation zones, pollutant concentrations increase steadily in time during the episode [32][33]. On the other hand, in ventilation zones, such as a valley section opening onto a plain, ventilation effects lead to the evacuation of pollutants [6]. The end of the persistent anticyclonic wintertime episode occurs when the upper-level wind is able to reach the valley floor and/or the energy input is sufficient to break up the inversion layer [34]. As a result, pollutants can be transported above crest level by vertical fluxes or out of the valley by the channeled wind. An example of the progressive accumulation of pollutants on the valley floor during an anticyclonic wintertime episode is reported in Figure 2. This figure displays a timeâheight plot of wind speed measured by a SODAR (SOnic Detection And Ranging), along with PM10 concentration, during a field campaign of the ALPNAP project in the Alpine Adige Valley [35]. It can be noted that PM10 concentration remains low in the first three days, when moderate winds reach the valley floor. On the other hand, a progressive accumulation of PM10 occurs in the subsequent days, characterized by weak winds, until a progressive increase in the wind speed terminates the air pollution episode.

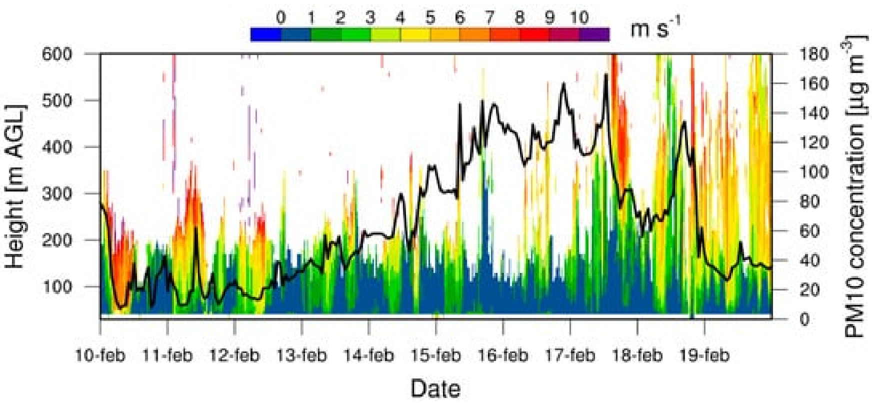

Figure 2. Wind speed measured by a SODAR (SOnic Detection And Ranging) (color contours) in the Adige Valley close to the town of Aldeno in the period 10â19 February 2006 in the framework of the ALPNAP project [35], along with PM10 concentrations (black line) measured at the same site.

Thermally driven circulations affect the transport of pollutants in many other different ways. For example, valley winds may advect highly polluted air downstream from major pollutant sources.

Conversely, valley circulations may also have a cleansing effect, when cleaner air is transported into polluted regions. More generally, pollutant transport by a down-valley flow depends both upon the stratification in the valley and upon local orographic features. Indeed, if a strong ground-based inversion exists at the valley bottom, the down-valley wind may detrain at its level of neutral buoyancy, leaving the valley bottom unperturbed. The detrainment may be also associated with the excitation of internal gravity waves [36][37][38], which may result in fluctuations of the pollutant concentration [6]. On the other hand, up-slope or up-valley winds may advect primary pollutants or precursors (also from natural sources, such as forests) to upper levels in the atmosphere; there, the different exposure to stronger radiation and/or other ambient conditions may affect (photo)chemical reactions, producing secondary pollutants (e.g., ozone), which eventually get drained to lower levels by nocturnal down-slope flows. At larger spatial scales, plain-to-mountain circulations can advect pollutants and their precursors towards mountain ranges [39], where they may be embedded into smaller scale circulations, and eventually transported into the free atmosphere (a process referred to as âmountain ventingâ [40][41][42]), also depending upon the geometry of the mountain range.

The development of thermally driven circulations is strongly affected by land cover heterogeneities, which are more common in mountainous areas. Changes in surface properties (such as albedo, thermal capacity, and conductivity) between valley floors, sidewalls, and mountain tops may modify surfaceâatmosphere heat exchanges and thermal contrasts driving these local circulations. Other climatic influences being equal, mountainous areas are more likely to have snow-covered terrain for a significant part of the year. Snow cover has many effects on the surface layer. First, snow cover on the ground affects the thermal structure, favoring stable stratification. Moreover, irregular snow cover, typically associated with the different exposure to the solar radiation of the valley sidewalls or with the varying altitude of the valley floor, may also produce asymmetric local circulations, influencing the redistribution of pollutants [31]. The higher amount of reflected radiation from extended snow-covered areas may also favor photochemical reactions, leading to an increased production of secondary pollutants [43][44].

5. Urban Areas

Local circulations may also be affected by land cover heterogeneity associated with extended urban areas. Indeed, cities usually experience higher near-surface temperatures, especially during nighttime [45], leading to the so-called âurban heat islandâ effect. Higher urban temperatures can cause the development of an âurban breezeâ, with convergent motions toward the city center at low levels [46]. Thermal hot-spots induced by urban areas may superimpose to the temperature gradients developing inside valleys, and locally modify the normal along-valley horizontal pressure gradients driving the diurnal pattern of up- and down-valley flows [47]. This usually implies a wind convergence over the city, especially during nighttime, when the urban heat island is stronger, thus favoring the accumulation of air pollutants [48]. Moreover, the higher roughness associated with buildings may produce an internal urban boundary layer [49], preventing or limiting the penetration of flows and the ventilation into the urban canopy [50][51]. Similar to the action of upper-level winds on the circulation in a valley, the orientation of urban canyons with respect to the flow direction may determine very different internal circulations, resulting in better ventilation in streets aligned with the mean flow. As a consequence, in cities lying within valleys, streets aligned along the main valley axis are usually better ventilated. Urban areas can also modify the development of the ground-based temperature inversion at night [52][53], as well as its break-up in the morning, with a significant impact both on air quality and on the cross-valley wind system [54][55]. All these aspects still make the case of urban areas over complex terrain a particularly challenging situation.

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