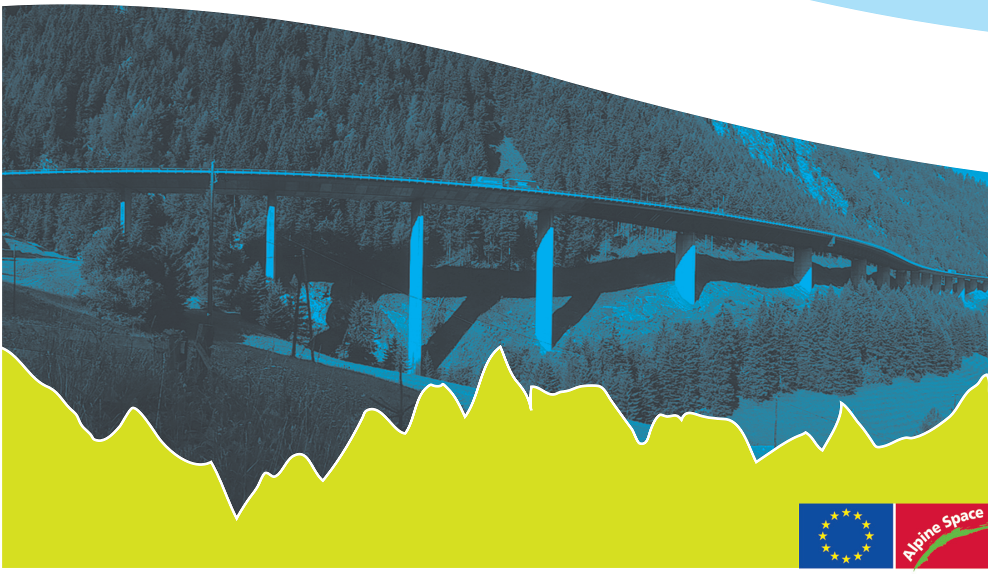
ALPNAP

Living along a transit route
air pollution, noise and health in the Alps

ALPNAP
Project Consortium



Interreg III B

ALPNAP project steering group

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Preface

This booklet was produced by the ALPNAP project consortium, a group of eleven partners from Austria, Germany, Italy and France. The three-year project (2005–2007) was co-funded by the European Regional Development Fund (ERDF) within the European Interreg IIIB Alpine Space programme. The objectives of ALPNAP were to collect and describe up-to-date science-based methods to observe and predict air and noise pollution along trans-Alpine transport corridors and to assess the related effects on health and well-being. These methods can be used to assess the consequences of new transport infrastructures (roads and railways) already in the planning phase or to design appropriate administrative or technological abatement measures against the violation of air pollution and noise limits. The results of the project are published in a comprehensive report for the use by the experts in environmental and transport administrations.

This booklet is directed to the inhabitants of the Alps who may be concerned by the environmental nuisances in their immediate neighbourhood. The booklet describes how air pollution and noise is generated. It further describes how the air pollutants are transported and how the noise propagates depending on the meteorological situation, i.e. the weather. The booklet shows in particular what is special in the Alpine topography and what is different from the situation in flat terrain. Eventually, the booklet summarises the possibilities of modern tools that were developed at universities and research centres to predict air pollution concentrations or noise levels and their related impact for future traffic scenarios.

ALPNAP

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Alpine Space
Interreg III B

The Alps: living space, recreation resort and transit area

The Alps are one of the most important natural reserves in Europe. The Alps are also the living space for 13 million people which are about two percent of the European population. With 68 people per km^2 the population density in the Alps is therefore of the same order as the average population density of Europe. At the same time, the 950 km long and in average 250 km wide Alpine arc is a topographical barrier that separates major economic centres and agglomerations in Europe (Italy – France, Italy – Germany, Slovenia – Czech Republic). The mountains also act as a barrier between the intra-Alpine residential areas. In addition, the natural beauties and mountain sports resorts attract a high number of tourists.

Domestic traffic, source and destination traffic from and to the inner Alpine tourist regions and the transit traffic across the Alps add up to an enormous flow of vehicles. The free trade within the European Union has increased and still increases the demand for the transport of goods across the Alps. This causes growing freight traffic along the Alpine transit routes. Between 1980 and 2005 the total transit transport volume has more than doubled and now amounts to 193 million tons.

The increasing transport volume makes air pollution and noise a growing problem in the Alps and solutions are urgently needed. Compared to the flat country the environmental burden in

Fig. 1 A beautiful valley is cut by the Brenner transit motorway. The viaduct spans above parts of the village Steinach/Tyrol.

Fig. 2 A long fright train climbs up the track towards the Austrian-Italian border. It carries swap bodies and trailers and thus symbolises modern intermodal transport.

mountainous areas is much more serious.

The ecosystems in the mountainous area of the Alps are very sensitive, in particular in elevated regions where they are also exposed to climatic stress. Alpine forests have an important protective function against avalanches and land slides. Air pollution has therefore more negative consequences than outside the mountains. Both air pollution and noise counteract the expectations of tourists and jeopardise the development of recreation areas.

Most villages and towns in the Alps also concentrate along the valleys, especially those with major motorways and railway lines. Therefore a rather large portion of the Alpine inhabitants live in close neighbourhood with the cross-Alpine transport corridors and are consequently exposed to the adverse environmental effects of transit traffic with negative consequences to their health and general well-being.

Sustainable Transport policies need scientific support

While the transport volume continues to rise, conflicts between economic and ecologic interests are expected to aggravate. Unless targeted measures are implemented, legal limits of air quality and noise will be more frequently violated and new infrastructure may cause new nuisances in formally sound areas.

Support from experts in air pollution, noise and related health effects and the application of scientific tools are indispensable to provide a solid base for political and administrative decisions towards a sustainable balance of mobility, economics, conservation of nature, environmental protection, public health and satisfaction with life.

New infrastructures will change the emissions and thus the environmental impact. Significant consequences are expected from new railway tunnels which are under construction or in planning. The same holds true for administrative measures (e.g. night-time heavy traffic ban) and incentives for either modal shift or co-modality in freight transport. Extended road tolls and the introduction of an Alpine transit rights trading system are other instruments which are currently discussed. Such means may partly improve the situation, but may also produce contradictory effects, or introduce new sources of noise while air pollution is reduced.

Steps towards a dialogue between researchers and administrations

A systematic, Alpine-wide co-operation of experts was missing in the past and the dialogue between researchers and administrations was not very intensive. The ALPNAP project ("Monitoring and Minimisation of Traffic-Induced Noise and Air Pollution Along Major Alpine Transport Routes") with its partners from universities and research centres was designed to overcome these deficiencies.

It was the objective of ALPNAP to describe the Alpine-specific processes that determine the air quality and noise in Alpine valleys and to collect innovative scientific tools and evaluation methods that allow to measure, assess, and predict air pollution and noise and their impact on health. These tools and methods were applied to selected areas and situations in order to demonstrate their abilities and to elucidate the complexity of the processes involved. Finally, recommendations for authorities and consultants were worked out how to best assess the environmental impact of administrative measures, incentives and new infrastructure, thereby properly considering the complexity of natural processes in the Alpine region.

The added value of ALPNAP was increased by a coordinated cooperation with the contemporaneous project MONITRAF ("Monitoring of Road-Traffic Related Effects and Common Measures"), a network of regional transport and environment administrations in the Alps. The objectives of MONITRAF were to develop comprehensive measures that aim at reducing the negative effects of road traffic, while simultaneously enhancing the quality of life within the Alpine region.

Emissions of air pollutants and noise

The term *emission* refers to the release of gaseous or particulate air pollutants and noise by diverse sources. Most air pollutants are emitted by combustion processes such as domestic heating, industrial production in units ranging from small-sized enterprises to huge power plants, and the operation of all kinds of motorized transport vehicles except electric railways. Ultra-fine particles are also released by abrasion and friction processes, e.g. during breaking, or are blown up from road surfaces (e.g. dust) by the air stream of passing vehicles. Noise is emitted from engines and exhaust pipes (propulsion noise of motorised road vehicles, Diesel driven rail vehicles, and aircraft), the interaction between wheels / tyres with the rail / road surfaces (rolling noise) or the air stream around very fast transport means (aerodynamic noise of high-speed trains and aircraft). Noise can be also emitted by industrial processes, constructions, agriculture. In addition, some human activities such as lawn cutting, handcraft, music, and sport events generate noise. Noise is also emitted by some domestic, farm and wildlife animals.

Fig. 3 An endless caravan of heavy trucks crosses the Austrian "Europabrücke" on a late autumn afternoon. The viaduct is part of the Brenner traverse between southern Germany and northern Italy.

Road traffic causes emissions of both air pollution and noise. In mountainous areas the emission is determined by additional factors as compared with flat terrain. Uphill drives play an important role. Driving with full engine load at high revs causes substantially higher emissions than on flat roads. Hence, the emission of nitrogen oxides (NO_x) along an inclined road segment with a steepness of five percent is twice of that for a flat road. The noise emission of heavy trucks is not only increased for uphill drives but also for downhill drives when engine retarders are activated. The rolling noise also depends on the road surface: rough or wet roads (in rain) are noisier while smooth or snow covered roads are quieter. Rolling noise of trains largely depends on the surface condition of the wheels and rail heads. Old freight wagons with bake shoes roughen the surfaces and thus emit more noise.

Viaducts (Fig. 3) and tunnels are also typical of mountain roads. They have a positive net effect on the emissions because they reduce the driving distance between the destinations and help to avoid steep uphill and downhill drives. The emissions that are released from elevated bridges are likely to be more diluted until they reach the housing areas than emissions from nearby surface roads. On the other hand one has to consider that the exhausts released in a tunnel must leave the tunnel through its entrances and/or special vent pipes. In any case the air emissions of a tunnel enter the atmosphere at single spots with high concentration.

Railway lines in the Alps are almost all electrified so that emissions of air pollutants along the tracks do not play a role. Trains however remain a source of noise. Specifically in the mountains the noise emission can be amplified (Fig. 4).

Fig. 4 Three electric locomotives, two pulling and one pushing, are necessary to move the rumbling waggons of this heavy fright train up the steep ramp towards the Brenner pass nearby the village of St. Jodok/Tyrol.

The spatial distribution of the emission sources is also influenced by the topography in the Alps. Major motorways and railway lines lead through valleys where also most of the settlements are found. As a consequence the distance between the sources of pollutants and noise and the housing areas is much shorter in the Alpine environment than in the flat country.

Alpine meteorology

Mountains like the Alps are very specific features of the Earth's surface. They reach into the atmosphere and are therefore a barrier which exerts drag on the spacious wind circulations that are driven by the low and high pressure systems. Such air currents are forced to lift or divert once they approach the mountains. In valleys the air is frequently channelled and the winds often follow the valley axis. Friction at the ground causes air turbulence which leads to a mixing of air masses and thus to an exchange of air near the ground with the air aloft. Horizontal transport by the mean wind and turbu-

Fig. 5 The Alps cause specific meteorological phenomena like mountain waves which are visible as characteristic *altocumulus lenticularis* clouds.

lent mixing are an important meteorological mechanism to remove air pollutants from the source region and to limit their concentration.

Under special conditions fall winds at the leeward side of mountain ridges develop. Such winds are known as “foehn” (Fig. 5). They can be extremely turbulent and gusty. In weak wind situations as they occur in the vicinity of high pressure areas, a horizontal exchange of air by the mean wind and a mixing by roughness-induced turbulence is not possible. On unclouded days the solar radiation warms the ground which in turn warms the overlying air. The warmed air tends to rise up in bubbles (so called thermals) and cause compensating downward motion. Also this mechanism leads to a mixing and a vertical exchange of air masses and its suspended pollutants.

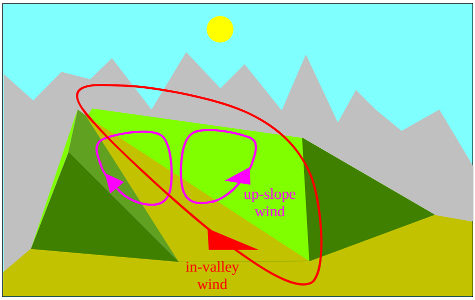

Fig. 6a In the early afternoon of sunny days up-slope winds (magenta) and in-valley currents (red) are well developed.

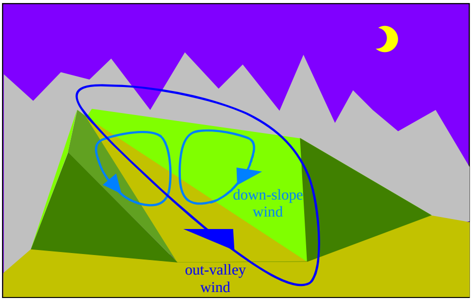

Fig. 6b In the late hours of clear-sky nights down-slope winds (light blue) occur together with an out-valley flow (dark blue).

As another mountain effect, the radiation budget and the heat transfer between atmosphere and ground are influenced by the slope inclination and the elevation of the ground surfaces. Under the condition of clear sky and weak large-scale flow this causes differential heating and cooling between the air layers near the slopes and the air at the same altitude above lower parts of the terrain. Differential heating and cooling are the drivers for thermal wind systems which change its direction twice a day. Air that is cooled at the side slopes of a valley is denser (heavier) than the non-cooled air in the centre of the valley. Vice versa, air that is heated at the side slopes of the valley is less dense (lighter) than the adjacent non-heated air. The difference in density lets the cooled air flow down the slope and the heated air flow up the slope. This effect does not only work between cooled/heated areas on the sides of valley, but also – on a larger scale – between the mountains and their forelands.

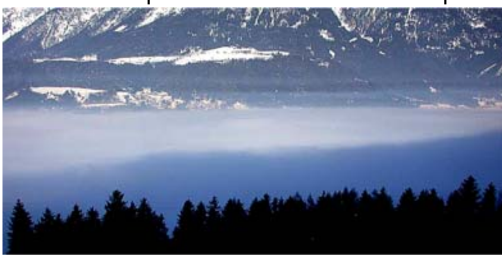

Fig. 7 A layer of low-stratus clouds or elevated fog has developed in the valley indicating a temperature inversion. Above the stratus cloud additional thin layers of haze are visible and reflect the complexity of valley atmosphere.

Thermal winds in the Alps (Fig. 6) therefore consist of two, often superimposing circulation systems, namely the slope winds and mountain-plane winds: (1) The slope wind circulation shows upslope winds during the day and downslope winds during the night. (2) The mountain-plain circulation is a few hours time-displaced such that in-valley flow sets on in the late morning hour and persists until the late evening while out-valley flow starts in the late night and continuous until the morning hour.

If weak wind is combined with only little or no solar radiation an exchange of air limited or nearly suppressed. This is the case in and near high pressure areas during night or when the sky is overcast. In particular in basins, the air near the ground is caught by the surrounding mountain chains. The air becomes stagnant and a horizontal exchange of air is limited. This situation can be even aggravated during the winter half year when the air in such basins but also in extended valleys cools in lower layers while subsidence of the air aloft causes a warming in higher altitudes. As a consequence a so-called inversion layer forms in which the temperature rises with height. If the air is moist enough persistent fog or low stratus (Fig. 7) is forming which hinders the sun to shine. Such inversions virtually act as lid on top of the near-ground atmosphere which then completely suppresses a vertical exchange of air. Pollutants cannot be transported away from its sources and the concentration tends to increase.

Channelling, foehn flows, stagnation, frequent inversion situations, and thermally-induced diurnal wind circulations largely determine the local climate of areas inside and close to mountains. These atmospheric features are real peculiarities of mountainous regions and are not found in the flat country.

Transport of air pollutants in the Alpine environment

The most important measure of air pollution is the concentration of harmful pollutants. These are gases like sulphur dioxide (SO_2), carbon monoxide (CO), nitrogen monoxide (NO), nitrogen dioxide (NO_2), ozone (O_3), etc. or suspended particles (dust, heavy metals like lead (Pb)) or abrasion from brakes, clutches and tyres. Aerosol and ultra-fine particles are classified according to their maximum diameter measured in micrometers (µm); e.g. PM10 stands for particles smaller than 10 µm. The concentration is the amount of mass of pollutants in a given volume of air. The concentration is therefore measured in milligrams or micrograms per cubic metre (mg/m^3 or $\mu g/m^3$).

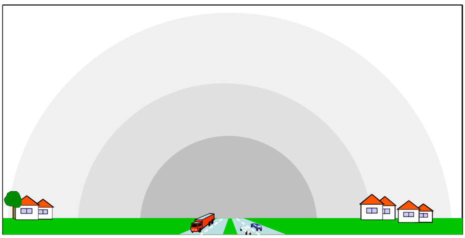

Fig. 8a Air pollution released in flat terrain can disperse into the full half space above the even ground surface. The grey tones of the sketch indicate the average concentration for a uniform distribution of wind directions.

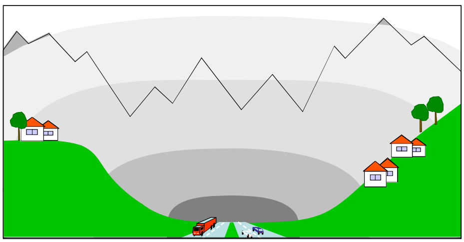

Fig. 8b In a valley the available volume of air is reduced by the side slopes. The grey tones of the sketch now indicate the increased average concentration again shown for a uniform distribution of wind directions.

The local concentration of a certain species of air pollution depends on the ratio between the emission of this species, i.e. how many mass of pollutants are released into a volume of air, and the net transmission, i.e. how many mass of pollutants are transported to or from by the mean wind (so called advection) and turbulent motions (turbulent diffusion). The diffusion process leads to a steady dilution and decrease of the concentration because a given amount of pollutants contaminates a continuously growing volume of air. If emission and transmission are in balance, the local concentration is constant. For a given emission rate the equilibrium concentration level is low if the wind speed is moderate or high and/or the turbulent exchange is efficient (summer half year, sunny days, high wind speeds, foehn). The equilibrium concentration level is particularly high for low wind speeds and weak turbulent mixing (winter half year, inversions, clear-sky nights).

In the mountainous area of the Alps additional effects are observed. Since the volume of air over a given area is reduced by the mountains, the same mass of air pollutants is distributed into a volume of air which is smaller than above flat terrain (Fig. 8). This in turn has the consequence that for a given emission rate the concentration in the mountains must be higher than in the flat country.

Fig. 9 Cold air has accumulated above the snow covered valley bottom. The associated temperature inversion traps the air pollution which is visible by its brownish colour. The air is too dry as to allow for fog during day.

The existence of inversions (increasing temperature with height) in combination with weak wind is critical and may cause high air pollution (Figs. 9 and 10). In the Alps such situations are especially frequent in basins and in valleys between two narrow sections. In both cases the horizontal air flow is strongly hindered by the surrounding mountains such that the mean winds are low and air pollutants cannot transported away while the inversion suppresses turbulent vertical mixing. As these situations may persist over a period of several days, the air pollutants can accumulate in the near-ground layer where the concentration level steadily increases.

Fig. 10 Shallow patches of polluted air are visible near the bottom of the valley while characteristic *altocumulus lenticularis* clouds indicate a strong large-scale flow across the Alps in higher levels.

Thermal wind systems have also a specific influence on air pollution in the mountains. Upslope winds (Fig. 11a) carry the pollutants from the valley bottom (where most of the emission takes place) up to the slope layers and from there to the centre of the valley atmosphere. Additional thermals (rising bubbles of air) which release from the slope wind layer near terrain irregularities (rocks, edges of forests) finally lead to a well mixed atmosphere in the valley. As the consequence the average concentration in the valley is low. The settlements on the valley bottom normally benefit from this, while housing areas at the slope or on elevated plateaus experience the polluted air that was carried up from the valley bottom.

In the case of nocturnal downslope winds (Fig. 11b) fresh cool air flows down the side slopes of the valley. After it has arrived the valley bottom it may continue its flow unless it is blocked by obstacles. Obviously, the fresh air of downslope winds can locally replace polluted air. It is therefore necessary to keep the paths of fresh air free of obstacles, e.g. by buildings. However, the most areas of larger Alpine valleys do not benefit from the fresh air flowing down the side slopes of the valley. Because vertical mixing is reduced during night and the mixing layer is shallow, the concentration of air pollutants in the valley bottom is high. Elevated villages benefit from this because emissions at the valley bottom are not transported upwards, albeit

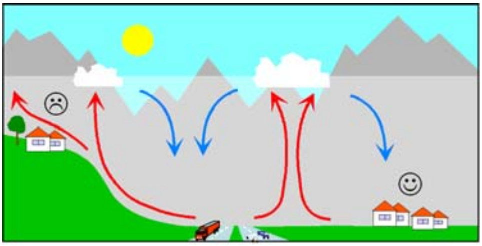

Fig. 11a Day-time up-slope winds (red, left) and thermals (red, right) lead to a deep mixing layer. It reduces the concentration in the valley bottom, but transports pollutants up the slopes. Compensating downward air motion is shown in blue.

Fig. 11b During clear nights the exhausts are caught in the inversion near the valley bottom. Places close to the foot of the side slopes benefit from down-slope winds (blue). Plateaus often rise above the polluted inversion layer and remain in the residual layer of the previous day.

the air quality might be still impaired by the pollutants that have been lifted up to the elevated levels during the previous day.

An accumulation of air pollution can occur if the weather with thermal winds continues over several days. In the along-valley mountain-plain circulation and cross-valley slopewind circulation the pollutants slosh back and forth while additional emissions pollute the air in the valley atmosphere. A large-scale exchange of air is not possible and the depth of the mixing layer is often limited by an elevated inversion. As a consequence the tracer concentration increases from day to day while it still may vary between day and night.

Propagation of noise in the Alps

Once generated at a source noise travels as invisible sound waves through the air. The loudness is physically given by the amplitude of the pressure oscillations which are associated with the passing sound waves. It can be measured by microphones. The amplitude of sound is expressed in terms of *sound level*, a logarithmic scale which is given in *decibels* (dB). Since noise is mostly composed of a broad frequency spectrum, but the human ear does not uniformly perceive different sound frequencies of the same amplitude, a frequency weighting has been introduced. The most common weighted sound level is the so-called “A-weighted sound level”, sometimes indicated by dB(A).

In practice short-term and long-term noise levels are defined. For single events (e.g. the passing of a train) the maximum A-weighted sound level is interesting. For the general assessment of traffic noise long-term (annual average) sound levels are used. The European Directive on Environmental Noise prescribes the use of the day-evening-night level. It is averaged within typical day-time periods (day, evening and night) where the evening and night contributions are given a higher weight than the day level to account for the human sensibility.

During unimpeded (free field) propagation the sound level decreases as a function of the distance. As a rough estimate, the sound level of noise emitted by a point source (e.g. a single car) decreases by 6 dB(A) per a doubling of the distance. For a line source (e.g. a motorway with continuous and dense traffic) the sound level decreases only by 3 dB(A) per a doubling of the distance. However, additional factor determine the sound level in the ambiance.

During propagation a part of the sound energy is absorbed in the air. This mainly concerns the high frequencies. Therefore bass tones of open-air concerts can be heard over long distances while high tones are strongly damped. The degree of absorption depends on the air temperature and humidity.

Sound which travels from a near-ground source (e.g. a road) to a near-ground receiver (e.g. a listening person) is attenuated also due to interactions of the sound waves with the ground. This damping effect depends on the acoustical ground property. It is strongest for acoustically soft ground (fresh snow cover, grass land) and almost not existent for acoustically hard ground (concrete, water surfaces).

The strongest meteorological influence on sound propagation is caused by the refraction of the sound waves. It is the reason for the cognition that a distant source of noise (e.g. a motorway or passing trains) can be sometimes heard very loudly while it is almost not audible during other times.

Refraction occurs in the case of vertical temperature differences or in wind. Upward refraction (Fig. 12a) usually occurs during day when the ground-based air is heated. It leads to a deflection of horizontally emitted sound away from the ground. As a consequence the sound amplitude near the ground rapidly decreases with growing distance from the source, much more than it would decrease in an atmosphere without temperature stratification.

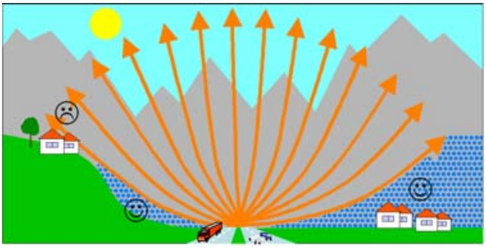

Fig. 12a Direction of sound spreading (sound rays) during day when the temperature decreases with height and the sound is refracted upward. In the dotted blue areas ("acoustical shadow zones") on the valley bottom the noise is remarkably reduced because the upward refracted sound rays cannot arrive here.

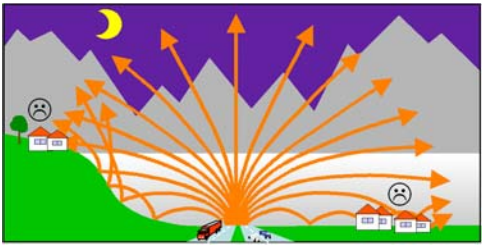

Fig. 12b Direction of sound spreading (sound rays) during night when the temperature increases with height in an inversion layer (grey) and the sound is refracted downward. Acoustical shadow zones do not appear. Instead the sound is reflected at the ground.

The audibility of motorways or railway line is thus limited to a few 100 m. On the contrary, downward refraction (Fig. 12b) usually occurs during night when an inversion has formed. Horizontally emitted sound rays are now deflected towards the ground where they are reflected, again deflected to the ground, etc., such that the sound is trapped in a ground based layer. In this case the noise is audible over a large distance. Refraction also occurs in the case of wind. Upward refraction with limited audibility occurs if the sound propagates against the wind. On the contrary, downward refraction with long-range audibility is observed if the sound propagates with the wind. Generally, the refraction due to the temperature stratification overlaps with that due to the wind. Both effects can mutually amplify (e.g. sound propagation with the wind in an inversion layer) or cancel out.

In mountainous areas some peculiarities have to be considered. If sound propagates from sources on the bottom of a valley to elevated dwellings on a side slope or plateau, the sound waves propagate slantwise through the atmosphere and not along the ground. Hence, the sound cannot be attenuated by the ground effect. This leads to relative high sound levels in elevated areas and even on mountain summits the traffic noise is well heard even if the direct distance amounts to several kilometres. In some cases the valley sides have the form of the rounded gallery of theatre (Fig. 13). People living in such situation may "enjoy" this amphitheatre effect by which they can hear the noise from the noise sources down in the valley.

Fig. 13 The artificial head microphone records the amphitheatre effect from a "premium gallery" at the east side of the Wipp valley with the Brenner motorway on the viaduct in the background.(near Steinach/Austria).

Air pollution and noise related health effects in the Alps

Air pollution and noise are harmful environmental factors. Both nuisances cannot only impair the human health, but also the quality of life in general, i.e. health, well-being and satisfaction with life. The latter is not only coupled with the objective measures of air pollution and noise but also by "soft factors" such as the positive expectations that are associated with a certain ambiance, e.g. a qualified residential area or a picturesque nature.

Polluted air directly causes or aggravates diseases such as asthma, bronchitis, emphysema, lung and heart diseases, and respiratory allergies. However, the awareness of air pollution and its personal appraisal may also indirectly initiate adverse effect on health. It is estimated that about 90 percent of the observed adverse health effects is caused by the direct biophysical pathway, while about 10 percent is attributed to the indirect causation chain. For noise this is much different. Noise can directly cause cardiovascular diseases for instance, but this pathway contributes only about 25 percent to the noise-related health effects. The remaining 75 percent are assumed to be indirectly caused, mainly due to sleep disturbance, annoyance and related stress which in turn increase the susceptibility for diseases.

The complexity of relationships between air pollution and noise on the one hand and their impact on health and well-being on the other hand, requires simple metrics which aggregate the various influences and may serve as criteria for political or technical decisions. These metrics are called *indicators* or *indices*. Air pollution indices (*API*) combine certain classes of concentrations of different pollutants according to their severity where different species (chemical compounds) can be given individual weights, according to their specific effects. The same is possible for noise pollution indices (*NPI*) where different noise sources (e.g. road and rail) are weighted. Universal noise indices are not easy to find, because some effects are better related to long-term noise levels, while other effects rather depend on maximum levels or the number of exceedances of appropriate threshold noise levels. This is still subject of ongoing research. Eventually, it is possible to combine air pollution and noise pollution indices to a common *exposure index* (*EI*) which describes the accumulative environmental state of air pollution and noise.

It is also convenient to define *health indices* by which environmental indicators are "crossed" with risk factors. The latter are given by demographic parameters that provide the number of people, the distribution of gender and age, etc. The *exposure-response function* is an index which expresses the health impact (response) by the product of the exposure or received dose of air pollution and/or noise and the relative risk (Fig. 14). The latter depends on a detailed territorial analysis of the impact zone. The computed doses are integrated over the exposure duration, which covers the average lifetime and the time spent in the area. With exposure-response functions it is possible to predict the number of additional hospital admissions which can be expected from an increase of air pollution. Also the "years of life lost" (YOLL) is a common target parameter of an exposure-response function. It describes the reduction of the life expectancy according to an increase in pollution.

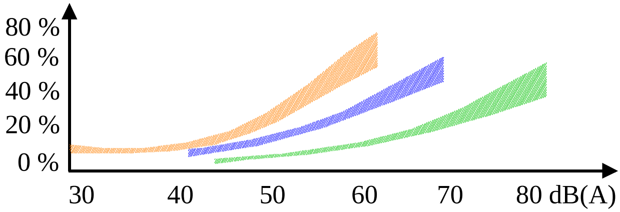

Fig. 14 Example of an exposure-response function showing the portion of "highly annoyed" people as a function of the long-term sound level for the noise of a main road (red), motorway (blue) and railway (green).

Under the key word *monetisation* another type of impact description is used. Monetisation expresses the consequences of health impairments in terms of its monetary value. This is the prerequisite to calculate the "external costs" of air pollution or noise, i.e. costs which arise from human activities which are not paid according to the perpetrator principle but are socialised and often paid by the next generation.

Assessments for abatement and planning

Since several decades, international research has been directed to the development of better instruments to detect air pollutants and noise, modelling procedures and numerical techniques to predict concentrations and sound levels, and methods to assess the impact of environmental burdens on health and well-being. In the recent years this research has made substantial progress. New sensor technologies and the rapid growth in computer performance have opened additional opportunities in observation and prediction methodologies. In particular, it is now possible to describe the complex air flow in mountainous areas with higher accuracy. This in turn is a prerequisite for reliable predictions of air pollution concentrations and noise levels since both are largely determined by the atmospheric conditions for tracer transports and sound propagation. These predictions also require precise information of the spatial and time distribution of emissions, i.e. the exhaust of harmful chemical compounds and the generation of noise as a function of traffic flow, fleet composition and road or rail conditions. Eventually, comprehensive studies about the effects of air pollution and noise on the human health and the degree of annoyance have been performed.

Monitoring and Observation methods

Measurements of environmental burdens are made in a twofold manner:

1. Continuous observations (monitoring) serve for the general surveillance of the state of the environment at fixed places. From these measurements it is possible to derive statis-

tics such as daily or annual mean values, extreme values, or the number of violations of limits.

2. Temporary observations are made for special investigations during planned campaigns or as a reaction to specific complaints. They often extend over only a few days or weeks. It is also possible to use mobile measurement platforms (cars, vans or even aircrafts) to cover not only a few spots but to get information of a larger area or volume. With temporary measurements it is possible to observe the situation in much detail, e.g. synchronous observation of a greater number of different species of pollutants by a dense array of instruments, or to sample meteorological, air pollution and noise parameters in combination.

The traffic flow (number of vehicles per hour) and the composition of the passing vehicles (e.g. cars and trucks) are routinely monitored at many sections of Alpine motorways and other major roads. Traffic flow counts are not primarily used for environmental reasons but mainly serve for the traffic control in general. Besides at the fixed routine counting stations, traffic is also sporadically counted during special actions at many streets, sometimes together with inquiries of the drivers about their departure and destination places.

Meteorological measurements

Basic meteorological parameters (air pressure, temperature and humidity, wind speed and direction) are routinely measured every hour at manned or automatic weather stations. The average distance between the stations is about 50 km which is actually too far as to account for the complexity of meteorological phenomena in the Alpine topography. Most of the weather stations are situated on the bottom of the valley, e.g. at airports. Only a very few ones are located on top of mountains. Vertical profiles of temperature, humidity, and air pressure are typically measured with the help of weather balloon ascents (radiosondes). Only some ten routine radiosonde stations are distributed around the Alps and only one is situated in the Alps (Innsbruck/Austria). At these stations the soundings are normally performed only once or twice a day.

Since there is a general lack in exhaustive meteorological observations which could for instance account for the three-dimensional complexity of wind systems in the Alps, it is from time to time necessary to perform special observations during coordinated campaigns. In such field activities it is possible to operate very sophisticated instruments. Two basic types of instrumentation can be distinguished:

1. “in-situ” measurements
2. “remote sensing” measurements

In-situ devices measure the state of the atmosphere at the spot of the sensor. They are normally used to record meteorological parameters near the ground (Fig. 15a). They can be mounted on a mast to measure vertical profiles (Fig. 15b). However, temporarily installed masts normally are not higher than some 10 m. To gain data from higher level, it is possible to install the sensors at a “tethered balloon” which one can be moved up and down a few 100 m (Fig. 15c). In-situ measurements can also be operated on specially instrumented aircraft. This is a flexible though very expensive method to gain meteorological data in three dimensions. A less expensive method to measure “vertical” profiles is the use of sensor-equipped cars which drive up the sides of valleys on roads and gain data in different altitudes above the valley bottom.

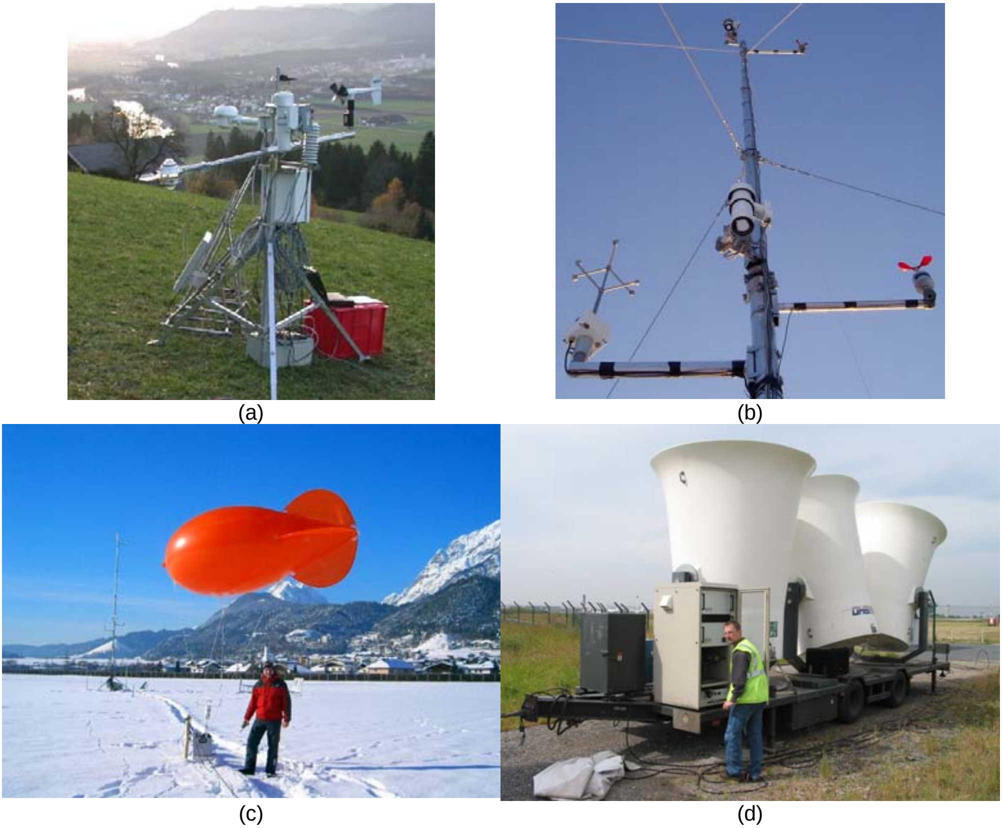

Fig. 15 (a) Automatic weather station with 2 m mast for the measurement of temperature (centre), wind (right) and radiation (left); (b) automatic weather station with 10 m mast; (c) Tethered balloon with meteorological sonde shortly before ascent; (d) Doppler Sodar.

Remote-sensing devices are ground-based but yet able to measure vertical profiles. Remote-sensing measurements use Radar, Lidar or Sodar (Fig. 15d) technologies, i.e. electromagnetic, optical (laser), or acoustical waves, to receive continuous information of the air column above the sensor.

Air pollution measurements

Long-term air pollution monitoring is nowadays a standard in European countries. Stationary observations are routinely performed in cities and in rural areas near busy motorways or in critical areas with high industrial emissions. The stations measure mainly those chemical compounds which are legally regulated, i.e. for which limit values are set that refer to long-term averages, short-term values, or the number of exceedance of a threshold within a certain period of time. The following components are usually monitored (however not all at all stations): carbon monoxide (CO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), ozone (O_3), volatile organic compounds (VOC), and particulate matter with a diameter $\leq$ 10 µm (PM10).

In addition to the stationary air pollution monitoring networks, temporary measurements are performed either routinely (e.g. sequential mobile observations at a selection of locations) or at special occasions (e.g. during high pollution episodes or in the framework of research projects).

Like for meteorological measurement, "in situ" and "remote sensing" instruments are used. Commercial in-situ measurement devices are available for a large variety of chemical compounds. They can be installed in containers, mobile cars, vans (Fig. 16), or in flying aircraft. Remote-sensing devices are used to determine the concentration of air pollutants over a certain distance.

Fig. 16 The air-quality mobile station of the Environmental Protection Agency of the Autonomous Province of Bolzano

Noise measurements

Routine long-term noise monitoring as it is often required by law in the vicinity of airports, is not commonly established along transport routes. Noise measurements are therefore performed during special campaigns. They can reach from short-term samplings to continuous observations over a week or longer.

Standard instruments measure the A-weighted sound pressure level and can store it in 1-second intervals. More advanced instruments have integrated analysers which provide the spectral distribution of the noise, i.e. the contribution of the main octave or 1/3 octave bands within the audible frequency spectrum (20 Hz – 16 kHz). The noise level meters use highly sensitive microphones which are normally wind-protected. According to standards the noise is measured at 1.5 m or 4 m above ground.

For binaural (stereo) sound measurements artificial head microphones are used. Here a pair of microphones is integrated in the "ears" of a head-like plastic body (Fig. 17). With the binaural recording it is possible to derive the direction of arrival of noise. Binaural measurements are mainly used in noise impact studies because it is possible to measure the noise as it is perceived by the human sense of hearing.

Fig. 17 A binaural artificial head microphone (left) and a monaural microphone (right) are listening the traffic noise in a recreation area of the French Maurienne valley. Both sensors are wind protected with foam.

Simulations and predictions

The impact of planned infrastructures (e.g. new motorways or railway lines), administrative measures (e.g. speed limits, night-time ban on trucks), modal-shift (e.g. from road to rail), and future traffic scenarios (e.g. due to the opening of new railway base tunnels, economic growth or changing tourism) on air pollution and noise and their consequences cannot be assessed from monitoring or observations. It is much more necessary to apply simulation tool and prediction procedures.

Basically, the major processes in the atmosphere which govern the terrain-induced winds and temperature stratifications, the transport, dispersion, chemical reaction and deposition of air pollutants, and the propagation, absorption, reflection, refraction and diffraction of sound waves are largely known and can be described by mathematical, physical and chemical formulae. The solution of these equations principally provides the temporal evolution and/or the spatial distribution of the concentrations of air pollutants and noise levels for prescribed boundary conditions. Precursory emission models are used to convert traffic data into emissions. Subsequent impact assessments relay on exposure-effect relationships which describe health effects as a consequence of air pollution or noise.

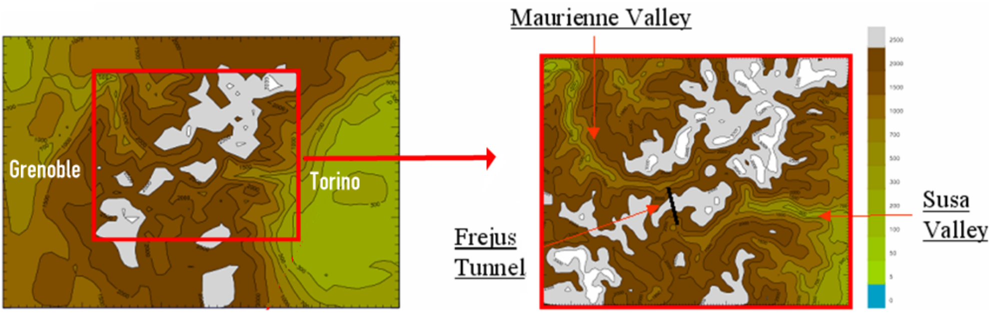

Fig. 18 Effect of the spatial resolution: The graph shows the terrain elevation of the western Alps with a 4 km grid spacing (left). In the subdomain (red box) the grid spacing is reduced to 1 km (right) so that much more details of the topography are visible.

Many man-made and natural processes which are responsible for the environmental burdens of traffic can be thus simulated by so-called computer "models" or "model systems". However, one still has to note that "models" always are a simplification of the reality. While the processes in nature depend on the interactions of myriads of single molecules, even the most powerful computers are not able to calculate all these interactions. Much more it is necessary to aggregate and to approximate the processes for computational reasons, but this a source of inaccuracies. Most computer models have a certain spatial "resolution", i.e. a length-scale which determines the extension of the smallest terrain features and processes which can be represented in the simulation (Fig. 18).

During the last decades powerful computer models have been developed at universities and research institutes. They have been validated (proofed for correctness) by comparisons of their results with data which were gained by monitoring or special observations during validation campaigns. If a model has shown its capability to simulate a documented real case with sufficient accuracy it can be used also as a prediction tool for the simulation of future scenarios with sufficient reliability.

Since accurate solutions require a high computational effort, very simple models have been derived for routine practical purposes. Such models are often fixed in regulations and are used by authorities or consulting bureaus in the approval procedures during the planning phase of new infrastructures to make a prediction whether legal air quality or noise limits would by violated by the measure or not. The disadvantage of these models is the fact that they are mostly designed for flat terrain and therefore disregard the complexity associated with the Alpine topography, in particular the relationship between topography and meteorology. The consequences can be considerable errors.

Advanced models which are nowadays ready for use cannot immediately replace the regulated standard models. However, they can be used as supplementary tools for

- the investigation of complex situations for which standard methods are likely to fail,
- the assessment of worst-case conditions, i.e. situations in which extreme pollution is expected and countermeasures are required,
- the optimisation of abatement measures in very specific geographical situations,
- the assessment of future traffic scenarios.

In practice however, the use of computer models often suffers from the following circumstances:

- detailed input data are missing or are not available in sufficient quality, either because they were not collected in a certain area or they are not provided by the owners,
- economic reasons require a trade-off between computational effort and accuracy.

Nevertheless, the application of advanced computer models is often superior to the use of engineering methods or simple estimates.

Emission models

Emission models are used to calculate emissions rates (e.g. mass of released air pollutants per time interval or sound power levels) along a road or railway line from traffic data (number of vehicles/trains per time interval, composition of vehicle/train types, speed distribution, slope ratio, road or rail surface conditions). The traffic data can be observed, estimated or forecast. The quality of the emission data depends on the quality of the traffic data. Traffic and other emissions, i.e. domestic heating, industry, are catalogued by the environment agencies in so-called emission inventories.

Meteorological models

Meteorological models are used to calculate the spatial distribution of all parameters that control the transport and dispersion of air tracers and the propagation of sound waves

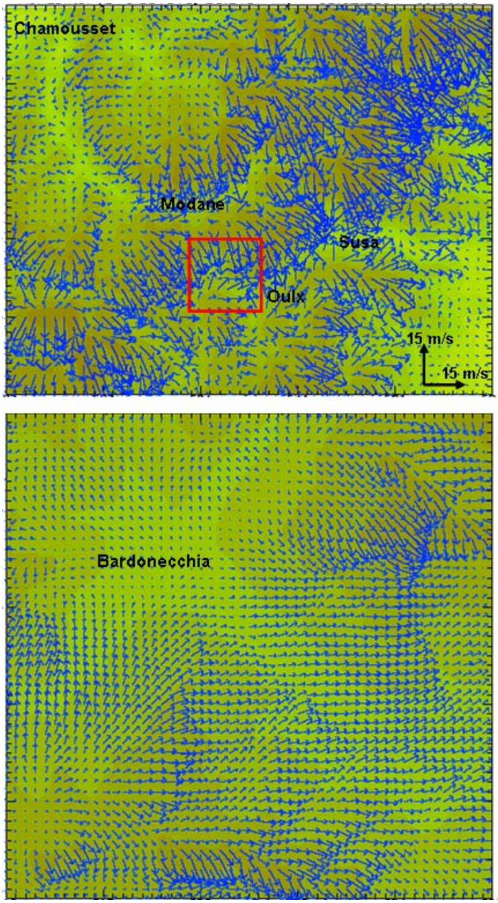

Fig. 19 Example of nested meteorological simulations showing the wind field at 1 km resolution (top) and in a subdomain (red box) at 100 m resolution (bottom).

in three-dimensions. The detailed meteorological parameter fields in mountainous areas are determined by simulating all processes which are influenced by topographical factors (terrain elevation, land use, aerodynamic and thermodynamic ground properties), astronomical factors (time of sunrise/sunset, inclination), and large-scale meteorological factors (e.g. high-level wind flow, air mass). In particular, the models must be capable of reproducing the mountain-induced wind systems (slope winds, mountain-plain circulation, channelling, foehn) and the formation of inversions. Typical meteorological models for the use in the Alps have a horizontal resolution between some 100 m and some 10 km. Models with coarse resolution cannot simulate the wind systems in narrow valley, but can cover a larger portion of the Alps. Nesting methods (interlacing of model domains with successively higher resolution) allow to cover a large range with a detailed focus on a certain area (Fig. 19).

Air pollution models

Air pollution models calculate the transport, dispersion, deposition and chemical transformation of pollutants for given emission rates and meteorological fields. The information about emission and meteorology are often taken from the results of precursory emission and meteorological modelling. In addition, it is necessary to acquire topographical data. The air pollution models provide the spatial distribution of tracer concentrations in the air (noise immission) and/or the mass of deposed pollutants at the ground surface or in the vegetation (wet and dry deposition, sedimentation). As for the spatial resolution of air pollution models the same applies what was explained for the meteorological models (Fig. 20).

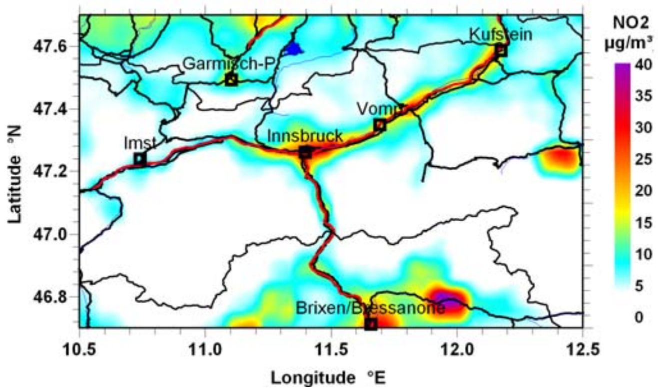

Fig. 20 Example of simulated annual mean NO_2 concentration in a larger area of the eastern Alps.

Noise models

Depending on their complexity noise models partly or fully simulate the effects of sound propagation between the source of noise and the receivers (e.g. housing areas) for given emission levels and meteorological situations. As in air pollution models the input data can be taken from the results of precursory emission or meteorological model runs. Additional input data are necessary to accurately describe the topography (terrain, ground characteristics, buildings).

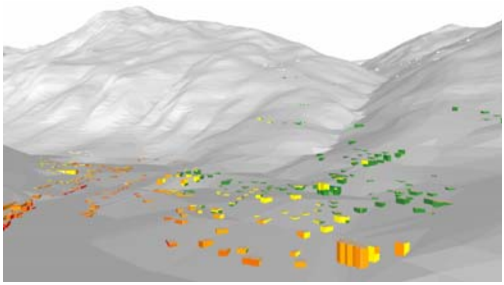

Fig. 21 Example of noise mapping. The colours show the simulated noise level L_{den} at the facades of buildings in a part of the French Maurienne valley. Reddish and greenish colours indicate high and low level, respectively.

The noise models provide the noise level at selected receiver positions or for an extended area (“noise mapping”, Fig. 21).

Impact models

Impact models take air pollution and/or noise data which have been either measured or simulated and calculate the impact on the human health, the level of annoyance, the potential increase in hospitalisations, the decrease in the expectancy of life, or the external costs of the environmental burden. Impact models are based on exposure-response functions. In addition they need demographic data (population density, age distribution, typical sojourn times indoors and outdoors, etc.).

With the help of Geographical Information Systems (GIS) it is possible to combine maps of the population density and health impact parameters in a cartographic presentation (Fig. 22).

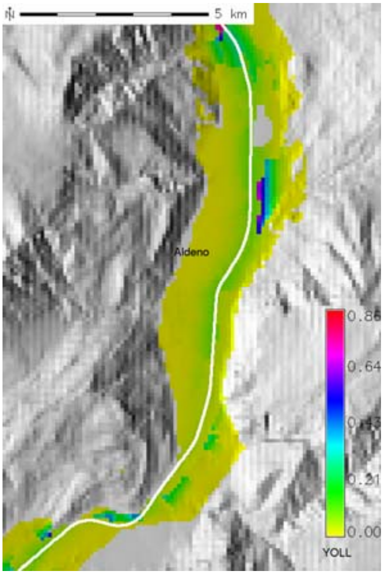

Fig 22 “Years of life lost” (increasing froem yellow to red) according to the air pollution in a sction of the Adige/Etsch valley

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