Air Quality of the Urban Alps

Innsbruck's new observatory

Adapted from “Studying Urban Climate and Air Quality in the Alps: The Innsbruck Atmospheric Observatory,” by **Thomas Karl** (University of Innsbruck), **Alexander Gohm**, **Mathias W. Rotach**, **Helen C. Ward**, **Martin Graus**, **Alexander Cede**, **Georg Wohlfahrt**, **Albin Hammerle**, **Maren Haid**, **Martin Tiefengraber**, **Christian Lamprecht**, **Johannes Vergeiner**, **Axel Kreuter**, **Jochen Wagner**, and **Michael Staudinger**. Published online in *BAMS*, April 2020. For the full, citable article see [DOI:10.1175/BAMS-D-19-0270.1](https://doi.org/10.1175/BAMS-D-19-0270.1).

To disentangle the emission, chemistry, and transport of air pollutants in the urban atmosphere in complex terrain, interdisciplinary long-term observations supplemented by short-term process studies are needed. Above: Rooftop instruments at the University of Innsbruck (left foreground).

The Alps are home to about 14 million inhabitants, mostly clustering along valleys where increasing traffic and an interplay between meteorology and orography is raising vulnerability to air pollution. Climate change may make conditions more conducive to summer air pollution episodes (e.g., during heat waves): urban areas are generally expected to be warmer, with slower flow, than rural surroundings, but boundary layer interactions may lead to early morning cooling and accelerate flow. The complex interactions between surfaces and the boundary layer—especially at the street scale—make predicting urban transport and diffusion of air pollutants a challenge. Furthermore, linking concentrations of these constituents to emissions is not trivial in the Alps due to the vertical layering of reactive gases and aerosols.

Emission inputs are also among the most uncertain components of complex atmospheric models. Improved predictions require a careful evaluation of projections of anthropogenic emissions based on a better understanding of urban chemistry and dispersion at smaller scales.

The Innsbruck Atmospheric Observatory (IAO) was established in 2017 to address these issues by providing long-term observations and infrastructure to synergistically study air pollution and climate change and their interaction in an Alpine urban environment.

Observatory setting and climate

Innsbruck, Austria, is a city of 130,000 inhabitants within a wider area of 300,000 people who live in the east–west-oriented Inn Valley. Approximately 6 million

vehicles pass through the eastern traffic corridor of the 510-km-long valley, which is approximately 15 km wide (peak to peak) at Innsbruck and surrounded by mountain ridges about 2.5 km high. It is joined by the north-south-oriented Wipp Valley.

IAO is set in the city center; 70% of the source area, covered mostly in (typically 5–7 story) buildings and paved surfaces, is within 500 m of IAO's micrometeorological tower.

In the northern Alps, dry, cold winter and warm, humid summer conditions can persist when eastern continental or Mediterranean air dominates. Mean monthly temperatures range from close to 0°C in winter to about 20°C in summer, but there has been pronounced warming since the 1980s. In 2016–18, all months were warmer than the 1981–2010 normals. Due to the topography, annual precipitation in Innsbruck is below 1,000 mm. In the central Alps, precipitation has high year-to-year variability but no significant trend, and 2016–18 was slightly wet. Sunshine sums up to around 2,000 h per year.

The mountain boundary layer dynamics modulate the temporal distribution of pollutants, decoupling them from emissions. The inversion can adversely affect valley air quality in an approximately 340-m thick layer. It peaks in December and January and averages 16% yearly.

In characteristic along-valley winds, the northeasterly upvalley flow tends to be stronger than the southwesterly downvalley flow. The strongest winds are southerly foehn winds from the exit of the Wipp Valley. These winds occasion rapid and extensive air mass exchange in the Inn Valley atmosphere. In 2016–18, about 311 h of foehn conditions per year were observed. During our 2018 intensive observing period (IOP2018), winds changed from downvalley to upvalley at about 1000 UTC, and back again after 2300 UTC.

All year, the city is a source of CO₂, which builds up near street level. Exchange of greenhouse gas emissions is driven by location-specific venting of street canyon air.

Organic compounds

NO_x emissions are typically excessive, as are nonmethane volatile organic compound (NMVOC) emissions. In the Inn Valley, concentrations of aromatic VOCs, CO, and aerosols (PM_{2.5} and PM₁₀) have decreased considerably despite increasing traffic and population.

*** 50%, 60%, 70%, and 80% composite flux source area at the IAO overlaid on ground height (gray) and building and tree height (color). The cross marks the position of the IAO tower (42.8 m above street level), and the dashed circle has a radius of 500 m. Spatial datasets are from Land Tirol. The flux footprint was calculated for 42.8-m height during IOP2018. IAO is surrounded by approximately 100 m × 100 m blocks of buildings, with buildings typically 19 m high. Within the line describing 70% of the source area, the plan area fraction of buildings is 31%, roads and paved surfaces 42%, vegetation 19%, and water 8%. For easterly winds, however, the fraction of buildings in the source area is larger (40%) than for westerly winds.**

Nitrogen dioxide (NO₂), which contributes to tropospheric ozone formation, has increased since 2000, similar to in other European areas. A substantial amount of ozone seems to be imported into the valley by the foehn. Our goal is to expand the analysis of trends in valley-integrated NO_x concentrations and serve as a testbed for the Pandonia Global Network of Pandora spectrometers.

Certain NMVOCs can serve as tracers to fingerprint anthropogenic emission sources. The complexity of NMVOC emissions and

*** Distribution of wind direction at Innsbruck University in the period 2016–18 color-coded with the wind speed frequency in each 10° wind sector. Wind rose is based on half-hourly mean values.**

distributions, which fuel ozone chemistry and serve as precursors to secondary organic aerosol formation, is a major focus. The distribution of urban NMVOCs is nowadays mostly dominated by volatile chemical products. Emission fluxes of these compounds exhibit a significant rush hour peak and show pronounced differences between weekdays and Sundays.

Preliminary analysis also warrants future investigations about the role of biogenic and oxidized NMVOCs in Alpine regions. Combining different measurement techniques and observations of OH reactivity—a measure that helps constrain the catalytic ozone production efficiency in the air—could help tackle this problem and determine important sources of NMVOC in urban environments.

NMVOC loading also has ramifications for understanding the distribution of aerosols. The fraction of biogenically derived aerosols could

be particularly large in the Alps, where they are mixed into a NO_x -rich valley atmosphere. Further study is required to elucidate the complex behavior of secondary air pollutant formation in the Alps, particularly aerosols.

Meanwhile, direct flux measurements of carbonyl sulfide (COS) are increasingly used to decipher photosynthetic CO_2 uptake and respiration fluxes above ecosystems. COS correlates with the uptake of CO_2 by plants, whereas any uptake signal in the observed CO_2 fluxes would be masked by fossil fuel combustion. We observed net nighttime uptake of COS, when photosynthesis is halted, which is understood to reflect the fact that plants do not completely close stomata in darkness. Increased COS uptake was observed during the early morning, but around midday observations switched to net COS emission: vehicular exhaust might be a major COS source. Using COS as a tracer

for plant photosynthesis in urban areas therefore requires an accurate characterization of urban emission sources.

Further perspective

Biogenic–anthropogenic emission interactions in Alpine valleys complicate any possible strategy

of mitigation through greening cities. Thus, understanding the interplay between anthropogenic and biogenic emissions and the valley circulation is a prerequisite to designing such strategies.

IAO offers a chemical and physical measurements infrastructure for campaign-based community experiments in addition to long-

term tracking of urban air pollutants. Future plans include conducting more detailed investigations of the fate of pollutants. IAO enables studies of sources and transformations of aerosols and gases, numerical simulation

of dispersion over complex terrain, and extension of an existing Alpine network of turbulence observations to an urban site. With its flux tower, the IAO can also help to test new micrometeorological instrumentation. ☼

◀* (a) Potential temperature (color contours) and wind barbs for horizontal winds as a function of height, (b) vertical velocity variance (color contours) and corresponding ABL height (red dots), and (c) near-surface temperature (red), wind speed (blue), and wind direction (black): Combining remote sensing and in situ data shows the impact of boundary layer evolution on fluxes and concentrations of trace gases. On a representative day (28 August) toward the end of the 2018 heat wave, weak synoptic forcing and clear skies resulted in a strong diurnal cycle of radiative forcing, generating thermally driven flows. The morning transition from downvalley to upvalley flow occurred at about 1000 UTC. The convective boundary layer grew to between 600 and 900 m AGL at midday.

(d) Turbulent kinetic energy (TKE, black), sensible and latent heat fluxes (red and green), and shortwave incoming radiation (orange): Sensible heat peaked in the morning and, as expected from the built land-cover, latent heat fluxes were low. Urban trace gases fluxes peaked during midday along with turbulent kinetic energy.

(e) CO₂ fluxes (blue) and mixing ratios (black); (f) ozone fluxes (blue) mixing ratios (black); and (g) NO and NO₂ fluxes (blue solid and dashed), NO and NO₂ mixing ratios (black solid and dashed), and NO₂ columns (red); and (h) summed NMHC concentrations (black) and fluxes (blue). NO₂ has strong emission sources along the valley, suppressing net ozone formation in the urban core. Ozone exhibited a substantial downward flux above the city, which is mainly driven by the conversion of NO to NO₂. All other trace gases exhibit concentration minima during daytime due to dilution initiated by ABL growth and winds.

In situ NO_x shows an early morning peak due to traffic and a shallow ABL. A large fraction of NO_x is converted to NO₂ suppressing local ozone concentrations. Dilution due to ABL growth alone cannot explain the decline of column NO₂; the Pandora column measurement system measured less polluted air south of Innsbruck in the morning, but in the wind transition the NO₂ column density increased as more polluted air masses were advected past the instrument's field of view.

≡ METADATA

BAMS: What would you like readers to learn from this article?

Thomas Karl (University of Innsbruck): *Understanding interconnections between meteorology and air chemistry in urban environments is paramount for creating sustainable cities.*

BAMS: How did you become interested in this topic?

TK: *As part of my tenure at NCAR, I was involved in numerous interdisciplinary field campaigns on urban air pollution. When I moved back to Austria, my colleagues here in Innsbruck and I were discussing the idea to combine research aspects of classical micrometeorology, mountain meteorology, and atmospheric chemistry in an urban setting in the Alps.*

BAMS: What surprised you in the data you've collected?

TK: *We were surprised to see significant nonsteady-state conditions of ozone chemistry due to atmospheric dynamics—for example, the föhn. Further, a significant diversity of urban nonmethane volatile organic compounds that fuel ozone chemistry shows that urban emissions are still poorly constrained. In Europe, excessive nitrogen oxide emissions are still a challenge, and we observed significant urban NO_x emission fluxes.*

BAMS: What was the biggest challenge you encountered in the experiment?

TK: *Apart from accruing the necessary funding, the biggest challenge was establishing an urban site suitable for micrometeorological measurements that would also allow operation of remote sensing and atmospheric chemistry equipment. So, setting up a sizeable laboratory next to a flux tower above the roofs of Innsbruck proved logistically the most challenging part.*

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