URBAN CLIMATOLOGY

VII. Spatio-temporal variability of other meteorological elements in urban areas

Air humidity in urban climate

Table U2 Urban climate effects for a mid-latitude city with about 1 million inhabitants (values for summer unless otherwise noted)

Variable	Change	Magnitude/comments
Turbulence intensity	Greater	10–50%
Wind speed	Decreased	5–30% at 10 m in strong flow
	Increased	In weak flow with heat island
Wind direction	Altered	1–10 degrees
UV radiation	Much less	25–90%
Solar radiation	Less	1–25%
Infrared input	Greater	5–40%
Visibility	Reduced	
Evaporation	Less	About 50%
Convective heat flux	Greater	About 50%
Heat storage	Greater	About 200%
Air temperature	Warmer	1–3°C per 100 years; 1–3°C annual mean up to 12°C hourly mean
Humidity	Drier	Summer daytime
	More moist	Summer night, all day winter
Cloud	More haze	In and downwind of city
	More cloud	Especially in lee of city
Fog	More or less	Depends on aerosol and surroundings
Precipitation		
Snow	Less	Some turns to rain
Total	More?	To the lee of rather than in city
Thunderstorms	More	

Atmospheric moisture in urban areas

- Not many studies - atmospheric moisture is quite complex and variable
- **Importance**
  1) transition between the vapour, liquid and solid states has **energetic implications** due to an uptake and release of latent heat
  2) As a suspended liquid or solid atmospheric humidity **forms clouds and precipitation**
- In specific situations densely built up areas may be „**arid**“ or „**humid**“ due to impervious surface cover, relative lack of vegetation, UHI existence, local geography, water supply sources etc.
- Existing studies are hardly comparable as they use different instrumentation as well as **different air humidity measures**

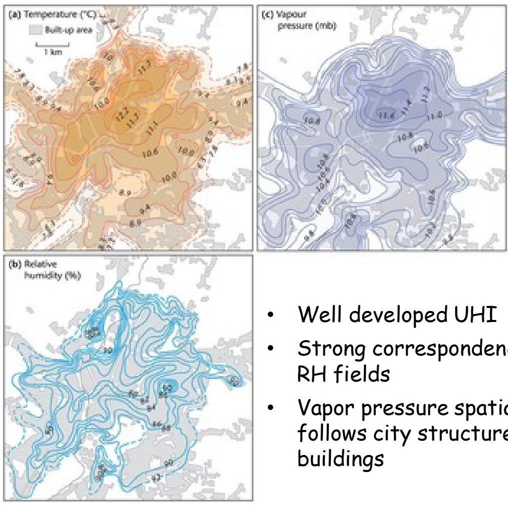
Atmospheric moisture in urban areas

A hair tension dial hygrometer

Air humidity measures

- **Absolute humidity** – (grams of water vapor per cubic meter volume of air) – it is a measure of the actual amount of water vapor (moisture) in the air, regardless of the air's temperature. The higher the amount of water vapor, the higher the absolute humidity.
- **Specific humidity** (or moisture content) is the ratio of the mass of water vapor to the total mass of the air parcel.
- **Vapor pressure -** the partial pressure of water vapor in the atmosphere
- **Relative humidity** - the ratio of how much water vapour is in the air to how much water vapour the air could potentially contain at a given temperature.
- RH varies with the temperature of the air: colder air can contain less vapour, and water will tend to condense out of the air more at lower temperatures.
- **Temperature-dependent** and **T-independent measures** often provide contradictory results

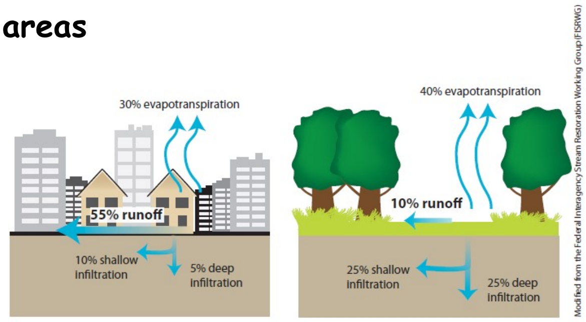
Spatial variability of air humidity and its relation to air temparature



- Well developed UHI
- Strong correspondence between T and RH fields
- Vapor pressure spatial distribution follows city structure and density of buildings

Spatial variability of air temperature (a), relative humidity (b) and vapor pressure (c) in Leicester (UK), calm, clear sky summer night (Oke et al. 2017)

Humidity in urban areas



Spatial and temporal variability of air humidity in urban areas is the result of evapotranspiration, condensation and advection processes.

There are several positive and negative feedbacks.

- Higher temperature -> higher intensity of evapotranspiration (that is however low due to lack of vegetation)
- No consumption of latent heat -> rising temperature
- Fast runoff -> les intensity of evaporation

Humidity in urban areas

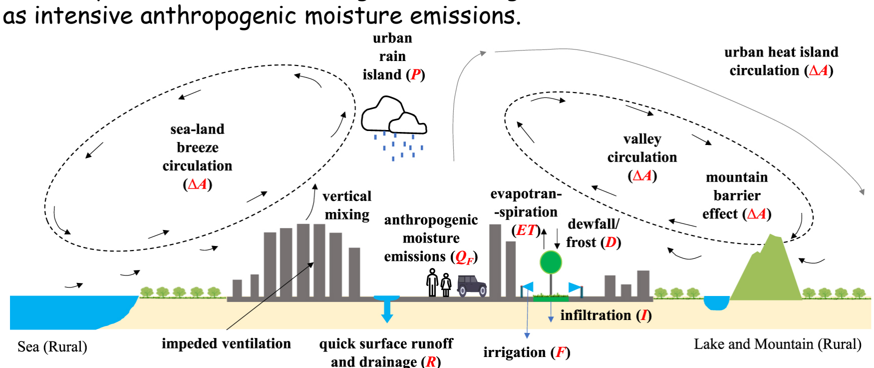
- **Atmospheric humidity** is generally **lower** in cities during **daytime** (due to lower evapotranspiration compared to rural areas – there is smaller fraction of vegetation cover)
- **At night and in winter there is an urban moisture excess** (UME) in mid- and high latitude cities. The reason is: i) additional water vapor from anthropogenic activities; ii) weak evapotranspiration in unstable atmosphere
- In some situations (dry spells, arid climate) **humidity can be higher** in cities due to extensive irrigation compared to neighborhoods
- Bad air quality mostly cause increase of fog frequency and intensity

Urbanization-induced atmospheric moisture changes

Urban dry island (UDI) – drier urban areas; first documented in 1950s in Europe

Urban moisture island (UMI) - wetter urban areas compared to rural areas, in numerous European, North American, and Asian cities especially in clear summer nights

The occurrence of UMI can be attributed to the enhanced evapotranspiration and delayed dewfall of urban vegetation at night due to UHI effect, as well as intensive anthropogenic moisture emissions.



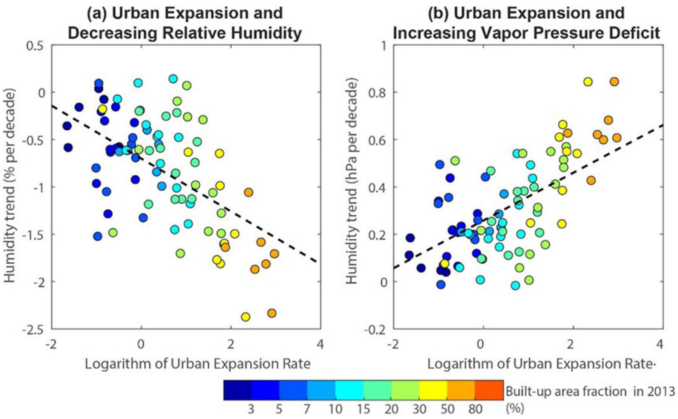
Schematic of multi-faceted urban changes in local and regional hydrometeorological cycles. Source: https://iopscience.iop.org/article/10.1088/1748-9326/acf7d7

Urbanization-induced atmospheric moisture changes

Detailed understanding on urban humidity changes still lacks exploration due to the following **challenges**:

1) the **inconsistency of humidity metrics** measured and analyzed in different studies (temperature dependent and independent metrics)
2) ensuring the richness and representativeness of observation data.
3) a comprehensive **urban moisture modeling**, due to the difficulty in accurate physical and mathematical representation of hydrometeorological cycles and water phase-changing processes
4) coupling and decoupling with UHI studies as the **relationship between air temperature and humidity** is complex and interdependent.

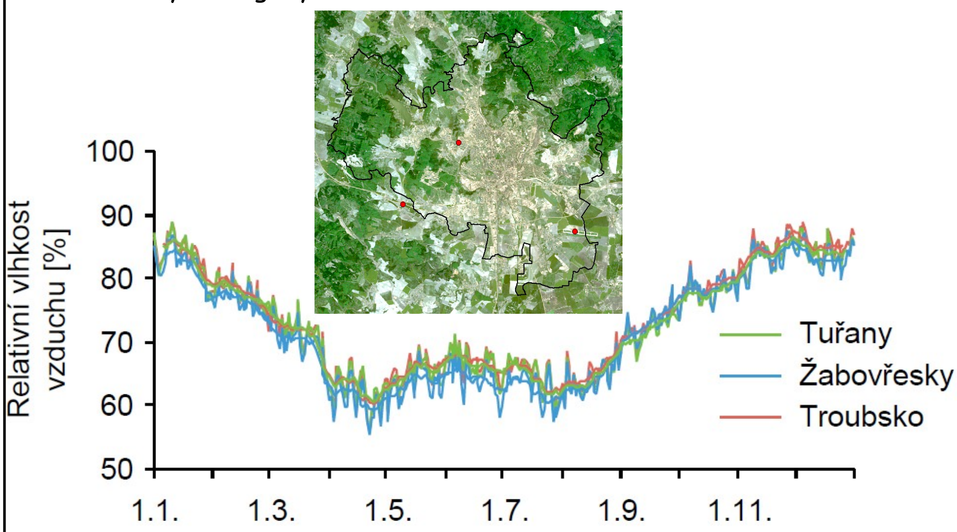
Air humidity and rapid urbanization



Rapid urban land expansion significantly accelerates the decrease in atmospheric moisture over the area, and urbanization contributes to approximately 50% of the increase of vapor pressure deficit and the decrease of atmospheric humidity in the urban areas of Guangdong Province, South China (Lin et al. 2020)

Relative humidity in Brno

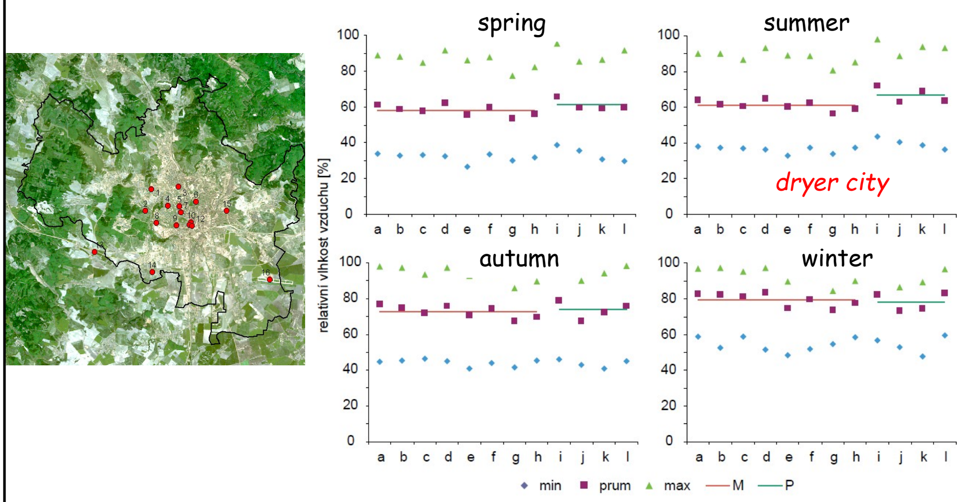
Variability during a year



Annual variations in daily means of relative humidity at three stations in Brno area in the period 1987–2010

Relative humidity in Brno

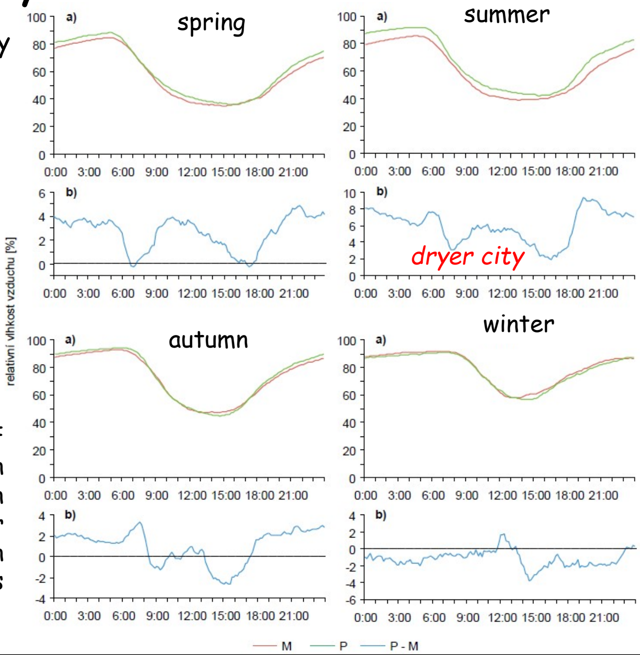
Seasonal differences



Mean, min a max relative humidity in Brno area in individual seasons during days with radiation driven weather for urban stations (red) and rural stations (blue)

Relative humidity in Brno

Variability during a day



Mean daily variations of relative humidity at urban (M) and rural (P) stations in Brno area (a) and their differences P – M (b) in individual seasons

Urbanization-induced moisture changes summary

ENVIRONMENTAL RESEARCH LETTERS
TOPICAL REVIEW • OPEN ACCESS

Urban moisture and dry islands: spatiotemporal variation patterns and mechanisms of urban air humidity changes across the globe

Xinjie Huang[1,2] and Jiyun Song[6,1,3,4,5]

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Environmental Research Letters, Volume 18, Number 10

- Mid-latitude cities predominantly exhibit moderate UMI and UDI effects,
- Cities with low mean annual precipitation and distinct dry/wet seasons, however, exhibit extreme UMI and UDI effects.

- **The diurnal cycle** - more pronounced UMI effects at night, largely due to increased evapotranspiration and delayed dewfall linked with UHI.
- **On a seasonal scale**, - UDI effects dominate in spring, while UMI effects peak in winter for mid-latitude cities and in summer for low-latitude cities.

- **Topography, morphology, and size** significantly shape urban–rural humidity contrasts.

- **Coastal cities** are subject to sea-breeze circulation, importing moisture from sea to land, whereas **mountainous** cities can accumulate humidity and precipitation due to geographical barriers and vertical airflow.
- **High-density** urban areas generally experience heightened UMI effects due to restricted airflow and ventilation.
- Larger cities with higher populations contribute to increased UMI effects, particularly in winter, due to stronger **anthropogenic moisture sources**.

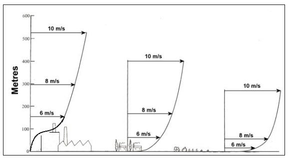
Wind field in urban climate

Table U2 Urban climate effects for a mid-latitude city with about 1 million inhabitants (values for summer unless otherwise noted)

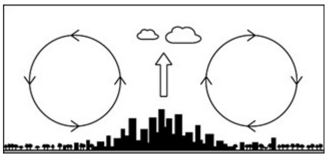
Variable	Change	Magnitude/comments
Turbulence intensity	Greater	10–50%
Wind speed	Decreased	5–30% at 10 m in strong flow
	Increased	In weak flow with heat island
Wind direction	Altered	1–10 degrees

Landsberg (1981)

Wind filed in urban environment is modified due to **mechanical** (left) and **thermal** (right) effects



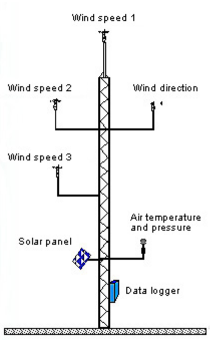
Wind velocity vertical profile modified due to different surface roughness (http://www.wind-power-program.com/windestimates.htm)



Circulation resulting from temperature differences between rural and urban areas (modified after Munn 1968)

Both effects dominate on different scales and the resulting fields of wind **speed** and wind **direction** in cities are superposition of both effects.

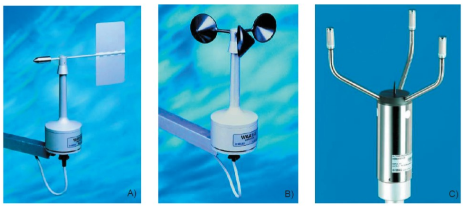
Wind field measurements



www.windtest-nrw.de

Standard meteorological stations - measurement of the horizontal component of the wind flow at a height of 10 m

Special purpose stations - measurement of horizontal and vertical components of the flow component on special masts at several levels

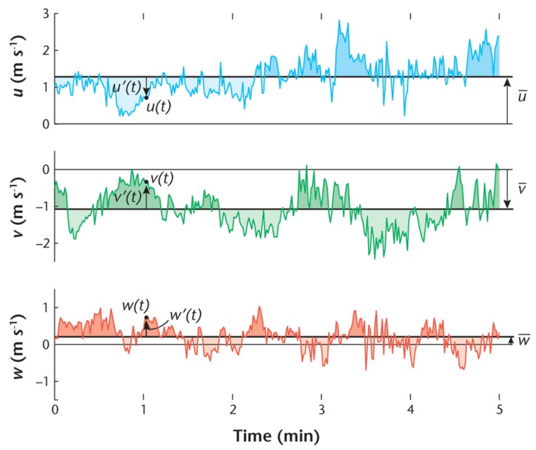


Digital wind vane, anemometer and ultrasonic sensor (source CHMI)

Mean and turbulent parts of wind field

Wind is described as a 3D vector with two horizontal velocity components (u, v) and one vertical velocity component (w)

All components consist of **mean wind** velocity and **turbulent fluctuation**



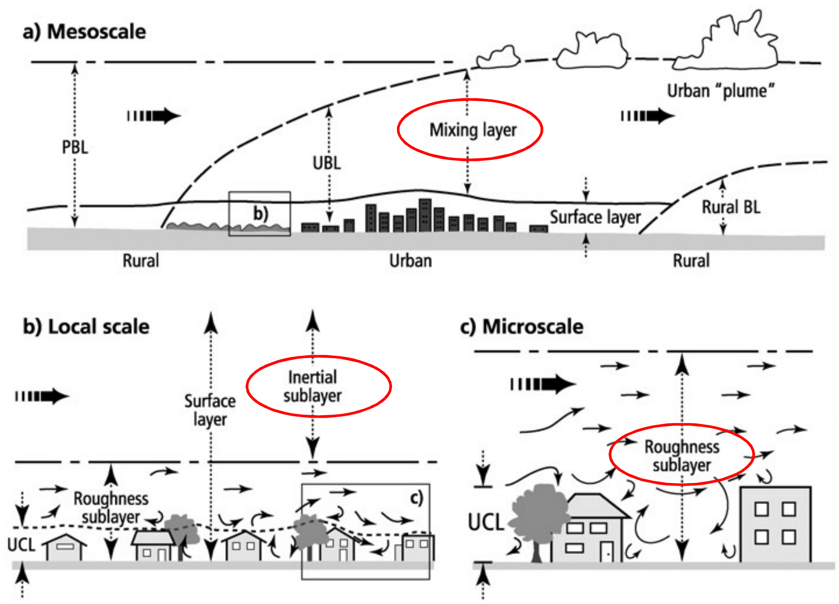
Mechanical turbulence – from roughness

Thermal turbulence – from surface heating

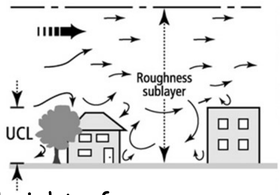
Eddies – short life-time quasi random fluctuations rotating faster or slower than the average

Oke *et al.*, 2017, *Urban Climates*

Wind field in urban environment



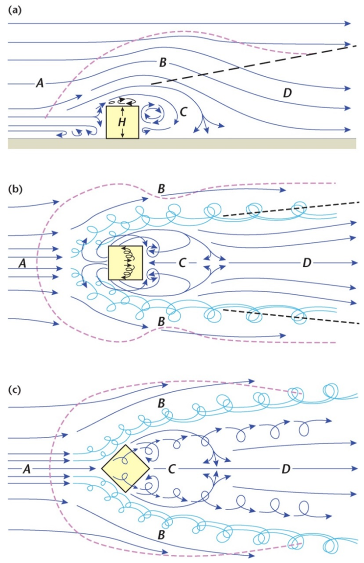
Wind flow in the roughness sublayer (RSL)



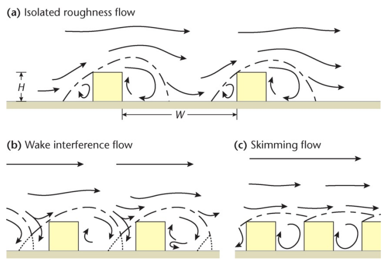
- RSL extends from ground up to 2-5 times the height of buildings/trees.
- Formed due to very diverse forms, shapes and dimensions of individual objects.
- **Mechanical turbulence dominates** and air flow is affected by individual elements (buildings)
- Classical laws (e.g. logarithmic wind profile) do not apply
- **Usually mean air flow is reduced, however turbulence is increased**
- The main control affecting mean flow and turbulence is **height(H) and width (W)** of individual elements
- Microscale circulation is formed in Urban Canopy Layer and it may be separated from the flow above; vertical exchange may be limited

Wind flow in the roughness sublayer (RSL)

Various urban elements and structures cause specific wind-field modifications:

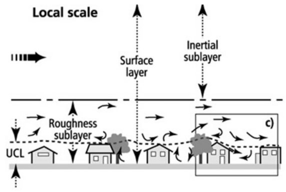


- Isolated buildings
- Uniform building arrays
- Tall buildings
- Streets, canyons and intersections



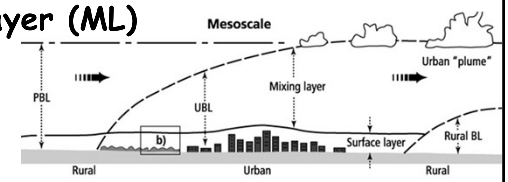
Oke *et al.*, 2017, *Urban Climates*

Wind flow in the inertial sublayer (ISL)

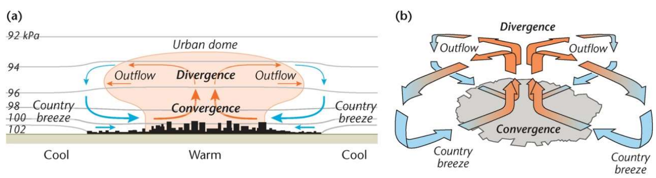


- ISL is usually formed above RSL
- May exists above **relatively homogeneous larger areas** (neighborhood)
- Airflow is an **integral** (blended) **response** of the urban environment
- Logarithmic velocity profile
- Relatively homogeneous in horizontal components
- No significant change in mean vertical component
- Variation of the turbulence with height is small
- Most of atmospheric variables are only a function of height

Wind flow in the mixing layer (ML)

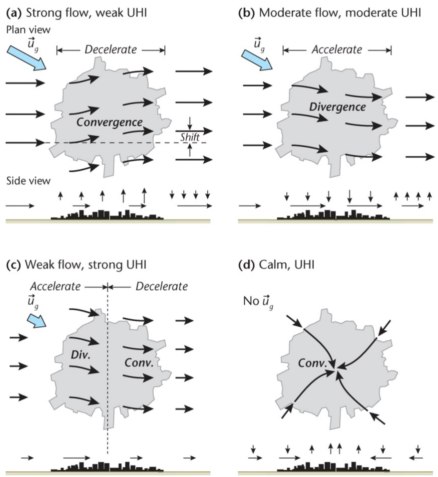


- ML reflects changes in the wind field in the **scale of the entire city**
- Contribution of different urban neighborhoods is blended
- ML wind flow **integrate both the roughness and the thermal effect**
- Airflow in ML may strongly affect convection processes and precipitation
- Wind flow usually leads to convergence (slowing due to roughness), and uplift
- Low pressure zone over warmer city initiates **UHI circulation**



Oke *et al.*, 2017, *Urban Climates*

Combined roughness and thermal effects



Oke *et al.*, 2017, *Urban Climates*

ENVIRONMENTAL RESEARCH
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Introducing the urban wind island effect

A M Droste[1], G J Steeneveld[1] and A A M Holtslag[1]

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Environmental Research Letters, Volume 13, Number 9
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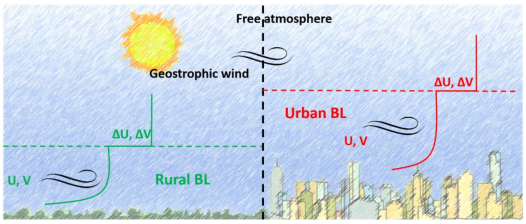
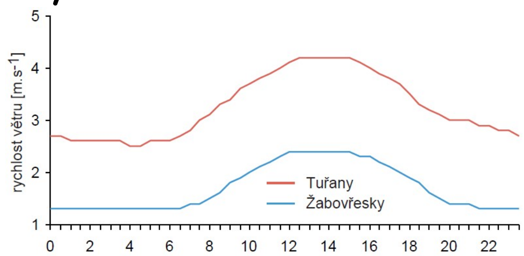
DOI 10.1088/1748-9326/aad8ef

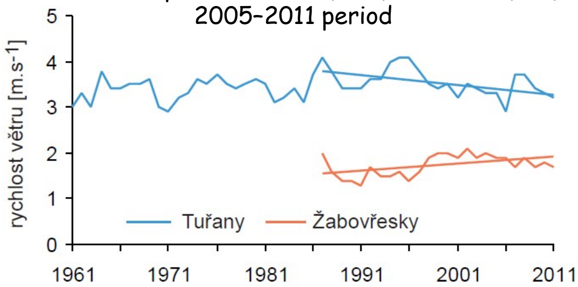


- For certain atmospheric conditions the boundary-layer mean wind speed in a city can surprisingly be higher than its rural counterpart, despite the higher roughness of cities.
- This **urban wind island** effect (UWI) prevails in the afternoon, and appears to be caused by a combination of differences in ABL growth, surface roughness and the ageostrophic wind, between city and countryside.
- The UWI phenomenon challenges the commonly held perception that urban wind is usually reduced due to drag processes.

Wind velocity in Brno

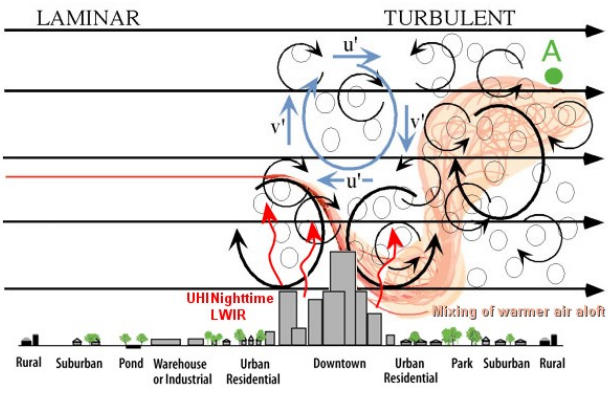


Daily course of mean wind speed at urban (blue) and rural (red) stations in the 2005–2011 period



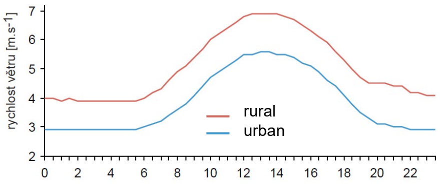
Variability of mean annual wind speed at rural (blue, 1961–2011) and urban (red, 1987–2011) stations

Intensity of turbulence



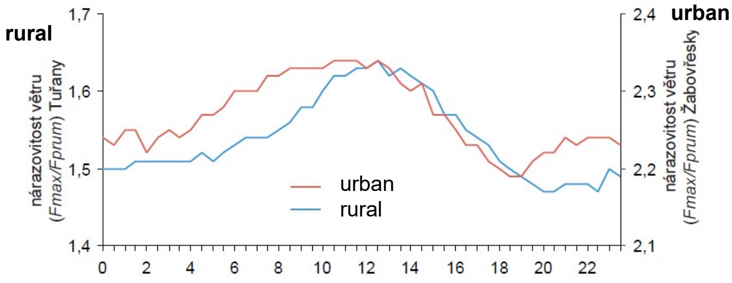
The ratio between maximum daily wind speed and mean daily wind speed may be used as a simple measure of **intensity of turbulence.** The ratio is clearly higher at the urban station.

Intensity of turbulence



Daily variation of **mean maximum wind speed** at rural and urban stations in the period 2005–2011

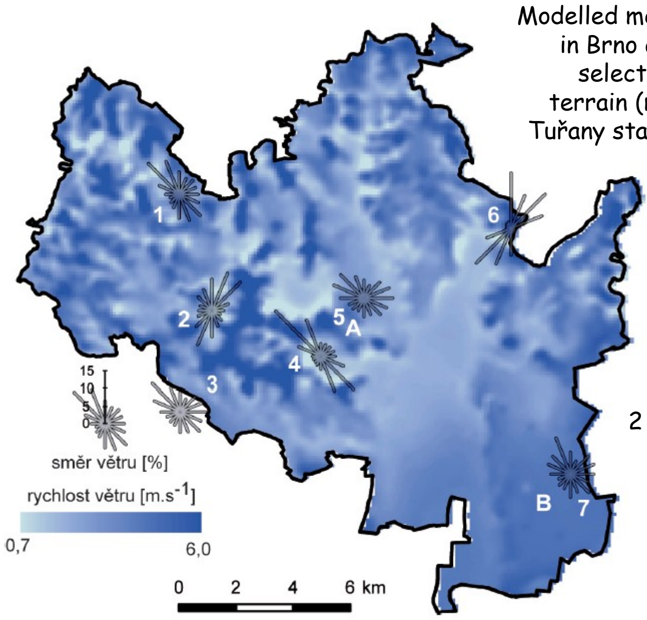
Daily variation of the **intensity of turbulence** defined as a ratio of maximum wind speed (*Fmax*) and mean wind speed (*Fprum*) at urban and rural stations, period 2005–2011



- Intensity of turbulence is much higher at urban station
- The maximum and minimum in the daily course of the turbulence occur earlier in the city compared to countryside

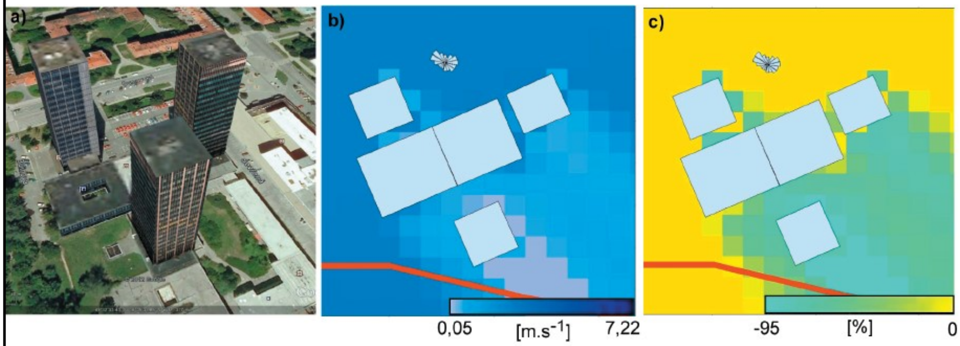
Wind field modification

Modelled mean annual wind velocity in Brno area and wind roses for selected points at 10 m above terrain (model WAsP, data from Tuřany station, period 1961–1998)



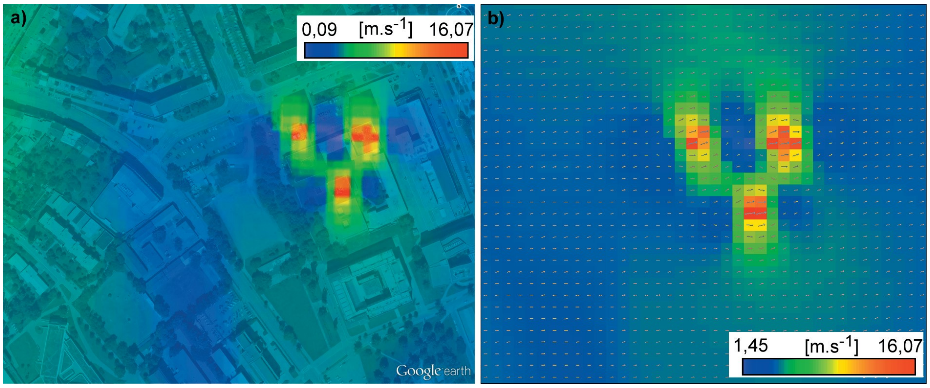
Localities:
1 – Brněnská přehrada
2 – oblast Staré dálnice
3 – Troubsko
4 – ul. Hroznová
5 – ul. Šumavská
6 – údolí Svitavy
7 – Tuřany, letiště.

Wind field modification



Modification of wind speed near obstacles calculated using WAsP model – an example for for high-rise buildings (60 m) at Šumavská str. a) study area; b) mean wind speed near buildings for NW wind direction; c) relative reduction of mean wind speed near buildings for NW wind direction

Wind field modification



Modification of mean wind speed (a) and wind direction (b) near high-rise buildings at Šumavská str. calculated using WAsP model for wind speed 8.0 $m.s^{-1}$ and for wind direction 260° (reference values for Tuřany airport station)

Final remarks and questions

Transition between water vapor, liquid water and solid states has energetic implications due to consumption or release of latent heat

Extensive irrigation may significantly modify **moisture conditions** especially in an arid climate.

Wind field may be significant factor reducing thermal heat load and the urban heat island intensity.

Intentional wind field modifications in scale of city may contribute significantly to mitigation strategies (see lecture 10)

1. How does the vegetation in urban areas influence humidity?
2. What is a typical variability of humidity in urban area during a day and during a year?
3. What are main factors modifying wind field in urban areas
4. What can be the most important negative effects of wind field modification in urban areas?