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Understanding Air Quality under Different Weather and Climate Conditions in the Pannonian Basin

Background material for PannEx White Book
FQ2 (Flagship Questions)

Edited by Tamás Weidinger

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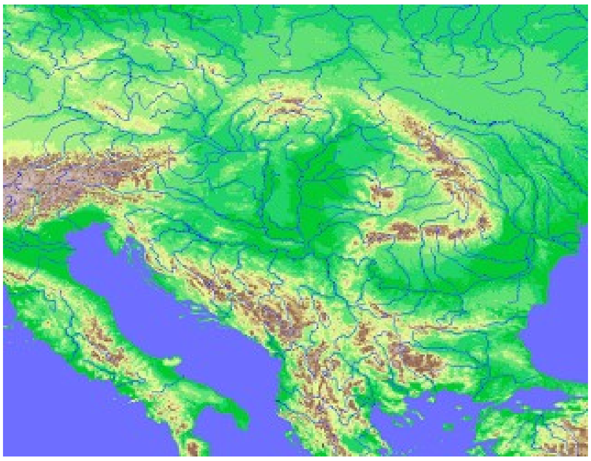

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PannEx White Book – FQ2 (Flagship Questions) title:

Understanding Air Quality under Different Weather and Climate Conditions in the Pannonian Basin

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Regional Hydroclimate Project over the Pannonian Basin (PannEx)

PannEx WB – FQ2 (Flagship Questions) title:

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Contents

Preface

PannEx is a mosaic word (Pannonian Experiment) referring to the long term cooperation in the region of the Carpathian Basin in the fields of meteorology, environmental protection and hydrology. The cooperation programme began in 2015 in Osijek, Croatia. PannEx is becoming a *Regional Hydroclimate Project* (RHP) of the *Global Energy and Water Exchanges Project* (GEWEX) of the *World Climate Research Programme* (WCRP).
GEWEX aims to observe, understand and model the hydrological cycle and energy fluxes in the Earth's atmosphere and at the surface. It proceeds by means of an integrated program of research, observations and science activities that focus on the atmospheric, terrestrial, radiative, hydrological, coupled processes and interactions that determine the global and regional hydrological cycle, radiation and energy transitions, and their involvement in climate change. The almost closed structure of the Pannonian Basin makes it a very good natural laboratory for the study of the water and energy cycles, focusing on the physical processes of relevance. The PannEx area (*Figure 1*) involves the Carpathian Basin and surrounding areas that give possibilities for investigation of the regional effects of the Pannonian Basin on the weather and climate system. (*projectpannex/home*).

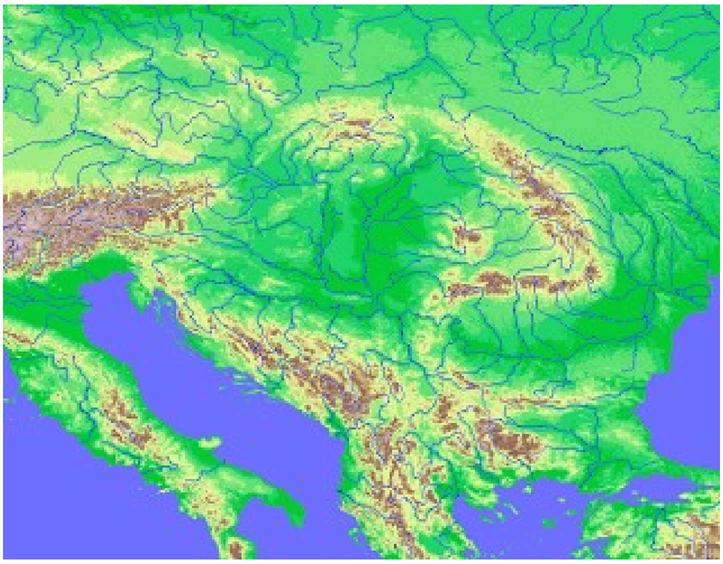

Figure 1: Research area of the PannEx (projectpannex/home).

The structure of PannEx was formed during the Osijek Workshop. The next step was the official invitation from GEWEX for the formation of the so called cooperation White Book. The program consists of 5 Flagship Questions (FQ1 – FQ5):

- adaptation of agronomic activities to weather and climate extremes;
- understanding of air quality under different weather and climate conditions;
- continued sustainable development;
- water management, droughts and floods;
- education, knowledge transfer and outreach;

and three Cross Cutting questions (CC1 – CC3), which give the technical and scientific background of the flagship questions:

- data and knowledge rescue and consolidation;
- process modelling;
- development and validation of modelling tools.

The main goal of the present publication (first issue of PannEx material) is to overview the background material for the second chapter of the White Book (FQ2) on the environmental problems of the Pannonian Basin connected with the soil, water and atmosphere in the present and future climates.

We hope this booklet provides a good starting point for future planning of regional scientific activity and for better understanding of the climate system, environmental (air quality) problems and surface-atmosphere interactions in the Carpathian Basin.

1. Introduction and motivation

Air quality is highly dependent on weather and therefore is sensitive to climate change. Globally the climate of the future is expected to be more stagnant, due to weaker global circulation and a decreasing frequency of mid-latitude cyclones (Jacob and Winner, 2009). In the western part of Europe, cyclone activity will decrease in the future while the Mediterranean displays different patterns concerning the main cyclogenesis domains. A decrease in cyclone frequency is projected for the northern and middle parts of the Mediterranean (from the Gulf of Genoa to the Black Sea region) bordering the Pannonian Basin, but an increase in cyclonic precipitation is also likely, except in summer, due to the more available atmospheric moisture in the warmer climate (Zappa et al., 2015; Kelemen, 2016). The climate in the Pannonian Basin will be warmer and more extreme in the 21st century. The significant temperature increase may exceed the global warming rate considerably. Wetter winters and more frequent droughts during the other seasons are expected (Bartholy et al., 2009).

Air pollution processes, such as emissions, transport, dilution, chemical transformation, and eventual deposition of air pollutants, can be influenced by the meteorological variables of radiation, temperature, humidity, wind speed and direction, mixing height, etc. (Kinney, 2008). This climate penalty means that stronger emission controls will be needed to meet a given air quality standard. Development of optimal control strategies for key pollutants like ozone, nitrogen oxides and fine particles now requires assessment of potential future climate conditions and their influence on the attainment of air quality objectives. In addition, other air contaminants of relevance to human health, including smoke from wildfires and airborne pollens may be influenced by climate change (Kinney, 2008).

The Pannonian Basin, in the heart of Europe, is one of the world's largest enclosed basins with special meteorological, hydrological and air pollution situations. One merely has to consider the winter cold air pool (Szabóné Andre et al., 2016), which affects the pollutant enrichment in a similar way to other basin areas, for example the Uintah Basin in Utah (Neemann et al., 2015). The increasing frequency of heat waves also has significant environmental impacts (Szepszo, 2008), which particularly affect the people living in large cities (Páldy et al., 2005; Baccini et al., 2011), but affect agricultural production, too (Gaál et al., 2014). The weather and climate of the basin develops under three effects (oceanic, continental and Mediterranean), depending on the air masses drifting over the region (Micu et al., 2015). The weather is formed mainly by the alternating cyclones and anticyclones in the basin through the propagation of the westerly Rossby waves. The Mediterranean cyclones also have an important role in forming local weather conditions, especially in the autumn and spring.

In addition to the growing rate of greenhouse gas (GHG) emissions, more serious air quality problems for the future include i) reactive nitrogen compounds ii) near-surface ozone (O_3) and particulate matter from the nanoscale to PM_{10}. The simulated climate changes relating to O_3 and PM_{10} – based on the coupled climate and air quality model systems (RegCM/CAMx and ALADIN-Climate/CMAQ) – have quite weak impacts on the air quality of the middle of the 21st century as compared to the end of the century. The results show an increase in mean O_3 in summer and a decrease in annual mean of PM_{10}. The main climate factors responsible for the projected changes in our region are, for O_3, the increasing summer temperature and the decrease in summer precipitation and, for PM_{10}, the increase of the winter precipitation (Juda-Rezler et al., 2012).

In order to understand and predict the variety of the different atmospheric processes and to determine the particularities of the climate system, an appropriate i) measurement, ii) database and iii) modelling background is required.

- We need measurements based on international standards (see *Table 1*), high quality experimental set ups and measuring platforms (for micrometeorology, trace gases and aerosol concentrations and fluxes, nucleation, cloud physics, etc.), which certainly require strong cooperation between the countries in the Pannonian region. In addition to cooperation in the profession and the field of education (from elementary to university level) also has an important role. For example, the Global Learning and Observations to Benefit the Environment (GLOBE) Program (*globe.gov*) has a long tradition and many participating countries from all over the region.

Table 1: Coordination of different types of baseline observations.

Type of observation	***International coordination***
Meteorology (surface and space based)	WMO GOS – Global Observing System, *wmo.int/pages/prog/www/OSY/GOS.html*
Hydrology	WMO WHOS – World Hydrological Observing System, *wmo.int/pages/prog/hwrp/chy/whos/index.php*
Air quality	WMO GAW – Global Atmosphere Watch, *wmo.int/pages/prog/arep/gaw/gaw_home_en.html*
Ecology	LTER – Long Term Ecological Research, *lternet.edu/* FLUXNET – Integrating Worldwide CO_2 Water and Energy Flux Measurements, *fluxnet.ornl.gov/fluxnetdb*

- We need well organised surface databases that include and harmonise the various types of measurement and data structure at the national scale (*Table 2*).

Table 2: Some European surface data banks.

Type of data set	***International coordination***
Soil (type, structure, etc.)	ESDAC – European Soil Data Centre, *esdac.jrc.ec.europa.eu/resource-type/datasets*
Terrain information (elevation, etc.)	EEA – European Environmental Agency, *eea.europa.eu/data-and-maps/data/digital-elevation-model-of-europe*
Land cover	CORINE – Coordination of Information on the Environment *land.copernicus.eu/pan-european/corine-land-cover*

The transport models require emission databases using the EMEP (*emep.int*) and the IPCC methodologies (*ipcc-nggip.iges.or.jp/public/2006gl/*) among others.

Agricultural emission estimates are also becoming increasingly important for the development of region-specific models (energy, water and pollutant budget). On this basis, more detailed national and regional databases and common field campaigns are required, which are prerequisites for statistic and dynamic processing in order to describe the surface-atmosphere interactions, transboundary pollutant transport, etc.

- Air quality models exist for and are used in each country (from the local to the basin-level scale); in addition there is an enhanced international cooperation between the institutes hosting the core models (*Table 3*) and datasets. Well organised information regarding air quality forecast products can be accessed on the European scale from:

  - European Air Quality Monitoring and Forecasting program coordinated by ECMWF (*atmosphere.copernicus.eu/services/air-quality-atmospheric-composition*)
  - EUrad program (*db.eurad.uni-koeln.de/index_e.html*) – University of Cologne.

These are good examples for the purposed future cooperation in the Pannonian region. The implementation of coupled climate and air quality model systems is also in progress

(Juda-Rezler et al., 2012) (*Table 3*).

Table 3: Numerical weather prediction and air quality models used in Pannonian region.

Regional NWP model	***Air quality and/or trajectory model***
Data sources (initial and boundary conditions)	
ECMWF (*ecmwf.int*), GFS (*nomads.ncdc.noaa.gov/data.php*)	ECMWF MACC – Monitoring Atmospheric Composition and Climate, *gmes-atmosphere.eu*, Geos-Chem model (*acmg.seas.harvard.edu/geos/*)
Model sources	
ALADIN (*cnrm-game-meteo.fr/aladin/*)	EMEP (*emep.int/mscw/index_mscw.html*)
WRF (*wrf-model.org/index.php*)	IIASA-GAIN (*Amann*, 2012)
AROME (*umr-cnrm.fr/spip.php?article120&lang=en*)	ECMWF MACCIII (*ecmwf.int/en/research/projects/macc-iii*)
	CMAQ (*cmascenter.org/cmaq/*)
	WRF-CHEM (*www2.acom.ucar.edu/wrf-chem*)
	FlexPart (*flexpart.eu*)
	Hysplit (*ready.arl.noaa.gov/HYSPLIT.php*)
	CAMx (*camx.com/*)

NWP – numerical weather prediction

The main task for the near future is to develop coupled meteorological-climatological and air pollution models (Kukkonen et al., 2012; Žabkar et al., 2015). This is so-called chemical weather/climate modelling. Besides one-way coupling, these two-way models will appear in the near future (Kong et al., 2015). The new variables (trace gases, aerosol particles, airborne pollen) and interactions (radiation, cloud formation, etc.), of course cause further uncertainties in the chemical weather models. In addition, the parameterisation-specific optimisation procedures for the region have high priority, which require an excellent measuring background. This contributes to the harmonisation of models used in the Pannonian region (Ivančan-Picek et al., 2011; Syrakov et al., 2015; Žabkar et al., 2015). With respect to the integrated modelling of present and future air quality under a changing climate, there is a need for greater use of model ensembles and also to capture the full range of uncertainties in future impacts (see also Kinney, 2008).

Preliminary coupled model results are presented in *Figure 2* for the European domain using the WRF-CMAQ coupled model from Bulgaria based on Syrakov et al. (2015).

Cooperation with international organisations is essential, such as with the WMO (*wmo.int*), the EMEP (*emep.int*), the ALADIN consortium (*cnrm-game-meteo.fr/aladin*), the Visegrad countries (or the Visegrad Group, *visegradgroup.eu*), the Danube Region Strategy (*danube-region.eu*), and the comprehensive educational GLOBE program (*globe.gov*). On the other hand, the framework of the regional cooperation program must be closely related to national research-development plans, e.g. the Hungarian Academy of Sciences is starting a long-term research program for the development of Hungarian water science.

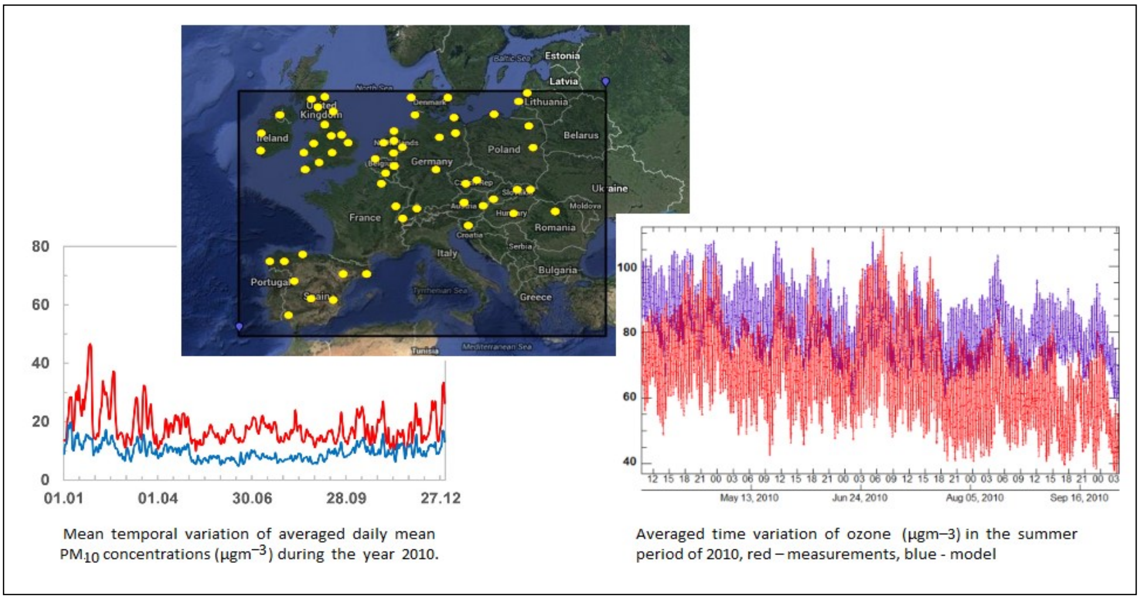

Figure 2: European domain (Reg2) and EMEP stations providing ozone data for testing of WRF-CMAQ coupled model system (middle), mean variation of daily average of PM_{10} in 2010 (left – here red also depicts measurements and blue modeled data) and time variation of average ozone concentration in summer of 2010 based on Syrakov et al. (2015).

Structure of the booklet

After the introduction section we review the theoretical background of physical, air chemistry and vegetation aspects (*Section 2*), air quality measurements and modelling capacity in the Pannonian region (*Section 3*), and the presentation of the key issues related to this topic (*Section 4*) are discussed. The main part of our work consists of 7 key questions starting from understanding "How does a warmer climate affect air quality and human health" to the harmonisation of regional inventories.

We deal with the interactions between 21st century warming and the development of a more extreme climate in the Pannonian Basin and with the issues of the future state of the air environment and health risks. An important question is the usage of regionally optimal weather and climate models and the development of parameterization methods (land-biosphere-atmosphere interactions, radiation, clouds and precipitation, boundary layer, etc.). Changing climate and air quality result in common problems in the fields of urban environment, agriculture, and the hydrological cycle, which also require regional answers. Basic conclusions, remarks (*Section 5*) and a detailed list of references close the booklet (*Section 6*).

2. Theoretical background

In this part of the booklet, we review the theoretical basics of understanding environmental, weather and climate processes in the Pannonian Basin. After the physical and chemical particularities of air, the role of vegetation in atmospheric processes is investigated.

The first step is an energy budget analysis of a single air column above the Pannonian Basin (*Table 4*). The radiation budget is –89 W m^{-2}, while the calculated heat transport from the advection, latent and sensible heat fluxes is approximately 92 W m^{-2}. The closure error is ~3 W m^{-2}.

Table 4: Annual energy budget of an air column over the Pannonian Basin (Major et al., 2002).

Energy budget components	***W m^{-2}***
Short wave radiation	
Incoming solar radiation	300
Outgoing solar radiation to space	–107
Surface absorption	–114
Absorption of solar radiation in the atmosphere	79
Long wave radiation	
Outgoing radiation into space	–225
Reflected radiation to the surface	–305
Outgoing radiation from the surface to the atmosphere	362
Outgoing radiation from the atmosphere	–168
RADIATION BUDGET	–89
Heat transport	
Anthropogenic heat sources	0.4
Latent heat flux (LE)	40
Sensible heat flux + convection (H)	17
Moisture advection	8
Sensible heat advection into the column	27
HEAT BUDGET	~92
WHOLE ENERGY BUDGET (closure error)	~3

The second step for understanding the general picture of the climate of the Pannonian Basin is the determination of the main source regions of precipitation (Bottyan, 2015; Bottyan et al., 2017): i) the drifting westerly cyclones, ii) the Mediterranean cyclones, and iii) the local effects dominate in the Pannonian Basin (*Figure 3)*.

2.1. Dynamic aspects

A significant seasonal dependency of the relevant atmospheric circulations appears due to the typical continental mid-latitude position of the Pannonian Basin. The general atmospheric circulation typically imposes a more or less gradually change on the overall conditions in the basin and usually ends up in one of the four basic groups of baric configuration. These tropospheric formations are: low-pressure systems (cyclone and trough), high-pressure systems (anticyclone, high pressure ridge and bridge), the almost zero-pressure gradient field (i.e. small regional pressure gradient with very weak regional flow that allows a multitude of various local flows over the basin) and transitional synoptic states with advection from almost any direction. Arguably, all these synoptic situations can be organised in a few tens of weather types; such in the case of the classification previously carried out in Croatia using 29 weather types (e.g., Zaninović et al., 2008). This classification can be applied and extended, e.g. specialised and clustered for the entire Pannonian Basin. A comparison of different types of classification (see also the Péczely and the well-known Hess Brezowsky classifications) is common but also raises important questions (Philipp et al., 2010; Mika, 2013; Mika et al., 2013).

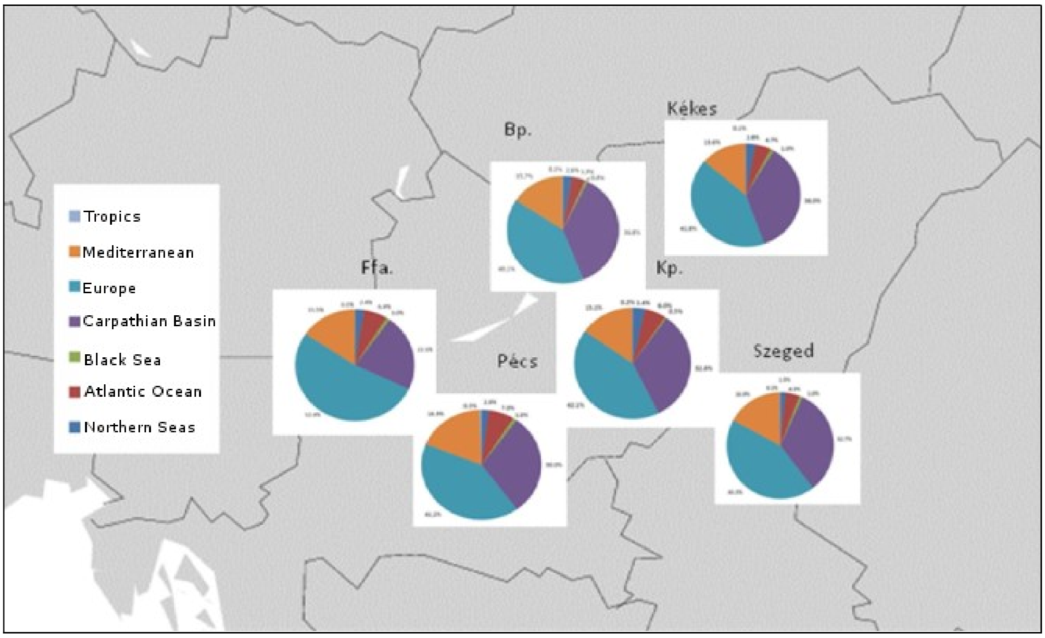

Figure 3: Source regions of precipitation for Hungary in 2013 after Bottyán (2015).
Bp. – Budapest, Ffa. – Farkasfa, Kp. – K-puszta

Many vigorous weather situations and extreme conditions in the Pannonian Basin are caused by synoptic cyclones and airflow blocking. Anticyclone weather types, with stable tropospheric stratification, relatively light winds and weak turbulent exchange processes, dominate in either the cold part of the year or in night-time conditions. The corresponding weather includes fog or/and low cloudiness, although it can be sunny in the sporadic highlands and the basin's surrounding mountains. Nevertheless, winters in the area may also be characterised by rapid cold air outbreaks from the N and NE, and thus inducing strong winds. Essentially, most of the impinging flows are somewhat modified by the mountains that surround the basin from all directions.

Maritime cold air typically flows into the basin from the NW while continental cold air flows in from the NE. The flow of warm and moist air usually arrives from the S and SW into the basin (e.g. Horvath et al., 2008). Flooding events may occur in the basin during persistent deep cyclones and intensive meridional moist flow. However, temporary alterations in large scale flows may allow various secondary circulations to take place, i.e. mesoscale and local flows, such as drainage flows, thermal lows, mesoscale convective systems, and low level jets in night time hours, etc. These flow types regularly depend on the underlying surface properties (orography, moisture, etc.) and air masses in play. Deep moisture-organised convective activities, often related to vigorous showers, lightning and hailstorms in the warm part of the year are likely to occur most often in the SW, less often in the NW or NE upper-level flow (e.g. Mikuš et al., 2011, 2012; Jurković et al., 2015). Under such conditions, the corresponding lower-level flow usually, but not necessarily, belongs to either weak or non-gradient pressure systems.

Other flow structures also occur over the basin. For example, summertime blocking situations often yield to heat waves and droughts (*Figure 4*), while certain weak pressure gradient conditions may promote significant trans-boundary transport and dispersion of air-pollution including airborne pollen, especially ragweed (e.g. Prtenjak et al., 2012). Hence, it is straightforward to conclude that various mesoscale and microscale meteorological processes take place in various chains of events over the Pannonian Basin. However, many of them are not well scientifically documented, not to mention the processes' interactions and effects toward and within other disciplines (hydrology, agriculture, etc.). Quantitative estimates of blocking intensity of the zonal flow can be associated with the large-scale meteorological conditions of air pollution using finding of stable (statistical/numerical) patterns or by the classification of synoptic processes (Semenova, 2013; Cherenkova et al., 2015).

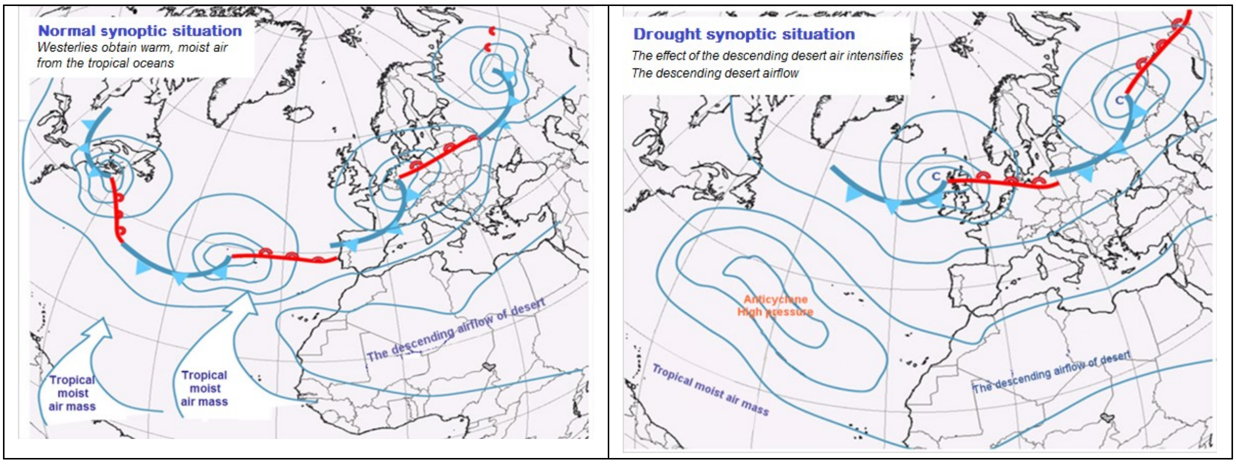

Figure 4: Normal and drought synoptic situation for Central Europe in summer (Horváth et al., 2012).

In terms of numerical weather prediction (NWP) systems, each country in the Pannonian Basin has its own modelling group and NWP resources within the national weather institutions, but also outside (e.g. universities and private enterprises). Several of the countries are involved in the ALADIN/AROME consortium, which is planning to merge with the HIRLAM consortium (hirlam.org).

Most of the operational NWP models run regularly for 2–3 days at a typical horizontal resolution of 7–10 km, with the lowest model level being around 15 m (insufficient for detailed boundary-layer studies). However, some of the national services are experimenting with or already using an operationally finer horizontal resolution of just a few kilometres, which means that non-hydrostatic dynamic cores should be deployed in the NWP models. There are also several teams using the WRF forecasting system, which belongs to the public domain. Regardless of the modelling system at play, they all may have difficulties with the treatment of moist processes, surface and turbulence parameterisation schemes, especially in night-time periods. Thus, improvements in weather modelling are required in these areas.

2.2. Atmospheric chemistry and physical aspects

Main chemical properties and the sources of air pollution

The chemical properties of air pollutants together with the physical properties of the atmospheric boundary layer need to be known in order to adequately parameterise and determine their behaviour (air pollutants) in the atmosphere, and to consequently and successfully manage the negative effects of air pollution on human health and the environment. Generally, air pollutants may be categorised as primary air pollutants (i.e.

pollutants directly emitted to the atmosphere) or secondary air pollutants, that is, pollutants formed in the atmosphere from the so-called precursor gases (e.g. secondary PM, O_3 and secondary nitrogen dioxide (NO_2)). Air pollutants can also be classified as natural and anthropogenic as a function of the origin of their emissions or precursors. Particulate matter (PM) is both directly emitted to the atmosphere (primary PM) and formed in the atmosphere (secondary PM). The main precursor gases for secondary PM are sulphur dioxide (SO_2), NO_x (a family of gases that includes nitrogen monoxide (NO) and NO_2), ammonia (NH_3) and volatile organic compounds (VOCs; a class of organic chemical compounds). The precursor gases NH_3, SO_2 and NO_x react in the atmosphere to form ammonium, sulphate and nitrate compounds. These compounds form new particles in the air or condense onto pre-existing ones and form so-called secondary inorganic aerosols. Certain VOCs are oxidised to form less volatile compounds, which form secondary organic aerosols.

Particulate matter

PM comes from a variety of natural and anthropogenic sources; they can be directly emitted to the atmosphere or formed as secondary pollutants in atmospheric chemical reactions. As a consequence, PM comprises a complex mixture of solid and liquid parcels of organic matter, Earth's crust elements iron (Fe), calcium (Ca), aluminium (Al), silicon (Si), potassium (K), and chlorine (Cl), secondary inorganic aerosols and trace metals. In addition, wind-blown soil and re-suspended dust contribute largely to the coarse particle fraction (e.g. Harrison et al., 1999; Putaud et al., 2004; Jeričević et al., 2012). It has been shown that the contribution of PM emissions and their origins can be relevant at the spatial scales ranging from the local to the regional and the long-range, and at transboundary transport scales and can be analysed accordingly (e.g. Querol et al., 2004; Juda-Rezler et al., 2011).

Black carbon (BC) is one of the constituents of fine PM and has a warming effect (Gelencsér, 2005). BC is a product of incomplete combustion of organic carbon as emitted from traffic, fossil fuels, biomass burning, and industry. Ground-level (tropospheric) ozone (O_3) is not directly emitted into the atmosphere. Instead, it is formed from complex chemical reactions following the emission of precursor gases such as NO_x and non-methane VOCs (NMVOCs) of both natural (biogenic) and anthropogenic origin. The major sources of nitrogen oxides (NO_x) are combustion processes (e.g. in fossil-fuelled vehicles and power plants). Most NO_2 is formed by the oxidation of emissions of NO. Benzo[a]pyrene (BaP) is emitted from the incomplete combustion of various fuels. The main sources of BaP in Europe are domestic home-heating, in particular wood and coal burning, waste burning, coke and steel production, and road traffic. Other sources include outdoor fires and rubber-tyre wear. Sulphur oxides (SO_x), a family of gases that includes SO_2 and sulphur trioxide (SO_3), are mainly emitted from the combustion of fuels containing sulphur. The main anthropogenic emissions of SO_2 derive from domestic heating, stationary power generation and transport. Benzene (C_6H_6) is an additive to petrol, and most of its emissions come from traffic.

Elevated atmospheric particulate matter (PM) concentrations are associated with significant adverse health effects (Samet et al., 2000; Peters et al., 2001; Pope et al., 2002; Samoli et al., 2005; Anderson, 2009). They affect ecosystems, influence visibility and cloud formation in the atmosphere and play an important role in climate change (e.g. Andreae et al., 2005; Molnár et al., 2008; Jiang et al., 2013). In most European countries air quality standards for PM have been introduced in order to protect human health and the environment. Current standards are set for PM_{10} (total mass concentration of particles smaller than 10 μm) and $PM_{2.5}$ (total mass concentration of particles smaller than 2.5 μm) (*European Air Quality Directive 2008/50/EC*).

Comprehensive analyses of PM data were carried out over the past decade at more than 60 regional backgrounds. Measurements at rural, suburban, urban and kerbside stations across Europe were conducted. Putaud et al. (2010) found that there is no uniform ratio between $PM_{2.5}$ and PM_{10} mass concentrations for all sites although fairly constant ratios ranging from 0.5 to 0.9 were observed at most individual sites. The main constituents of both PM_{10} and $PM_{2.5}$ were generally organic matter, sulphate and nitrate, while mineral dust was a major constituent of PM_{10} at kerbside sites in Southern Europe. Particulate matter source apportionment methods and results in Western Europe were reviewed by Viana et al. (2008). Previous European studies mainly did not include data from Eastern and South-eastern European countries (e.g. Croatia, Serbia, Romania, Bulgaria) and generally there is a gap in knowledge on the PM levels and compositions in those areas. In Jeričević et al. (2016) the pronounced spatial gradient in PM_{10} and $PM_{2.5}$ concentrations decrease from the north to the south, more precisely from the Pannonian Basin towards the coast for urban and rural sites in Croatia (*Figure 5*). The decrease was revealed both in average concentrations and the number of exceedances. Characteristic geographic and climatological conditions as well as intrinsic atmospheric processes influence PM concentrations in the air, such as local wind circulation; vertical diffusion and deposition were considerably different at the coast than inland. As in other parts in Europe, a significant correlation between the $PM_{2.5}$ and PM_{10} average mass concentrations was found indicating that both concentrations are governed by the same meteorological processes.

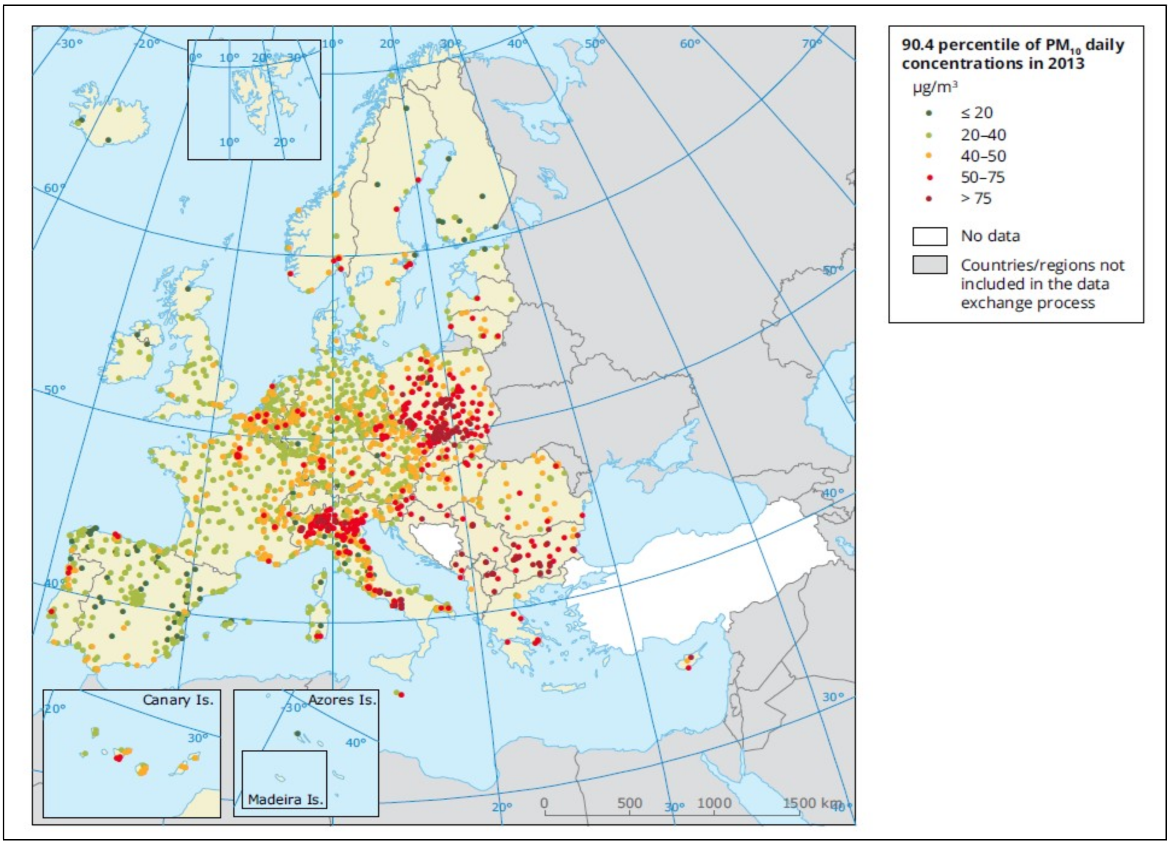

Figure 5: The 90.4 percentile of the data records in one year represents the 36th highest value in the complete series. It is related to the PM_{10} daily limit value, allowing 35 exceedances of the 50 mg m^{-3} threshold over 1 year. The red and dark-red dots indicate stations with exceedances of this daily limit value. Only stations with > 75% of valid data have been included in the map. (Based on Air Quality e-reporting database, EEA, 2015.)

Specific atmospheric conditions contributing to air pollution episodes

Air pollution research focusing on the Pannonian Basin is important for many reasons: the large emission sources located in the area, high observed PM levels, limited regional research studies and a strong indication that specific atmospheric conditions e.g., prolonged high atmospheric synoptic pressure systems are contributing to the regional air pollution episodes during the colder part of the year.

It was found that during 2011 the unfavourable meteorological conditions may have had a large influence on a regional increase in PM concentrations affecting countries in the Pannonian Basin. This was particularly due to the very below-average precipitation in the western areas of Eastern Europe during the autumn (e.g. Cindrić et al., 2010; Peterson, 2012), which was also sensible in the mainland of Croatia, the longest dry spells occurred due to the prevailing stationary anticyclonic weather during the cold part of the year.

Large-scale high pressure fields sustained stable atmospheric conditions and strong subsidence governed the total concentration levels, specifically the influence of the long-distance transportation, which is a considerable part of the PM_{10} concentrations in urban background air. Unfavourable meteorological conditions result in a decrease in local dispersion and lead to high PM concentrations mainly as a consequence of local anthropogenic sources. Reduced turbulent processes, such as vertical turbulent diffusion in the shallow stable atmospheric boundary layer, may lead to various air pollution episodes (e.g. Jeričević et al., 2010). Similar atmospheric conditions also favour the occurrence of maximum concentrations of ragweed pollen with an extremely high risk of producing allergy during summer time (Prtenjak et al., 2012). In these conditions, Croatia is significantly affected by a regional transport of bio-aerosols from Hungary and Serbia within the lower sector of a high pressure system that moves slowly eastward over Eastern Europe. Therefore, the long-lasting large anticyclonic system centred over Eastern Europe can be identified as the main weather type that enables different types of air pollution over the investigated area (see also in Matyasovszky et al., 2011).

Nucleation events (new particle formation) often develop within the basin. Understanding the nucleation process is one of the key questions of air quality and the climate system (cloud formation, etc.). Connection between the cloud physics processes and aerosol types and concentrations is also a fundamental question (Muhlbauer et al., 2012).

Annual mean nucleation frequencies and uncertainties for the city centre and near-city background of Budapest were (27 +9/−4) % and (28 +6/−4) %, respectively (Németh and Salma, 2014, *Figure 6*). A rigorous analysis of long-term datasets and further measurements are needed in order to better understand the nucleation mechanism on the basin scale (see also Salma et al., 2016a).

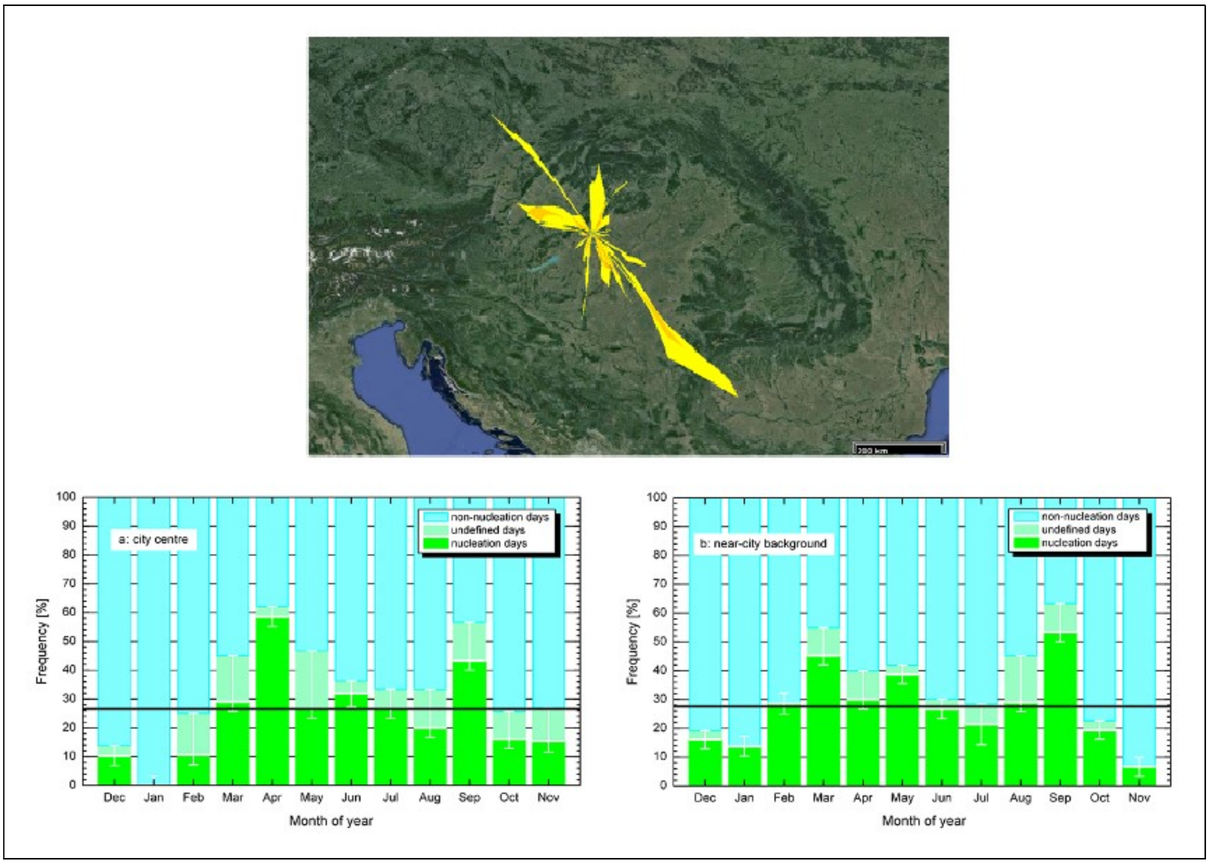

Figure 6: Arrival fields of nucleating air masses in the Carpathian Basin for the city centre of Budapest (top) from 3 November 2008 to 2 November 2009. The overlapping sections were indicated with darker colours (from yellow to orange).

Monthly mean frequencies for days with new particle formation, undefined days, and non-event days in the city centre (a, left) in the same time interval and near-city background (b, right) from January 2012 to January 2013. The horizontal lines indicate annual mean frequencies.
(Based on Figures 2 and 4 from Németh and Salma, 2014)

2.3. The role of vegetation

About 20% of the Earth's surface is covered by vegetation. In the case of forests and orchards, plant canopy is tall enough to question the assumption, introduced in some early modelling studies (Sellers et al., 1986; Bonan, 1996; Dickinson et al., 1998), that vegetation in models can be represented by a thin film layer at the surface ("Big leaf model"). Decades of experimental work in the framework of projects like ABRACOS (Gash and Nobre, 1997), Harvard forest experiment (Moore et al., 1996), BOREAS (Sellers et al., 1995, *daac.ornl.gov/BOREAS/boreas.shtml*), FLUXNET (Luyssaert et al., 2009; Haszpra, 2011), CarboEurope IP (Dolman et al., 2006), NitroEurope IP (Beier et al., 2010; Sutton et al., 2011) shed light on the physical, chemical and biological processes governing and determining the plant canopy as a complex and active biophysical system. This system is not just an interface between the atmosphere and the soil surface. It plays a dynamic role in changing atmospheric flows, the energy and water balance, gas exchange and particle deposition in the surface atmospheric layer.

1) *Atmospheric flow*. The presence of vegetation on the Earth's surface affects atmospheric flows in two ways; by changing the roughness of the underlying surface and by producing an additional flow which is a result of the canopy-internal air transfer. Drag and friction,

expressed through drag coefficient, C_d and friction velocity, u_* depend on the type of vegetation and its characteristics, as well as their changes over the seasons (Moore et al., 1996). The uptake of momentum, particularly within the plant canopy, is exerted to a much greater extent in the vertical direction than in the horizontal (Kaimal and Finigan, 1994). In the presence of vegetation, maximum drag force is disconnected from the ground surface and switched to leaf surfaces distributed within the canopy. In already established equations of turbulent atmospheric flows, it introduces a new important parameter – displacement height, d defined as the height within canopy layer with the most intensive turbulent exchange. Finally, the presence of vegetation and its structure completely changes the concept of viscous sublayer and so defined roughness length, z_0 since roughness elements, and associated viscous layers are distributed all over the canopy.

2) *Energy balance*. The presence of vegetation can make significant difference in the radiation spectra and energy balance of the Earth's surface. The absorption, reflection and transmission spectra of vegetation are affected by morphological and physiological characteristics that change over the year. It leads to a different treatment of photosynthetically active radiation, hereafter PAR and global solar radiation by plants. Therefore, the profound impact of vegetation on the energy balance comes from changed albedo, which consists of the effects of PAR albedo and global solar albedo with completely different courses during the vegetation season (see, for example, Moore et al., 1996). It is important to bear in mind that vegetation albedo differs in magnitude from other natural surfaces (*Table 5*).

Table 5: Mean annual albedo and emissivity of different land covers (Thompson, 1998).

Land cover	***Albedo***	***Emissivity***
Tropical forest	0.13	0.99
Woodland	0.14	0.98
Farmland/natural grassland	0.20	0.95
Semi-desert/stony desert	0.24	0.92
Dry sandy desert/salt pans	0.37	0.89
Water	<0.08	0.96
Sea Ice	0.25 – 0.60	0.90
Snow-covered vegetation	0.20 – 0.80	0.88
Snow-covered ice	0.80	0.92

The energy balance equation of a vegetated surface differs from the same equation in the case of bare soil or urban areas, by two fluxes: a) energy introduced by transpiration and b) biomass energy storage (*Figure 7*). While the second is often neglected, since it accounts for just a few percent of incoming radiation, energy flux related to transpiration plays a significant role in partitioning radiant energy into sensible and latent heat flux. Vegetation affects daily and annual variation of sensible and latent heat fluxes between the canopy and the atmosphere as well as ground storage. Plant-atmosphere sensible heat flux is a result of the temperature difference between plants and the atmosphere and depends on convection coefficient, which is mostly affected by the morphological characteristics of the plants and wind speed at the plant surface (depending on plant aerodynamic characteristics).

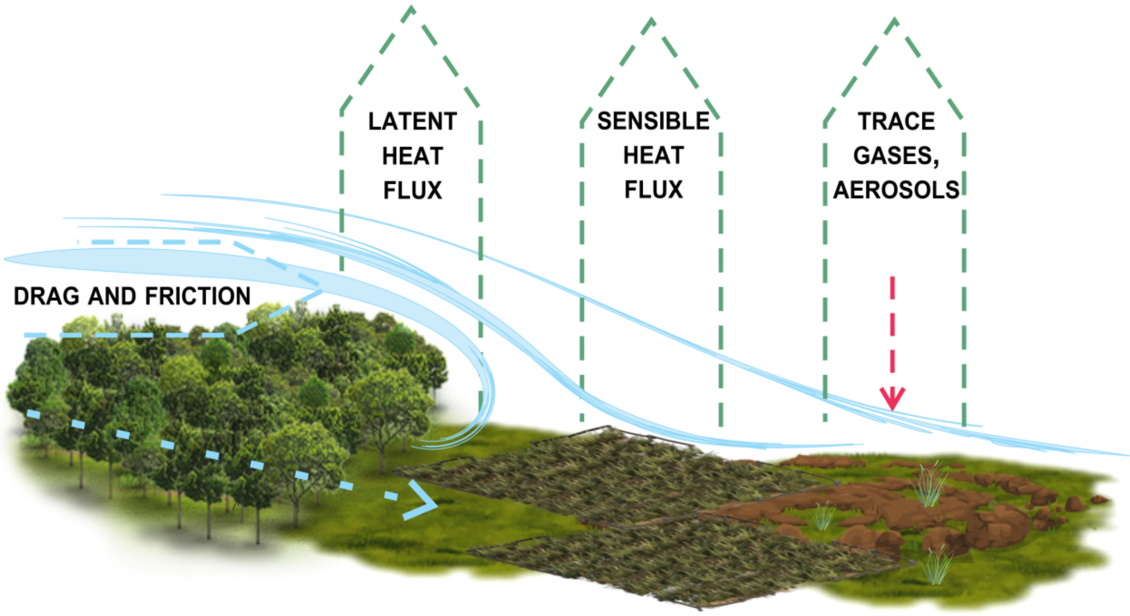

Figure 7: Main processes describing biosphere-atmosphere interaction.

Physiological, morphological and aerodynamic characteristics of plants vary during the day and season producing a significant variation of sensible heat flux from a vegetated surface in comparison to bare soil. Latent heat flux exchanged between plants and the atmosphere is split between the latent heat flux of evaporation from the plant surface (as a physical process) and the latent heat flux of plant transpiration (as a physiological process).

3) *Water balance*. Vegetation is a powerful source and sink of water and therefore it has a tremendous effect on: i) partitioning of precipitation on interception, runoff and soil moisture storage flows and ii) air humidity variation through water vapour inflow from plant evapotranspiration and ground evaporation. The presence of vegetation reduces runoff, increases soil moisture and delays the use of precipitation by interception. According to meteorological conditions, plant type and maturity, evapotranspiration intensity significantly varies on a daily and annual basis.

4) *Gas exchange/particle deposition*. The chemical composition of the lower atmosphere is strongly influenced by the surface processes. The concentrations and turbulent fluxes of the atmospheric trace substances (gases, aerosol particles) are a result of i) emission, ii) turbulent transfer, iii) dry and wet deposition and iv) chemical transformations. All of these processes are dependent on canopy homogeneity and horizontal isotropy, as well as morphological, aerodynamic and thermal characteristics. On the other hand, the chemical composition of the surrounding air can affect the physiological processes of the plant, such as photosynthesis, by intensifying or reducing its rate.

3. Capacity building: measurement and modelling

In this chapter we review the measurement, database and modelling infrastructure in the countries of the region that could help us towards a better understanding of the meteorological and atmospheric environmental processes of the Pannonian Basin that are crucial to be able to discover further changes that have an environmental, water quality and agronomical impact.

3.1. Air pollutants, long range transport, air quality measurement network

In the past few decades energy generation, industrial production and transportation have caused serious environmental contamination in central-east Europe. The rate of contamination can vary from place to place as a function of source densities and intensities of pollutant fluxes as well as meteorological conditions. The pattern of pollution may be characterised not only by local, highly concentrated sites such as densely populated urban areas, but also by lower concentrations of pollution widely dispersed over the landscape, including agricultural regions, forests and surface waters. Trace gases and aerosol particles can be transported far away from their sources before being deposited on the surface (Bozó, 2005b). Due to the deep economic changes in this region during the past 25 years, its energy and industry structures were reorganised, which resulted in a significant decrease of pollutant emission. Out-of-date industrial technologies are being replaced by those that are less energy consuming and more environmentally friendly. Thermal power plants have been equipped with efficient sulphur and dust filters. Leaded gasoline has been phased out. The rates of changes in pollutant emission, however, were different in the countries of the region. As a result of these changes, the region is now coping with atmospheric environmental problems that are less serious than 20–25 years ago.

Atmospheric emissions of SO_2 originate mainly from the combustion of sulphur containing coal and other fossil fuels (*for a historical time series of sulphur emissions see Figure 8*). Air pollution by long-range transported SO_2 is not a recent problem globally, but locally it can cause serious trouble.

The dominant sources of nitrogen oxides are anthropogenic emissions from combustion processes in transportation, power plants, industry and agricultural biomass burning, as well as natural sources such as lightning emissions, natural biomass burning and microbial soil emissions. The lifetime of NO_2 in the planetary boundary layer amounts to a few hours, depending on the strength of solar irradiation and on the available radical species. This, combined with low wind speeds near the surface, makes long-range transport of anthropogenic NO_2 in the planetary boundary layer very unlikely. However, its lifetime is up to a week in the middle and upper troposphere. More and larger plumes are emitted in winter, when the lifetime of NO_2 is long, anthropogenic emission rates are especially high and meteorological conditions are favourable with frequent cold fronts and cyclones.

PM_{10} particles mainly originate from sea salt, soil dust resuspension, construction/demolition, non-exhaust vehicle emissions, and industrial fugitives, whereas $PM_{2.5}$ and $PM_{0.1}$ particles are mainly produced by combustion processes, forest fires and transformation of gaseous species. The lifetime of smaller size particles can range from days to weeks, while bigger particles have a lifetime of hours to days. This is the reason why there is certain evidence of the long-range transport of fine aerosol particles over distances crossing national borders and this could have a significant effect on air quality in urban areas in Europe. Many scientific articles have described the long-range transport of particulate matter, which has a significant impact on PM_{10} levels in large European cities, while strong local sources could tend to mask long-range transport influences (*Figure 9*).

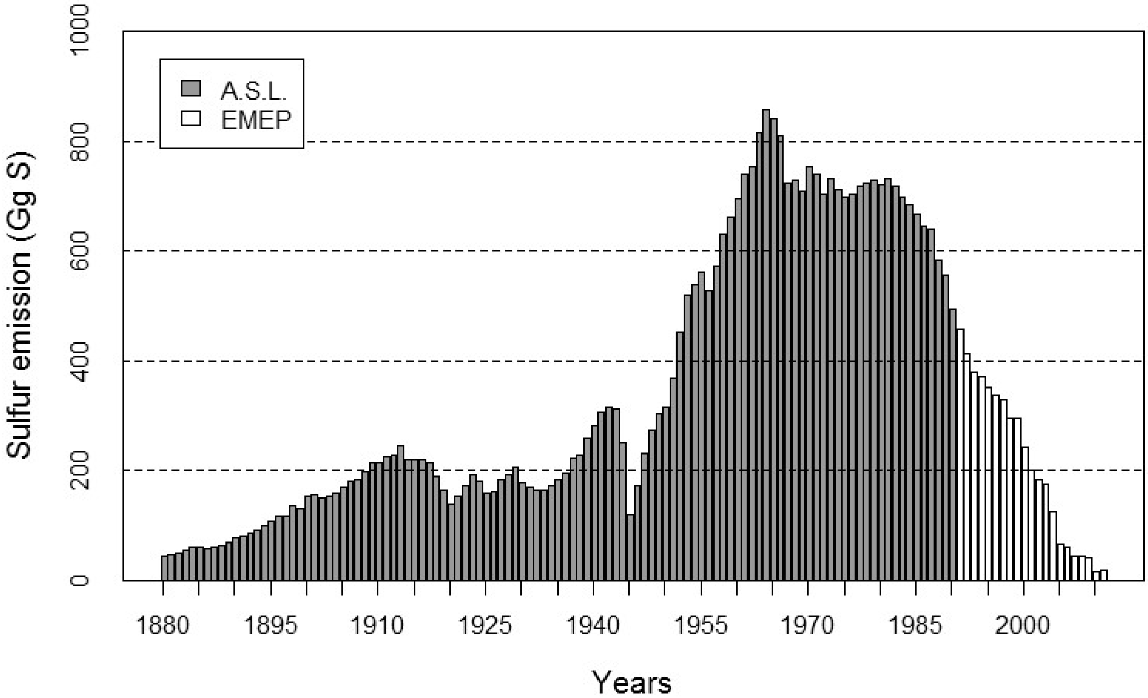

Figure 8: Sulphur emission in Hungary between 1880 and 2011
(Móring and Horváth, 2014, Fig. 4).

Historical emission database of A.S.L. & Associates (Lefohn et al., 1999) for the period 1880–1990 and from emissions reported to the EMEP (CEIP, 2013)

In central-east Europe the effect of long range transport determines the air quality. Polluted air may arrive with the wind from any direction. There are some notable industrial areas like the Po Valley and the southern part of Poland, which play a critical role in influencing the air quality of central-east Europe. These facts indicate that a qualitative analysis of long range transport is essential in order to distinguish the effects of local and distant sources, and to create an effective air quality plan to make the air healthier.

The monitoring of meteorological variables, such as wind speed and direction, air temperature, relative humidity and precipitation, is conducted at air quality stations. Measurements are needed for source identification analyses using different techniques e.g. bivariate polar plots (Jeričević et al., 2016).

Regional PM emission sources in the region

The largest PM_{10} source is located in the south of Macedonia with emissions of ~17 x 10^5 kg $year^{-1}$, following by sources in Serbia, near Belgrade where emissions of ~14 x 10^5 kg $year^{-1}$ are recorded, then in Bosnia and Herzegovina with emissions of ~9 x 10^5 kg $year^{-1}$ and in Budapest, Hungary with emissions of ~4 x 10^5 kg $year^{-1}$. The largest PM_{10} source with emissions of ~300 tons $year^{-1}$ in Croatia is located in the central continental part of Croatia and consists of the cement industry in the city of Našice. Selected data from the European Air quality database (AirBase) are shown for selected cities in Croatia, Hungary and Serbia. Classification and locations of the stations are shown in *Fig. 9*.

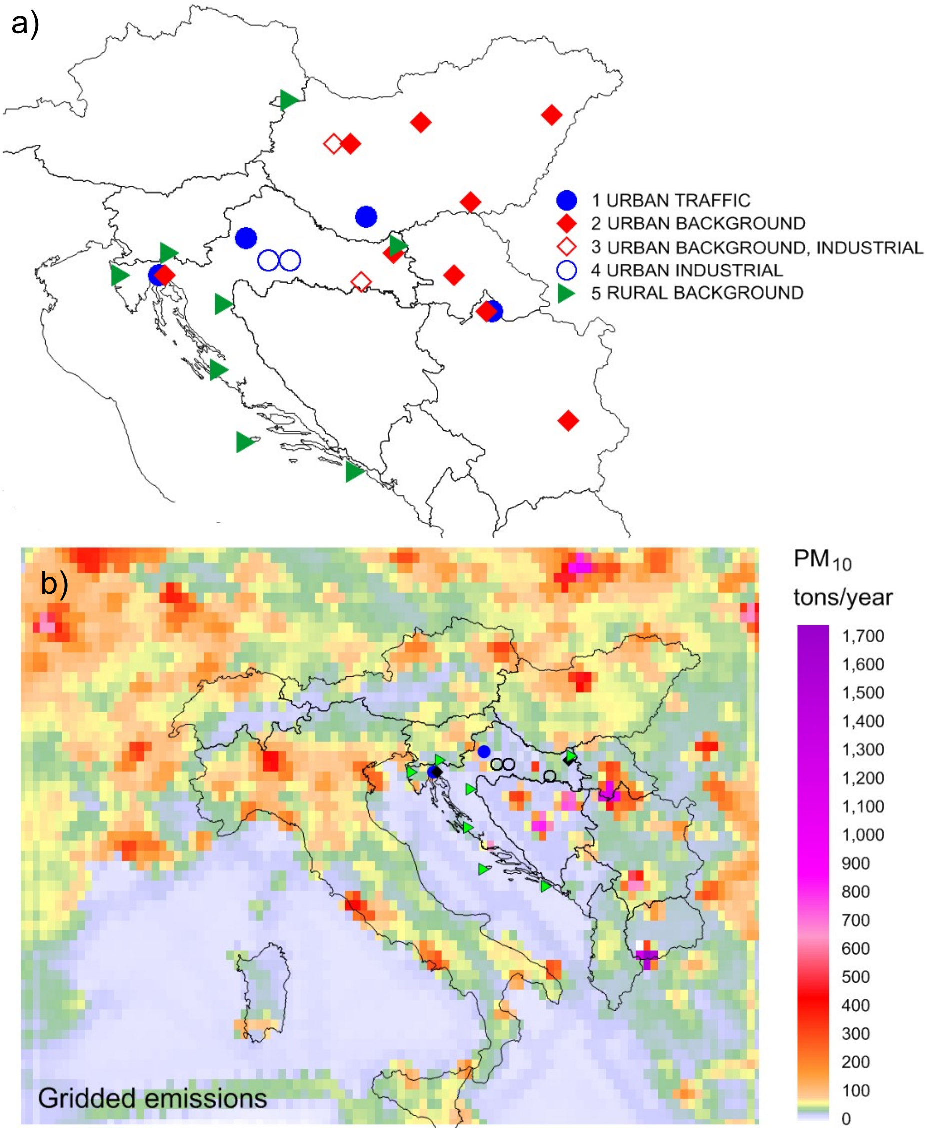

Figure 9: Stations in Croatia with the measurements of PM concentrations: a) name, location and type and b) gridded PM_{10} emissions EMEP4HR emissions on 10 km x 10 km horizontal resolution.

The urban traffic stations are marked with blue circles and urban industrial stations with empty blue circles, urban background stations are red squares, urban background stations under the influence of industry are red empty squares and rural background stations are green triangles (Jeričević et al., 2007, 2016).

A complete and homogenous database is required in order to validate regional climate/air chemistry models and surface energy budget calculations, which can be obtained by detailed data quality assessments (*Table 1*).

In addition to the air quality datasets, the most comprehensive solar surface radiation (SSR) databases available for the Pannonian Basin may also be combined. These include i) the Global Energy Balance Archive (GEBA, *geba.ethz.ch/*) developed and maintained by the Institute for Atmospheric and Climate Science of ETH Zurich containing monthly data, ii) the daily datasets from the World Radiation Data Centre (WRDC) and (iii) the highly accurate but shorter term records of the Baseline Surface Radiation Network (BSRN) also located at ETH Zurich. However, strong collaboration between national meteorological services is very much required in order to complete these databases. The significant deliverables of this future PannEx collaboration will be an integrated SSR dataset with enhanced spatial and temporal resolution.

National level of measurements – two examples

The national air quality monitoring network provides current and historical air quality monitoring data nationwide.

Croatia: the validated air quality measurements of different pollutants i.e.: SO_2, CO, NO_x, PM_{10} and $PM_{2.5}$ at the national scale are available from the Croatian Air Quality State Network operated and maintained by the Meteorological and Hydrological Service of Croatia (MHSC). The locations of all stations are shown in *Figure 9*(*a*).

The air quality measurements from 13 (urban and rural) stations from the state network are used. Stations: Rijeka-2 and Osijek are urban background stations, Sisak is urban industrial, and Kutina is urban background industrial while Zagreb-1 and Rijeka-1 are urban traffic stations. Kutina is under the influence of the petrochemical industry while Sisak is mainly impacted by the emissions of oil refineries. The city of Rijeka is situated on the Adriatic coast while all other urban stations are continental.

In Croatia 12 rural stations, forming a part of the EU-funded PHARE 2006 project "Establishment of Air Quality Monitoring and Management System" started measurements in 2011. Observed hourly PM_{10} and $PM_{2.5}$ concentrations were available for this study (Jeričević et al., 2007, 2016) from 7 rural background stations distributed throughout Croatia to capture the spatial and temporal concentration variations of different pollutants.

Hungary: the network (*levegominoseg.hu*) consists of two major parts: automatic monitoring stations (59 automatic stations, 12 in Budapest) with continuous measurements being performed of a wide range of air pollutants in ambient air (CO, O_3, NO_x, SO_2, PM_{10}, $PM_{2.5}$ with almost half of them measuring BTEX components), seven mobile measurement stations and a manual system (with almost 150 sampling points) and consecutive laboratory analysis. All instruments comply with the EU reference measurement methods in the Hungarian Air Quality Monitoring Network (*Figure 10*). Four stations (two in Budapest) collect data on $PM_{2.5}$ and their number will be increased significantly in the near future. There are also annual assessment reports drawn up for the Ministry of Agriculture and the EEA on both automatic and manual systems as well as on particulate matter (PM_{10}) components.

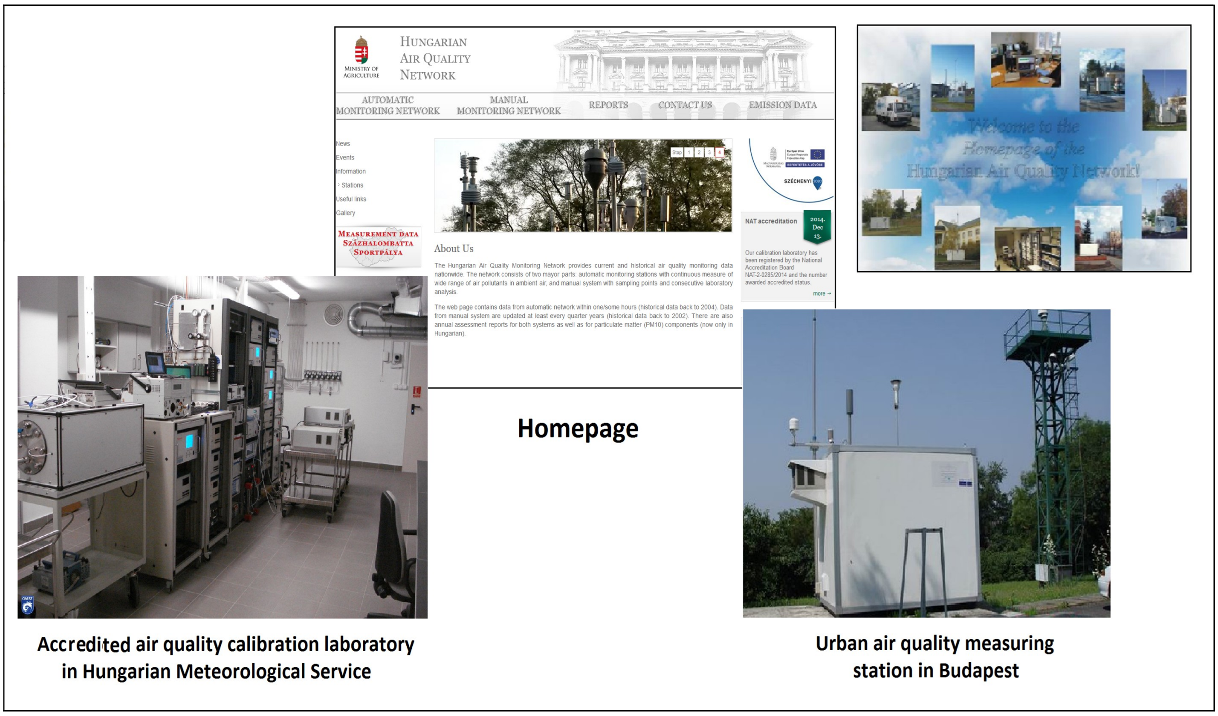

Figure 10: Hungarian Air Quality Network (*levegominoseg.hu*)

The National Institute of Environmental Health provides daily health-related information on the ambient air pollution levels in Budapest and five other cities (Debrecen, Miskolc, Szeged, Győr and Pécs) in order to protect the health of the population particularly at risk, e.g. people suffering from cardio-vascular or respiratory diseases, elderly people, and children. The Institute operates the Aerobiological Network (18 monitoring stations), which monitors the concentrations of pollen grains of 32 allergenic plant species and the spores of two fungus species, provides forecasts on expected short term concentrations during the nine-month flowering season. Weekly pollen reports are issued for medical personnel, patients and the general population through the internet.

3.2. Scale dependent modelling

European scale (international cooperation)

Many types of air pollutant have been observed to travel far from their sources to cause air quality problems. The potential of pollution for long-range transport, sometimes referred to as its characteristic travel distance or spatial range, depends not only on its real physicochemical properties, but also on its mode and point of release to the environment. This process becomes relevant only when the transported chemical material (or pollen) has a harmful effect on human health or on the ecosystems far from its source.

It was very important to begin the development of chemical transport models by investigating the long-range transport of air pollutants. A representative of these types of model is the EMEP Eulerian long-range transport model (Simpson, et al., 2012; see also Sofiev et al., 2015 for ensemble pollen forecast).

The amount of pollutants emitted in one location and the fraction that finally reaches a certain downwind location depends on three factors: i) the quantity of the pollutant emitted or produced at the source, ii) the meteorological conditions that transport the pollution from one location to another (in different scale), and iii) the physical and chemical transformation processes that modify the quantity and composition of the pollution during transport that lasts from days to weeks.

At the Earth's surface, aerosols, ozone and other reactive gases, such as nitrogen dioxide, determine the quality of the air around us, affecting human health and life expectancy, the health of ecosystems and the fabric of the built environment. Ozone distributions in the stratosphere influence the amount of ultraviolet radiation reaching the surface. Dust, sand, smoke and volcanic aerosols affect the safe operation of transport systems and the availability of power from solar generation, the formation of clouds and rainfall, and the remote sensing by satellite of land, ocean and atmosphere.

To address these environmental concerns there is a need for data and processed information. In the context of the Copernicus programme (*copernicus.eu*), the MACC-III project had the overall functional objective of delivering reliable operational products and information services that support research, European environmental policy and the on-going development of user specific downstream services. The transition to long-term sustainable operation as the fully-fledged Copernicus Atmosphere Monitoring Service (*CAMS atmosphere.copernicus.eu/*) took place in the second half of 2015.

Figure 11: Scale dependent determination of local and non-local (background) air pollution (Szepesi and Feketéné, 1987).

The effect of long range transport on the air quality of cities is very important when an air quality forecast system is being developed. Without this information the forecasted values of pollutants could be underestimated.

The mathematical modelling of air pollution processes is usually based on a system of nonlinear partial differential equations called a transport-chemistry system. The numerical integration of this system is a rather difficult computational task, especially in large-scale and global models, where the number of grid-points can range from a few thousand to a few hundred thousand, and the number of chemical species is typically between 20 and 200.

Total air pollution is the sum of locally (from the given scale) and non-locally produced pollution, transported from the outside. This non-local component is the so called background air pollution originating from natural and anthropogenic sources. Each of the scales (from continental to local) originates from a larger scale. By using this scheme (*Figure 11*) contributions from global, continental, regional and urban background pollution could be easily analysed for any geographic location (Szepesi and Fekete, 1987; Szepesi et al., 1995). Of course only locally produced pollution can be locally regulated. One of the most effective methodologies for regulation is the bubble theory, where the sum of the source intensities on the given scale (so called bubble) is limited (for more details see, for example, Hussen, 2005)

Coupled meteorological and air quality modelling on the national scale

The prediction and simulation of the coupled evolution of atmospheric transport and chemistry will remain one of the more challenging tasks in environmental modelling over the next decades. Many of the current environmental challenges regarding weather, climate, and air quality involve strongly coupled systems. It is well accepted that weather is of decisive importance for air quality, and for the aerial transport of hazardous materials.

Table 6: Coupled meteorological and air quality models for the Pannonian region

Country	***Meteorological driver***	***Air chemistry model***	***references***
Austria	ALADIN-Austria	CAMx	Baumann-Stanzer et al., 2015
Bulgaria	WRF	CMAQ	Syrakov et al., 2015
Croatia	ALADIN/HR	EMEP4HR (EMEP for Croatia,)	Jeričević et al., 2012; Kraljević et al., 2008 *emep.int/mscw/Projects/emep4hr/*
Hungary	WRF/AROME WRF	CHIMERE in HMS WRF-Chem in ELTE, CMAQ in ELTE	Ferenczi, 2013 Kovács et al., 2016 Lázár and Weidinger, 2016
Romania	WRF	CHIMERE	*romair.eu/model-description.php?lang=en*

CAMx – Comprehensive Air Quality Model with extensions, an open-source modelling system for multi-scale integrated assessment of gaseous and particulate air pollution.
CHIMERE – a multi-scale chemistry-transport model for air quality forecasting and simulation.

It is also recognised that chemical species influence the weather by changing the atmospheric radiation budget, as well as through cloud formation. Until recently however, because of the complexity and the lack of appropriate computer power, air chemistry and weather forecasts have developed as separate disciplines, leading to the development of separate modelling systems that are only loosely coupled (offline).

In large-scale simulations the effect of turbulent diffusion is much weaker than that of advection, as a first approximation, turbulent diffusion is neglected in the simulations. Uncertainties in large-scale atmospheric transport also seem to be an important question for regional scale air pollution modelling. How we can use an ensemble weather prediction to represent this uncertainty? NWP ensemble systems are designed specifically to sample a range of possible future weather states by representing both the analysis errors in the initial model state and the forecast errors that arise due to model limitations and deficiencies.

The more common offline approach only allows one-way coupling of the meteorology – sampled at fixed time intervals. The meteorological fields from the weather prediction model are often only snapshot values and have to be interpolated in time and space by the chemical transport model (Grell and Baklanov, 2011).

Table 6 shows a number of applied model systems in the Pannonian region. These models give possibilities for further cooperation (optimisation of parameterisations, comparison studies ensemble forecasts, etc.).

Urban and local scale air quality modelling, CFD

Urbanisation is a process of relative growth in a country's urban population, which is accompanied by an even faster increase in the economic, political, and cultural importance of cities relative to rural areas. Urbanisation is the integral part of economic development. It brings in its wake a number of challenges, like an increase in the population of urban settlements, high population density, an increase in industrial activities (medium and small scale within the urban limits and large scale in the vicinity), high-rise buildings and increased vehicle movement. All these activities contribute to air pollution. The shape of a city and the land use distribution determine the location of emission sources and the pattern of urban traffic, affecting urban air quality. The dispersion and distribution of air pollutants and thus the major factors affecting urban air quality are geographical setting, climatological and meteorological factors, city planning and design and human activities. Urban air models generally place their focus on scales starting from the local, then the micro (tens of meters to tens of kilometres) to the regional (meso) scale (Srivastava and Rao, 2011).

Urban wind flow is very complex, and appropriate tools are required for the characterisation of the flow and the related processes. Three main approaches can be distinguished:

- on-site full-scale experiments;
- reduced-scale wind tunnel measurements;
- numerical modelling with Computational Fluid Dynamics (CFD).

As opposed to experiments, the main advantages of CFD are that it provides information on the relevant flow variables in the whole calculation domain (whole-flow field data), under well-controlled conditions and without similarity constraints. However, the accuracy of CFD is an important matter of concern. Care is required in the geometrical implementation of the model and in grid generation, and solution verification and validation studies are imperative. CFD validation for urban wind flow in turn requires high-quality full-scale or reduced-scale measurements to be compared with the simulation results (Balczo, et al., 2011; Horváth, et al., 2016). Different urban air pollution problems deal with the complex structure of air flows and turbulence:

- local-scale circulations: mountain areas, canyons and valleys, street canyons, mining open casts, industrial buildings and mining workings;
- thermal effects: internal and stable-stratified (SBL) boundary layers, air circulations, katabatic and anabatic winds, nuclear and industrial accidents;
- transport and diffusion of heavy gas or particles in the atmosphere;
- artificial and ventilation sources of air dynamics and circulation.

CFD methods and tools have become widely used for such problems (Baklanov, 2000). Resolving the Navier-Stokes equation using finite difference and finite volume methods in three dimensions provides a solution to conservation of mass and momentum. Computational fluid dynamic models use this approach to analyse flows in urban areas. Obstacle-resolved modelling approaches are required in numerous planning and assessment situations and for the near-sources region. Large Eddy Simulation (LES) models explicitly resolve the largest eddies, and parameterise the effect of the sub grid features.

Harmonisation, comparison

In 1991, a European initiative was launched for increased cooperation and standardisation of atmospheric dispersion models for regulatory purposes. A "new generation" of models is emerging with physically more justifiable parametrisations of dispersion processes. A need was felt for these new models to be developed in a well-organised manner and turned into practical, generally accepted tools fit for the various needs of decision-makers. One of the ideas behind the initiative is to make the most of the knowledge available in the modelling community. A lot of experience with the use of models is acquired over time, but there is a lack of proper mechanisms to transfer this experience so it is used in modelling and in the decision making process. One of the roles of the initiative is to help establish such mechanisms (*harmo.org*).

The Forum for Air Quality Modelling (*fairmode.jrc.ec.europa.eu/index.html* – FAIRMODE) was launched in 2007 as a joint response initiative of the European Environment Agency (EEA) and the European Commission Joint Research Centre (JRC). The forum is currently chaired by the Joint Research Centre. Its aim is to bring together air quality modellers and users in order to promote and support the harmonised use of models by EU Member States, with emphasis on model application under the European Air Quality Directives. The FAIRMODE Working Group 1 proposes to initiate an activity aiming at collecting and assembling modelled air quality maps, following the work initiated in the European Topic Centre for Air Pollution and Climate Change Mitigation (ETC/ACM) pilot study. The objective is to create a bottom-up composition map of air quality over Europe. National/regional agencies or modelling teams are encouraged to provide their best available air quality map for their particular region and those maps will be compiled (hopefully) into an EU-wide bottom-up composite map. This mapping exercise will be used as common platform within FAIRMODE and as a catalyst to trigger discussions, such as:

- border effects which will become visible between neighbouring regions/countries;
- use of data assimilation or data fusion techniques to produce air quality maps;
- quality and consistency of underlying emission inventories;
- choice of an adequate spatial resolution for a particular application.

Furthermore, the exercise can also be used to convince countries or regions that are not yet using models on a regular basis (see in *fairmode.jrc.ec.europa.eu/tools.composite.map.html*) to participate in the process.

The Intercomparison Exercise (IE) for Receptor and Source Oriented Models is organised within the framework of the FAIRMODE Working Group 3 on Source Apportionment. The aim of the IE was to assess the performance and the uncertainty of the SA (Source Apportionment*)* methodologies and to compare different approaches. The intercomparison has been designed to test both receptor oriented models (or receptor models, RMs) and source oriented models (or chemical transport models, CTMs). The target pollutant of this IE was PM_{10}.

The Air Quality Model Evaluation International Initiative (AQMEII) is an unprecedented effort focused on the evaluation of regional air quality (AQ) models that are used to predict concentrations and deposition of a number of pollutants over the North American and European continents. More than 20 modelling groups participated in the AQMEII two-continent model evaluation activity, in which over 10 regional-scale air quality (AQ) models were used retrospectively to calculate concentration and deposition fields for the year 2006. The performance of the AQ models was evaluated using air quality and meteorological surface monitoring network measurements as well as sets of upper-air measurements obtained by ozonesondes and instrumented commercial aircraft. (*aqmeii-eu.wikidot.com/*).

3.3. Chemical weather forecast as the near future

The coupled meteorological and chemical transport models have two basic types: i) the offline (separately, without feedback), which appears in the daily forecast routine in all the countries of the Carpathian Basin (see *section 2.2*) and ii) the online (at the same time, with feedback) integrated models. Offline models are the present, while online models may be one of the dominant developments in the near future.

The online coupled chemical transport model system can forecast the dispersion and air pollution fields at the same time. The meteorological data is available for every time step. In this case they consider the interactions between the meteorological and chemical substances. The results may be used for a variety of purposes: we can obtain physical, chemical and biological related weather forecasts. The definition of the online models means that we used the interactions between the systems (*Figure 12*).

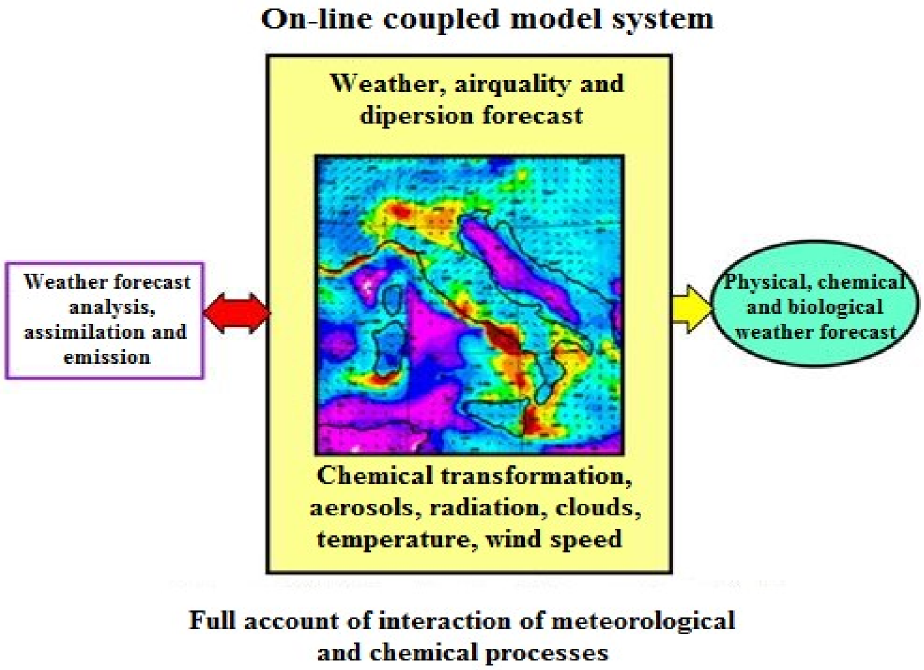

Figure 12: Schematic picture of the online coupled chemical weather forecast model. The online coupled chemical weather model for regional climate modelling (RCMs) is constructed in a similar way.

The main advantages of the online coupled model system:

- use of only one grid;
- no necessity to interpolate in time and space;
- takes into consideration the feedback mechanism of the interaction of aerosol pollutions and the atmosphere (radiative transfer processes, cloud and precipitation formation);
- easy reaching of all the 2D and 3D meteorological variables in all time steps;
- the physical parametrisation and numeric schemas (e.g. advection) are the same, there is no inconsistency between them;
- the opportunity to observe the feedback between meteorological emission and meteorological-chemical compounds;
- no need for meteorological pre- and postprocessors.

The difficulty comes from the greater complexity, the more input parameters and the lesser known interaction-systems. On the other hand, this is an important research goal of the near future, which will be appearing in the regional, nested climate models for the Pannonian Basin too. The countries of the region have a modelling routine for this type of international cooperation, so the computing background is well developed, and the earlier experiences of the COST ES0602 programme collaboration are also available (*chemicalweather.eu*, Baklanov et al., 2014).

3.4. Agricultural, ecological and water quality modelling

The numerical model results (weather and/or climate) and measurements (meteorological, environmental, air, soil and water quality) could be used as input data for coupled agricultural, ecological or/and water quality models. A schematic diagram of the climate-soil-vegetation system is illustrated on *Figure 13*.

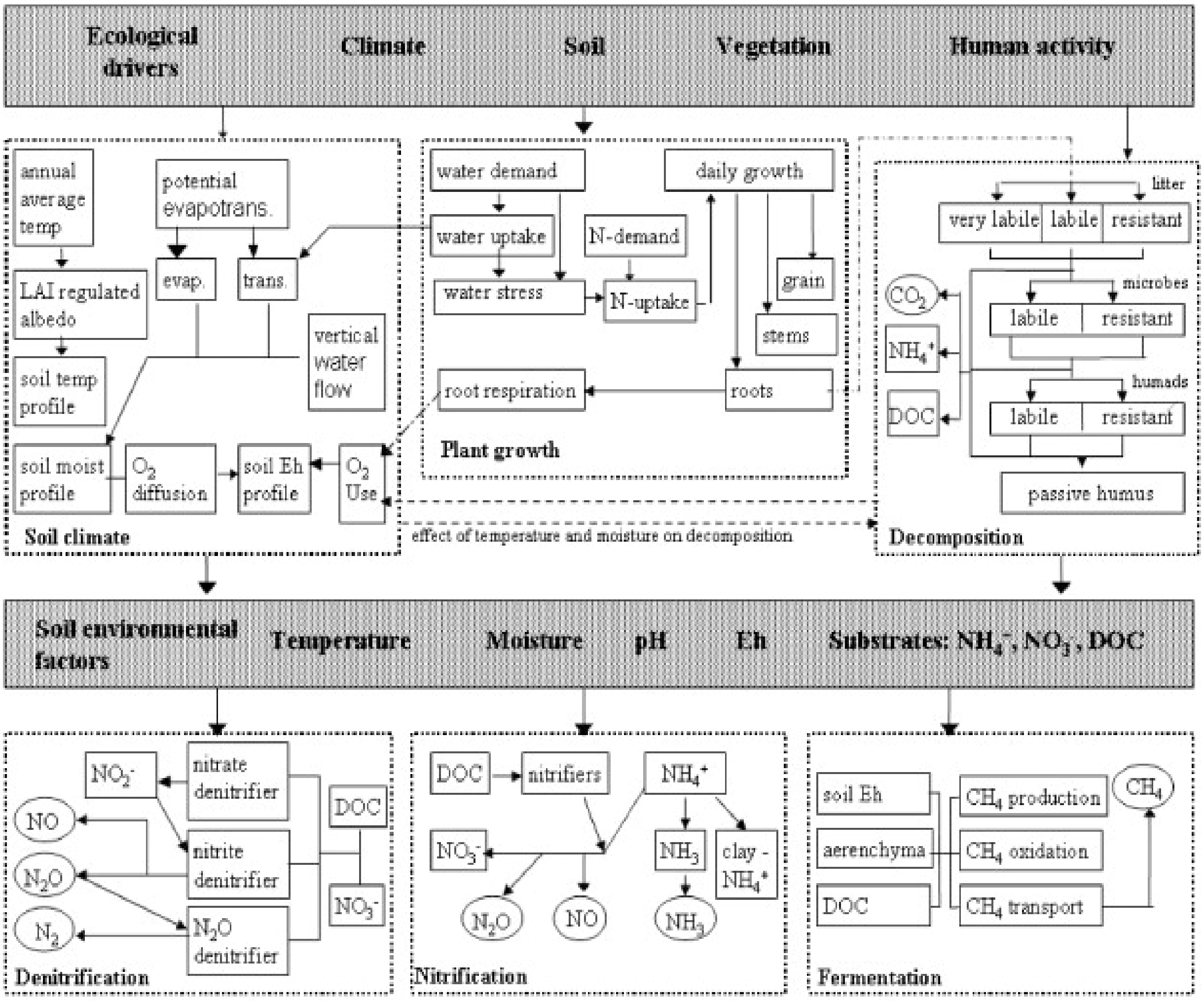

Figure 13: Schematic diagram of the DNDC model structure
(adapted from Li, 2000 and Giltrap et al., 2010).

As a process-based model, DNDC is capable of predicting the soil fluxes of all three terrestrial greenhouse gases: N_2O, carbon dioxide (CO_2), and methane (CH_4), as well as other important environmental and economic indicators such as crop production, ammonia (NH_3)

volatilisation and nitrate (NO_3) leaching. DNDC consists of five interacting submodels: i) thermal–hydraulic, ii) aerobic decomposition, iii) denitrification, iv) fermentation, and v) plant growth with different management practices such as crop rotation, tilling, irrigation, and fertiliser and manure addition. (See more detail in Giltrap et al., 2010).

To run *DNDC in Regional Mode*, the region is broken down into spatial units or zones with homogeneous soil and climate properties within each zone. "Farm Types" are defined as sets of common management practices and within each zone the number of hectares in each defined „Farm Type" is specified. Plant growth is modelled based on a daily crop growth curve (specific to the plant type) to calculate the daily N-uptake required (Giltrap et al., 2011, Machon et al., 2015).

Significant tasks in the field of the application of ecological models are i) the comparison of model calculations with regional meteorological, air quality and environmental databases, ii) the review of operative models and the investigation of applicability in the Pannonian Basin. Important modelling questions are the effects of precipitation and humidity; hence the specificity of our region is drought susceptibility. The results of the coupled environmental models depend on the quality of the NWP databases and the optimal settings of parameterisations (Grosz et al., 2015).

There are coupled models used in the Pannonian region.

- The plant growth and crop forecasting models are widely used i) in precision agriculture, ii) crop forecasting and iii) quantifying climate change (Kovács et al., 2014; Lalić et al., 2014). The methods of the comparison of the participating models are known. This is the Agricultural Model Intercomparison and Improvement Project (AgMIP). This model comparison programme and methodology may be of interest (Rosenzweig et al., 2013).
- The main goals of the constantly evolving bio-geochemical models are the simulation of the exchange of ecosystem carbon (C) and nitrogen (N) cycles; related C- and N-containing trace gases. We are able to monitor the exchange processes between soil, atmosphere and biosphere with these models, and indirectly develop the precision of field measurements and observations. Many models (PROGRASS, PaSim, CENTURY, COUP, FASSET, Biome-BGC, DNDC) exist in this field. In our region there are successfully used models, such as the DNDC (DeNitrification-DeComposition, *Figure 13*) and the Biom-BGC models. The computer backgrounds have been developed by earlier national and EU funded programs (FP4 – Graminae, FP5 – CarboEurope, FP5 – GreenGrass, FP6 – NitroEurope, FP7 – ECLAIRE, etc.) (Machon et al., 2011; Grosz et al., 2015; Hidy et al., 2015; Sándor et al., 2016).

Coupled meteorological-hydrological models are also used. For example: the FLake model is widely used for energy budget calculation of lakes in NWP models. The optimisation of model parameterisation for Lake Balaton was performed by Vörös et al. (2010).

The nitrogen budget of Lake Balaton was also investigated using a two-way exchange model of trace materials (Kugler et al., 2014) on the basis of the concentration (reactive nitrogen compounds) measurements and the calculation of the turbulent fluxes (momentum, sensible and latent heat) and eddy diffusivity coefficients for momentum and heat.

The 2D and 3D hydrological models (e.g. FVCOM) are used not only for reviewing the flow, but the energy balance and sediment processes of Lake Balaton, and Lake Fertő, and for producing wave-forecasts too (Krámer et al., 2012; Kiss and Józsa, 2015; Torma and Krámer, 2016). The emphasis is on the estimation of atmosphere-lake impulse transfer. In this area i) the information exchanging between the countries of the region, ii) the development and iii) comparisons of the applied lake and flood models is in our common interest.

4. Key questions

The 7 most important questions are reviewed in the topic of air quality of a changing climate in the Pannonian region. We are presenting interests, aspects, knowledge gaps and other relevant information of the topic. After that, we deal with the identification of problems, which will be the foundation for later collaborations.

4.1. How does a warmer climate affect air quality and human health?

Air pollution and climate change influence each other through complex interactions in the atmosphere. Increasing levels of GHGs alter the energy balance between the atmosphere and the Earth's surface which, in turn, can lead to temperature changes that change the chemical composition of the atmosphere. Direct emissions of air pollutants, or those formed from emissions such as sulphate and ozone, can also influence this energy balance, and through the surface energy balance, evaporation and the water budget. Thus, climate change and air pollution management have consequences for each other (Law, 2010). Growing anthropogenic and agricultural activity results in higher emission of reactive nitrogen compounds, and aerosol particles too. Greenhouse gas emission induces the climate change, but ozone, particulate matter and the reactive nitrogen compounds are more dangerous for the environment and for human health too. The health effects and transport processes (from the local to the long range scale) of different kinds of pollen is an important topic, which requires close international collaboration.

According to the study of Tagaris et al. (2009), the potential health effects induced by $PM_{2.5}$ dominate compared to those caused by ozone. $PM_{2.5}$-induced premature mortality is about 15 times higher than that due to ozone. However, the impacts vary spatially. Increased premature mortality due to elevated ozone concentrations will be offset by lower mortality from reductions in $PM_{2.5}$. Agricultural effects of high level ozone and reactive nitrogen compounds are also important.

The uncertainties related to different emissions projections used to simulate future climate, and chemical weather forecasts, are many although there are potentially important unaddressed uncertainties (e.g. dynamical or statistical downscaling, speciation, interaction, exposure, and concentration-response function of the human health studies).

Discussion

Climate change in association with extended urbanisation, with high levels of emissions and living in an artificial environment may contribute to increasing frequency of respiratory allergies and asthma. Pollens are also important triggers of respiratory diseases especially in central-east Europe. Higher temperatures may increase pollen quantity and induce longer pollen seasons and can also increase pollen allergy frequencies (Makra et al., 2015). The investigation of local effects and the transboundary transport of pollen are basic questions which require both the standardisation of measurements, dataset exchange and harmonisation of modelling work. Based on European-scale measurements of pollen types and concentrations and on application of coupled meteorological and air quality models many new possibilities are given for the development of pollen information databases and forecast systems (*Figure 14*). The effect of climate change processes on the pollen season and future concentration are also important issues (Liu et al., 2016).

From the results of the ECLAIRE FP7 program (Sutton et al., 2015) we also know that climate warming is likely to increase the vulnerability of ecosystems to air pollutant exposure or atmospheric deposition on the European scale, including Pannonian region. Such effects may occur as a consequence of combined perturbation, as well as through specific interactions, such as between droughts, and O_3, N and aerosol exposure. The impacts of air pollution on European ecosystems occur over a range of spatial scales from the global (ozone background), though the regional (O_3 and N deposition) to the local scale (N deposition and $PM_{2.5}$, NH_3 exposure). In a changing climate, the spatial patterns of impacts are likely to change as a result of changing emissions, land use and atmospheric processes.

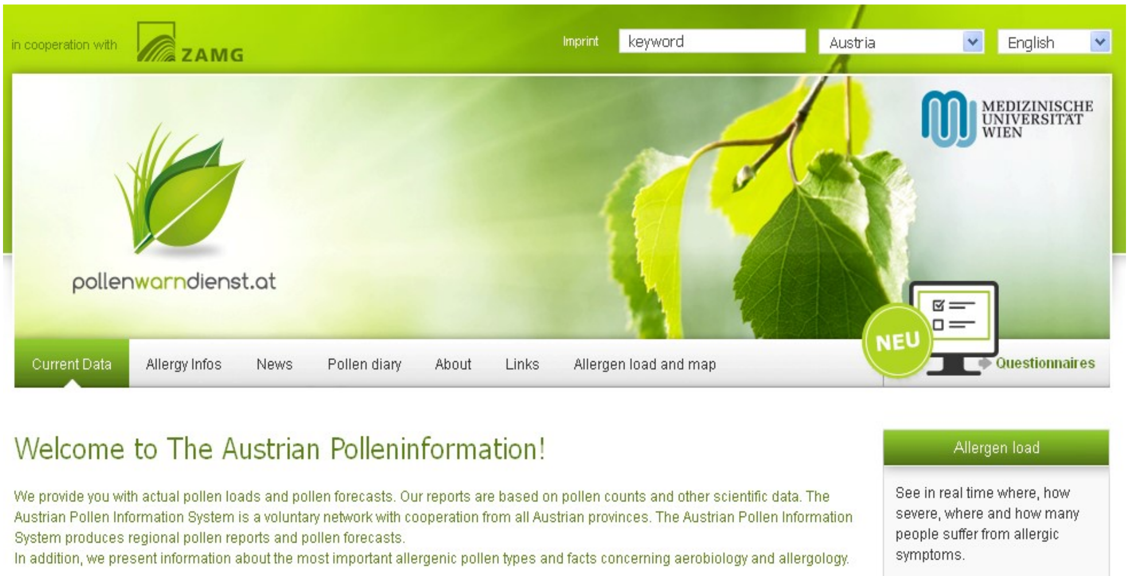

Figure 14: Country scale daily pollen information and forecast from the Austrian weather service (*pollenwarndienst.at/de/aktuelle-werte.html*).

Recent studies have shown that the observed correlation between surface ozone and temperature in polluted regions points to a detrimental effect of warming. Coupled GCM-CTM studies for the 21st-century climate assuming constant anthropogenic emissions do find widespread summertime increases of surface ozone in polluted regions (Jacob and Winner*,* 2009). Rising temperature is found to be the principal factor driving these increases. Ozone increases are of the order of 1–10 ppb depending on the time horizon, region, climate scenario, and model used. All models find that the sensitivity of ozone to climate change is particularly high in urban areas, reflecting the high potential for ozone formation. Most models find that the sensitivity is strongest at the high end of the frequency distribution, i.e. during pollution episodes, reflecting the increased frequency and duration of stagnation events. All models find significant ozone increases in south-central Europe, for example.

The response of PM to climate change is more complicated than that of ozone because of the diversity of PM components, compensating effects, and general uncertainty in GCM projections of the future hydrological cycle. Observations show little useful correlation of PM with climate variables to guide inferences of the effect of climate change. Rising temperature is expected to have a mild negative effect on PM due to volatilisation of semi-volatile components (nitrate, organic), partly compensated by increasing sulphate production. Increasing stagnation should cause PM to increase. PM is highly sensitive to mixing depths and precipitation frequency, but there is no consensus on how these will respond to climate change (Jacob and Winner*,* 2009).

Based on the results of the FP7–ECLAIRE program (Sutton et al., 2015), many atmospheric pollutants that affect ecosystems and human health, like ozone, nitrogen and secondary aerosols, are not only important climate forcing agents, but their atmospheric burden in turn strongly responds to climate change. The interactions of i) climate change, ii) change in nitrogen deposition, iii) increasing atmospheric CO_2 concentration, iv) changing aerosol burdens and v) changing ozone background and peak levels make projections of pollution impacts on terrestrial ecosystems challenging. This is especially so, since these affect ecosystem physical and biogeochemical responses on different spatial and temporal scales, and individually in either positive or negative ways (e.g. on ecosystem productivity, water use efficiency, carbon storage or biodiversity). Furthermore, changing biogenic emissions in response to air pollution and/or climate change can affect air pollution and climate change in turn, in a complex system that contains multiple, interacting forms of feedback.

Releases of hazardous agents in complex built environments are studied in COST ES 1006. Accidental releases pose a tremendous challenge to emergency first responders and authorities in charge due to the large number of casualties potentially involved. Air motions in built-up areas are very complex and adequate modelling tools have to be applied properly in order to predict the dispersion of hazardous materials with sufficient accuracy within a very short time. Different types of tools are applied and a detailed inventory of the different models and methodologies currently in use is compiled to characterise their performance and to establish strategies for their improvement. The COST program successfully demonstrated that the majority of local-scale hazmat (hazardous materials) dispersion models currently in use in urban environments are scientifically outdated and must be replaced by already existing, more reliable modelling concepts. The potential for improvement of local-scale hazmat dispersion modelling has been documented resulting from new simulation technologies, such as microscale meteorological and atmospheric dispersion modelling and computational fluid dynamics (CFD).

Summary

To optimise the efficacy of European emission control strategies in the global pollution-climate change context, it is important to develop a consistent and process-based observational and modelling framework on the EU and Pannonian Basin level to be able to understand how interactive atmospheric pollutants will impact ecosystems in response to climate and air pollution change.

An integrated approach to address the scientific questions is necessary in order to develop an integrated policy perspective. This integration then allows the selection of win-win scenarios or informs prioritisation needs, which leads to more effective policies (see also Sutton et al., 2015).

Concrete collaboration is needed for analysing the air pollution distribution in the Pannonian Basin in critical weather situations. Also the harmonisation of trace gases and aerosol flux calculations above different types of surface is an important question. A common measurement and modelling strategy is required.

In order to introduce future climate projections into climate impact studies, we need to evaluate the ability and accuracy of the models in simulating not only the basic climatic parameters (temperature and precipitation) but also the other components of the energy balance and hydrological cycle. For example, despite the large climate modelling communities, studies addressing the validation of solar surface radiation (SSR) in global and regional models using different parametrizations and different spatial scales are still low in number. However significant differences in the representation of solar radiation in global and regional climate models have been detected (Bartok et al., 2010; Jerez et al., 2015). Besides cloudiness, the different way of handling aerosols can explain the spread of SSR projections.

Also atmospheric absorption and cloud physics processes could have a key role in further surface solar radiation changes. In general, identifying the main factors causing discrepancies in different climate models regarding energy budget components would contribute significantly to detecting systematic errors that may occur in the physical climate modelling. On the other hand, quantifying the differences in SSR fields produced by different climate models indicates the degree of robustness of the projected SSR changes at different scales and gives a reference for the uncertainty transferred to impact studies**.**

4.2. Interaction of air quality and water cycle

The atmospheric load of trace materials is one of the most important nutrient sources for freshwater ecosystems. Nutrient enrichment causes a change in ecosystem structure and function; this process is termed eutrophication (Durand et al., 2011; Kugler et al., 2014). Long-lived toxic elements (Pb, Cd, etc.) can also accumulate in the environment, causing long term harmful effects for the ecosystems.

The deposition of air pollutants is an important loss of gases and aerosol particles from the atmosphere. At the same time, deposition processes of different air pollutants can cause various harmful effects both to ecosystems and the built environment. Deposition of an air pollutant affects its atmospheric concentration as well as the state of the environment or human health. Therefore, it is an important factor in different types of atmospheric chemical-transport models, and surface exchange models.

One of the main objectives of the EMEP (European Monitoring and Evaluation Programme) is to provide information about the deposition of different air pollutants, like acidifying pollutants, heavy metals (HM) or persistent organic pollutants (POPs) (*emep.int*). The results of the European scale harmonised monitoring network and model simulations show large reductions in the deposition of sulphur species during the last decades. However, orographic effects can lead to the formation of local maxima in wet deposition. Due to high annual precipitation amounts, wet deposition is typically high in southern Norway and the region around the Alps. Wet deposition of nitrogen ranges from less than 1 kg N ha^{-1} yr^{-1} to more than 20 kg N ha^{-1} yr^{-1}. The deposition of oxidized nitrogen is generally somewhat higher than reduced nitrogen in Scandinavia and the Mediterranean, except for a few sites influenced by nearby agriculture. However, in the Benelux area and in Ireland, the contribution of ammonium deposition exceeds that of nitrate, reflecting regional agricultural sources of ammonia.

The wet deposition of calcium in Europe is significantly influenced by Saharan dust. Wet deposition rates exceeding 10 kg Ca ha^{-1} yr^{-1} are observed at sites in Spain, Portugal, Italy, Serbia and Croatia. Sites with high precipitation amounts located close to the sea also experience high rates of wet deposition due to sea salt calcium.

The change of heavy metal deposition varied over the European countries. However, both modelling results and observations showed that wet deposition fluxes of lead, cadmium and mercury decreased between 1990 and 2010. It can be concluded from the measurements and model calculations that the atmospheric concentration and deposition of Pb and Cd in rural areas of Hungary are greatly affected by sources hundreds of kilometres away from the receptor area. In the case of Hungary, this is particularly true for Cd. Emission data for the model calculations were available only for the mid-eighties (Cd) and late- eighties (Pb).

a, bDue to the cumulative characteristics of Pb in our environment, it is advisable to estimate the cumulative lead deposition in Hungary for the past 60 years and to provide some quantitative estimates for the next decade (Bozó, 2005a, b). This type of simulation was also performed using TRACE model computations. For comparisons, the target of model simulations was not only Hungary but also a few other countries in different regions of

Europe – United Kingdom, the Netherlands, Spain, Austria, Romania and Poland. It is not surprising that cumulative lead deposition was much higher during the 30 years of the period 1955–1985 than during 1985–2015. Regarding Hungary, the rate of total lead deposition was 320 mg m^{-2} during 1955–1985, while on the basis of model computations it is expected that it does not exceed 95 mg m^{-2} during the following 30-year period (1985–2015). It can also be stated that in some selected countries (e.g. the Netherlands or Austria) the cumulative lead deposition rate was higher than in Hungary, while in the case of Romania and Spain lower cumulative lead deposition rates were estimated.

Summary

Harmonisation of air pollution (gases and aerosol particles) concentration calculations for open water surfaces from background or regional monitoring networks and the calculation of the deposition of aerosol particles and two directional fluxes of trace gases give basic knowledge for the quantification of the impact of air pollution for the aquatic ecosystem in the Pannonian Basin. The determination of wet deposition into the water and wetlands is also an important question. Modelling of eutrophication (dataset, methodology, and sensitivity study) seems to be a fruitful topic for future collaboration.

(*This section in the final version of the White Book is in the cross cutting section.*)

4.3. Interactions with agricultural practices (soil, water and air)

Agriculture is a significant part of human activity that profoundly influences the global environment, such as atmospheric chemistry, water quality / quantity, and nutrient cycles. Agricultural areas cover twice as much land as forest and more than 10 times as much as urban areas in Europe (EEA, 2005; Walls, 2006). The air quality is largely influenced by the (not always well-known) effects of anthropogenic activity that have i) impact on greenhouse gases concentrations, ii) distribution and flux of different reduced and oxidised compounds through affecting the a) atmospheric chemical processes, as well as b) the metabolic processes of animals, c) plants and a d) large variety of microorganisms.

Balancing food production, environmental protection, and predicting the impacts of climate change or alternative farming on both food production and environment safety in agro-ecosystems is a major question. Agricultural activities may modify the natural cycles (both directly and indirectly) such as increasing carbon dioxide (CO_2) emissions to the atmosphere by increasing the plant decomposition rate and burning plant biomass. Nitrogen fertilizer production and use contributes toward nitrous oxide (N_2O) – GHG – emissions with environmental aspects. The effects of the formation of secondary air pollutants (ozone, nucleation, etc.) and pollen transport are also important problems on different scales.

Discussion

The soil–biosphere–atmosphere system strongly depends on meteorological conditions, air pollution concentrations as well as on the characteristics of the agro-ecosystem and on soil physical, chemical and biological properties. For this reason, the investigation of exchange processes above different agricultural lands is important and necessary. The atmospheric lifetime of various compounds differs over a large time scale − from hours to hundreds of years − and their environmental impact ranges from local direct damage to climate change.

Reactive compounds (O_3, CH_4, SO_2, N_2O, NO_x, HNO_3, HNO_2, NH_3, NH_4^+, NO_3^-, VOCs, PAH, aerosol particles, etc.) in the atmosphere are characterised by different lifetimes and effects on various spheres of the Earth, including human health, ecosystems, climate, etc. Some of the atmospheric tracers (NH_4^+, NO_3^-) are deposited by wet and dry deposition processes, while other forms (e.g. NH_3, CO_2) have bidirectional fluxes between the atmosphere and the biosphere. Several compounds (e.g. NO, NH_3, HNO_3, N_2) are produced and/or consumed in the soil by microbial and chemical processes, depending on many parameters linked to soil, vegetation and climate. Quantifying the trace gas cycle is a relevant task for understanding the impacts of compounds on ecosystems or on the atmosphere (e.g. climate change, linked with the C cycle). The estimation of the amount of these pollutants on different land-use types and/or scales is a complex task. *More observations and measurements are needed to better understand the interactions between the water, air, soil and agricultural practices.*

The climate in the Pannonian Basin – as mentioned earlier – will likely be warmer, with drier summers; in some parts with shorter or mild and wetter winters, and more variable patterns of rainfall and temperature in the 21st century as predicted by the EEA (2004). Agricultural areas, grasslands and arable lands are the most widespread cultivation types in Europe and especially in the Pannonian Basin, which lands also appear to be drifting to desertification. This is an important environmental problem, because ecosystems are important in the cycle of nutrients (nitrogen, carbon, sulphur, etc.) between the land surface and the atmosphere. Interactions between climate perturbations and changing dynamics of air trace gas pollutions have received much less attention than the corresponding CO_2 interactions in forests. The markers such as heat and drought extremes, which will become more frequent as a result of the climate perturbations, can also have an impact on yields and the agronomy budget through the water and carbon balance as well as bidirectional trace gas fluxes (between the soil/crops and the atmosphere) due to soil functioning, and they may lead to reduced plant growth or changes in crop species (rotation). We also have to note that invasive (weed) species can spread from the south (from the Balkans) causing problems for farmers as a result of climate change.

Due to the forecasted potentially drying climate of the Pannonian Basin, more frequent natural fires (Strelcová et al., 2009), as ecosystem dysfunctions, will occur for example in the dry sandy Hungarian Great Plain. The estimated C and N_r loss from fires equals or even exceeds the amount of carbon or nitrogen from atmospheric deposition. Extended periods of soil water deficit and high air and soil temperatures can affect a wide range of plant physiological functions. The plant communities will be frequently exposed to naturally induced droughts and may become open grassland depending on the quality of the changing weather conditions.

Weather perturbation can also substantially modify both the timing and the magnitude of deposition and soil gas emission. Soil GHG emissions are strongly controlled by soil organic carbon (SOC) and soil mineral N-content, and by soil temperature and moisture (Rees et al., 2013). In summer time, in parallel with the precipitation deficit, less easily available N is deposited on the surface and leached to the rooting zone; thus it can limit mineral N uptake by plants or may affect the soil emission (through the suppression of microbial processes) of N-gases during the main vegetation period.

We have to note that in spring time a flooded period may also occur as another disadvantageous / unfavourable condition in fields. As a consequence of snowmelt and uneven distribution of rainfall, lands can get flooded and the denitrification processes (during these short anaerobic periods) can produce N_2O and N_2 emission peaks.

During the summer season microbial productivity is elevated (mineralization, nitrification, immobilization, decomposition, etc.). In the dormant period, despite the higher water filled pore space (WFPS), the activity of the microbial community decreases parallel with the drop in soil temperature. Changes in seasonality, distribution and frequency of precipitation and the total amount of rainfall may have a great impact on the carbon and nitrogen exchange of the Pannonian Basin. Both the seasonal and the long-term nutrient exchange of the agro-ecosystems are therefore linked to the soil water content (due to the rainfall regime) and soil temperature.

Ecological modelling

It is essential to monitor or measure the changes mentioned above and to determine the rate of pollutant emissions and the harmful effects in current and future contexts. Scientist can investigate this theme from many points of view, but we can agree that the need to predict (using models) the changing drivers and parameters (e.g. climate) is unavoidable. Using ecological models, we are able to provide C and N budget (gas fluxes) predictions or optimal farming practice predictions for those lands where soil and/or meteorological measurements are missing and we are able to simulate crop growing, fluxes of parameters and soil processes where field or laboratory measurements are difficult to carry out or too expensive.

This provides some support for future use of this kind of model in the regional mode for scaling up the analyses for different agro-ecotypes or gives a climate scenario estimation scaled up to the Pannonian Basin (using the GIS database by the CORINE Land Cover map from the European Topic Centre on Terrestrial Environment, Bossard et al., 2000). At the country scale the rough estimation of greenhouse gas emissions by IPCC methodologies can be refined using ecological models. The IPCC method is determined for many European areas.

Cultivated arable lands are also included in the IPCC method, but the three-dimensional heterogeneity of the agro-ecosystems should not be forgotten (even on the metre scale, which cannot be considered by the IPCC, but the models are able to deal with this scale), this is the reason that measurements should be taken at several locations simultaneously, which is not always possible.

Many research communities are developing ecological models (see *2.4 section*) which are also applicable to support climatic or land use scenarios for future planning. One of the popular ecological models is the DNDC. It has been used by many research groups all over the world (Beheydt et al., 2007; Leip et al., 2008; Smith et al., 2010; Li, 2000; Li et al., 2000) and also in our region (Grosz et al., 2015; Machon et al., 2015); therefore, extensive operational experience is available. The entire model is driven by four major ecological drivers, namely i) climate, ii) soil physical properties, iii) vegetation, and iv) anthropogenic activities (see also *Figure 13*). The model requires many input parameters, including ecological forcing, like a) soil properties (soil texture, density, slope, field capacity, wilting point, clay fraction, pH, soil organic carbon (SOC), NO_3^-, and NH_4^+ content), b) meteorological variables (daily minimum and maximum temperature, precipitation, and global radiation), c) vegetation characteristics (crop type, plant, and harvest time, details of crop phenology), d) and farming functions such as tillage, fertilizers, manure, weeds, irrigation, grazing pressure, and farming type (cattle, horses, sheep) with a start and end date of grazing, etc. These daily input parameters are required to simulate both crop and soil dynamics simultaneously.

The Biome-BGC model is also well known and widely used in our region (Barcza et al., 2009; Sándor et al., 2016).

The challenge of the future is the question of how to couple meteorological and ecological models online at the region scale to obtain better predictions (e.g. with higher resolutions and/or for smaller areas).

Summary

Based on the study Machon et al. (2011), it can be concluded that climate extremes are significant factors in soil organism functioning and the dynamics of C and N-exchange and emissions. Hence, the nutrient content of the soil is continuously changing in line with the climate extremes. The soil organic carbon pool (SOC), NH_4^+ and NO_3^-, which depend on the C and N-consumption and exchange of the soil microbial community, affect the plant N (and other nutrient) uptake (demand), plant growing, etc. The living roots and bacteria are competitors for the same nutrients, so plants also induce an effect on soil transformation.

Summarizing, many soil processes (e.g. decomposition, nitrification, denitrification, mineralization, etc.) are strongly dependent on soil temperature and moisture as ecological drivers. The changes in these parameters directly influence the crop growing and soil gas emission rates, though the complex system of relationships makes it difficult to explain all the changes of the C and N cycles and their formation. Example: reduced N_2O emission (desertification occurring due to perturbed climate conditions) can be a potential negative feedback for the greenhouse effect (Machon et al., 2015.) On the other hand, the vegetation can turn into being a net CO_2 source in extreme dry years as positive feedback for climate change (Barcza et al., 2009). The ratio and strength of these two phenomena cannot be neglected due to increasing aridity (and/or the agricultural policy in question).

In the rapidly changing world one of the main tasks is to optimize the efficiency of agro-cultivation (where and what kind of changes – crop type, tillage, etc. – are necessary) according to the ecological model scenarios.

4.4. Surface layer processes (energy budget, fluxes, deposition, profiles)

The biosphere is an important source and sink of radiation, momentum, heat, water and gas fluxes for the atmosphere. Therefore, biosphere-atmosphere feedback is important for understanding weather and climate causes and consequences and their proper treatment in NWP models with different temporal and spatial scales. It is not just scientific curiosity which governs research into turbulent transfer above and within plant canopies. The proper treatment of canopy micrometeorology is of utmost importance for numerous physiological, ecological, hydrological and agricultural applications. As Kaimal and Finnigan (1994) pointed out, "The understanding of turbulent transfer within foliage canopies provides the intellectual underpinning for the physical aspects of agricultural meteorology."

An enhanced level of knowledge in this complex field can be achieved only by full implementation of the "Experiment-Theory-Practice" framework based on regional (Pannonian region) integrative functions. Current micrometeorological measurements, data analysis and application should be combined in this framework in order to i) fill data gaps and optimize future experimental activities, ii) introduce new modules and parameterization procedures in NWP models in order to optimize their application for ecological and agricultural purposes, iii) increase visibility of research and findings by intensive introduction to young people and iv) use NWP products in agricultural production. These are the requirements we now address.

Discussion

Data management. Important issues related to micrometeorological measurements which should be addressed at the Pannonian region level are: data mining and analysis of available data sets, harmonisation of data recording protocols, inventories of the most important events (extreme and adverse weather events), identification of common data gaps, development of common procedures and tools to fill data gaps and missing data from available data series and calculation of surface mass and energy budget components using measured and gridded data sets at the regional scale.

NWP model optimization. There is a strong demand for a two-way approach to this issue: i) improved parameterization of chemical and physical processes describing biosphere-atmosphere interactions in order to reduce uncertainties and improve NWP on all time and spatial scales and ii) develop an agrometeorological module of the NWP model in order to provide full and physically consistent coupling between NWP model functionalities and applications.

Visibility increase. Train young scientists in fields of data management, data quality criteria, scaling and measurement techniques in micrometeorology with respect to potential applications (through Short-Term Scientific Missions (STSMs), for example). On the other hand, calculated agrometeorological data can be used to develop crop damage/loss related applications and to be able to avoid cropping risks and crop stress at the regional level. This fosters the implementation of many potential applications, both in research and practice.

NWP product application in agricultural production. Use of NWP outputs as input meteorological data in agrometeorological (incl. weather extremes), ecological and crop models can optimise field operations and crop management options as well as reduce risks in crop and livestock production (i.e. by the early warning of droughts and heat waves). NWP models have overall high economic potential for farmers to obtain higher yields with the same inputs and to minimise losses caused by weather. A precondition for the successful implementation of operational applications is performance testing, representativeness and uncertainty of the results for guiding farm management options.

Summary

Climate simulations and climate change assessment studies were common goals of the decades that have passed. The need for climate change adaptation and mitigation raised awareness of the importance of numerical weather prediction (NWP) in achieving these goals. Therefore, the improvement of short and long range (monthly and seasonal) NWPs are one of the most important goals and future challenges for the atmospheric sciences community of the 21^{st} century. In this context the micrometeorological community dealing with biosphere-atmosphere interaction has a very responsible role. Agricultural production in terms of quantity, quality and efficiency is significantly affected by weather conditions. Therefore, knowledge of future weather conditions is very important. Taking various crop management measures at the farm level is necessary to optimise agricultural production and to reduce risks and related economic losses. According to climate change impact studies, effect such as floods, droughts and heat waves will increase in the Central European Region, significantly affecting production risks in agriculture.

This flagship question will partly relocate to the cross cut section (SVAT model development) and to the ecological modelling section (4.3) and the boundary layer modelling section for improving forecasts (from the meteorological and air chemistry point of view (4.5).

4.5. Physics and chemistry of the boundary layer; improving forecasts

The Planetary Boundary Layer (PBL) is the lowest part of the atmosphere where a multitude of processes interact, i.e. atmospheric dynamics, atmospheric chemistry, physics of the land surfaces and biogeochemistry cycles. The main physical or dynamic characteristic of the PBL is its more or less continuous turbulence in space and time.

Hungary, together with several other European countries, has been participating in the ALADIN (Aire Limitée Adaptation Dynamique Développement International, *cnrm-game-meteo.fr/aladin/*) consortium since 1991. Besides the ALADIN collaboration numerous countries in the region are members of the RC-LACE consortium, which represents a closer collaboration between six Central European countries in certain areas (e.g. data pre-processing). The aim of both ALADIN and RC-LACE is to develop a short-range, limited-area numerical weather prediction (NWP) model. The ALADIN/AROME model family has emerged as a result of this collaboration and is constantly being developed in the participating countries.

At the beginning of the ALADIN collaboration the ALADIN model was a hydrostatic NWP model and was designed to be run at relatively coarse horizontal resolutions (i.e. no higher than 8 km), where hydrostatic approximation is valid (the vertical acceleration of air is neglected). Due to the rapid increase in available computing resources at the national weather services at the beginning of the 2000s it became possible to run operational non-hydrostatic models at a horizontal resolution of 2–3 km. The AROME (Application of Research to Operations at Mesoscale) project was initiated by Météo-France in 2002 with the aim of developing a non-hydrostatic NWP model running at a horizontal resolution of 2.5 km (Seity et al., 2011). The AROME model has three main components: the non-hydrostatic ALADIN dynamical core (Bubnová et al., 1995), the atmospheric physical parameterizations, which are taken from the French Meso-NH research model (Lafore et al., 1998) and the SURFEX surface model (Le Moigne et al., 2012).

AROME has a state-of-the-art physical parameterization package to describe subgrid scale processes. Radiation is parameterized with the European Centre for Medium-Range Weather Forecasts (ECMWF) radiation parameterizations. Processes related to cloud microphysics are described with the ICE3 mixed-phased parameterization scheme (Pinty and Jabouille, 1998), which computes five prognostic variables of water condensates. Subgrid scale turbulence is parameterized by a 1.5 order closure using prognostic turbulent kinetic energy (TKE) and a diagnostic mixing length (Cuxart et al., 2000). To implicitly handle phase changes, the scheme is formulated in terms of the conservative variables of liquid water potential temperature and total water content. Deep convection is assumed to be resolved explicitly at the 2.5 km horizontal resolution, consequently only shallow, non-precipitation convection has to be parameterized. This is done using the eddy diffusivity mass flux approach (EDMF, Soares et al., 2004), and applying Kain–Fritsch buoyancy sorting in the cloud layer (Pergaud et al., 2009). Surface processes are parameterized with the SURFEX externalized surface model, which distinguishes between four tiles (land, town, sea and inland waters). For each tile a specific parameterization is applied to compute surface properties, which are then used to compute the surface turbulent fluxes of heat, momentum and water vapour. The AROME model is now used in several countries of the ALADIN consortium (Hungary, Austria, Poland, etc.). At the Hungarian Meteorological Service work related to the AROME model began in 2006. After four years of scientific and technical development the AROME model became operational in December 2009. The model is run at a horizontal resolution of 2.5 km eight times a day (at 00, 03, 06, 09, 12, 15, 18 and 21 UTC) for a total of 48 hours (Szintai et al., 2015). Lateral boundary conditions are derived from the ECMWF/IFS global model. AROME runs a local data assimilation system consisting of a three-dimensional variational (3D-VAR) assimilation for the upper-air fields and an optimal interpolation (OI) for the surface variables (Mile et al., 2015).

The main objective of the present proposal is to improve simulation of the PBL in the NWP models mainly in AROME. This is envisaged during the completion of the following tasks:

- extensive validation of the applied NWP models in the PBL using measurement campaigns;
- installation of a single column version of the PBL models (AROME, WRF, etc.);
- research in connection with the grey zone of turbulence at very high model resolutions.

Discussion

Validation of AROME in the PBL. The forecasts of the operational AROME model are routinely validated at the Hungarian Meteorological Service using SYNOP measurements and radiosoundings. However, it is very difficult to judge the performance of the model in simulating the structure and evolution of the PBL with radiosonde data due to the limited vertical and temporal resolution of these measurements. Also, soil moisture can significantly influence PBL development, and unfortunately, this variable is not measured routinely in Hungary. Consequently, measurement campaigns concentrating on PBL evolution and soil characteristics are crucial to understanding the behaviour of the model in the lowest part of the atmosphere. For example, a group from Eötvös University Budapest has performed several measurement campaigns near Szeged, Hungary (Weidinger et al., 2014; Cuxart et al., 2016). It is planned that this dataset will be used to evaluate the performance of the AROME model in the PBL to understand possible deficiencies and to try developing further physical parameterizations, especially microphysics and turbulence.

Development of a high precision PBL dataset in the Pannonian Basin is useful for the NWP model comparison and investigations of surface-atmosphere interactions. This is in the common interest of other Pannonian region modellers also.

Single column version of AROME, WRF, etc. Single column versions of operational NWP models are widely used during the development of physical parameterizations. In the single column version of an NWP model the full model (dynamics and physics) is run, but only for one selected grid point. With such an approach we can gain full control over the simulation, making it is easier to understand the behaviour of the model. Furthermore, it is more expedient to run the single column version than the full three dimensional model, so development work can be made much faster.

For example the single column version of AROME has already been developed by Météo-France. It is planned that it will also be installed at the Hungarian Meteorological Service, and used in the PBL model validation work described above.

Grey zone of turbulence. At very fine horizontal resolutions NWP models are approaching the so-called grey zone of boundary layer turbulence and shallow convection. This means that a part of the turbulent transport is resolved explicitly by the model and only the remaining part has to be parameterized, meaning that the classical parameterization approaches cannot be applied successfully, and new methods need to be used. Research connected to the “grey zone of turbulence” began in 2013 within the AROME community. During this work the hybrid turbulence – shallow convection parameterization of AROME was made scale adaptive and first tests were carried out. It is planned that this modification will be further tested in AROME using both idealized and real case studies and continuous periods.

Investigation of PBL structure, parameterization of development of nocturnal PBL and low level jet are hot topics from both theoretical and practical (air pollution transport) aspects. Classification of the daily course of PBL height is also an important question.

Summary

A correct simulation of the PBL is crucial for operational NWP models in two aspects. On one hand, PBL is a significant source of heat, moisture, momentum and air pollutants for the upper part of the atmosphere, thus it can play an important role in the development of mesoscale weather phenomena. Overall, the PBL is an interface layer between the underlying surfaces and the so-called free atmosphere. On the other hand, human society is located in the lowest part of the atmosphere, so this is the part of the atmosphere which directly influences the citizens' quality of life. Consequently, development work related to PBL processes is very important to improving the usability of NWP models.

4.6. Refinement of emission inventories

On the global scale, the harmonisation and improvement of emission inventories is imperative to get consolidated estimates on the formation of global air pollution. As it influences human health and climate greatly, so these improvements would be beneficial for future policies combating these air pollution aspects.

Emission estimates are limited in their utility since (1) the environmental issues depend on the spatial and temporal resolution of the models of because short atmospheric lifetime (for example NO_x, SO_x), human activity, land cover and (2) because the relationships of emissions to environmental effects (atmospheric concentrations, impacts on ecological systems) are nonlinear. Uncertainty estimates for emission data also provide important information which enables the performance of ensemble type investigations (Benkovitz et al., 1996).

The quantification of chemical emissions into the air is a key step in explaining observed variability and trends in atmospheric composition and in attributing these observed changes to their causes on local to global scales. Accurate emission data is necessary to identify feasible controls that reduce adverse impacts associated with air quality and climate, to track the success of implemented policies, and to estimate future impacts.

Top-down and bottom-up methodologies

The "top-down" estimate is a methodology which starts from annual emission values assessed at the national level, and detailed in several activities following specific SNAP codes (Selected Nomenclature for Air Pollution). These emissions are spatially disaggregated at different levels, such as the provincial and municipal, by means of statistical indicators (population, roads, and land-use). This methodology also considers temporal disaggregation, because the hourly resolution of emissions is achieved from the annual level.

The "bottom-up" approach begins instead from local data at the municipal level or even from the specific object of the emission (so may be a road graph or industry location) and, using this information and proper emission factors, directly assesses hourly emissions at the local level. Approaches used for inventories are often an alloy of the two types, as for some emissions it is possible to find disaggregated data while for others an approach of disaggregation from aggregated data is unavoidable. (Thunis et al., 2016a, b.)

Discussion

The EMEP (European Monitoring and Evaluation Programme) is a scientifically based and policy driven programme under the Convention on Long-Range Transboundary Air Pollution (CLRTAP) for international co-operation to solve transboundary air pollution problems: reported spatial emission data is input for models used to assess atmospheric concentrations and deposition, as the spatial location of emissions largely determine atmospheric dispersion patterns and impact area. The results of model assessments inform national and international policies responsible for improving the environment and human health. The area within which monitoring – coordinated by the international centres of the EMEP – is carried out is defined as geographical scope of the EMEP. At the 36th session of the EMEP Steering Body, the EMEP Centres suggested to increase the spatial resolution of reported emissions from the 50 km x 50 km EMEP grid to 0.1° × 0.1° longitude–latitude in a geographic coordinate system to improve the quality of monitoring. The new EMEP domain will cover the geographic area between 30°N – 82°N latitude and 30°W – 90°E longitude. The reporting of gridded emissions in the new resolution (0.1°× 0.1°) is requested from 2017 onwards (*ceip.at*).

The TNO's (Netherlands Organisation for Applied Scientific Research) involvement in MACC (Monitoring Atmospheric Composition and Climate) is attributable to its high-tech expertise in the field of emissions and research in air quality and climate. For this project a high resolution European emissions database has been developed and is being maintained (the TNO-MACC emission data). The LOTOS-Euros air quality model is used to contribute to the operational air quality expectation across Europe, which is available from the MACC website (*gmes-atmosphere.eu*). The TNO-MACC emission data set is widely used in Europe, not only in MACC but in many scientific projects as well as in important model comparisons. The original database is at a higher resolution (0.125° × 0.0625° longitude-latitude ~7 × 7 km) and provides emissions by substance at the source sector level (SNAP 97 1st levels, which consists of 10 source categories).

The annual emissions by source sector can be combined with a set of default temporal emission fractions to break down the annual totals by month, week, day and hour (*Figure 15*).

- *accent.aero.jussieu.fr/TNO_metadata.php*
- *accent.aero.jussieu.fr/database_table_inventories.php*
- *eccad.sedoo.fr/eccad_extract_interface/JSF/page_login.jsf*
- *geiacenter.org/access*

The EDGAR (Emissions Database for Global Atmospheric Research) provides global past and present day anthropogenic emission data on greenhouse gases and air pollutants by country and on spatial grid. The current development of EDGAR is a joint project of the European Commission Joint Research Centre (JRC) and the Netherlands Environmental Assessment Agency (NEAA) (*edgar.jrc.ec.europa.eu/datasets_grid_list_htap_v1.php#d*).

The EDGAR v4.3.1 global anthropogenic emission inventory of several gaseous (SO_2, NO_x, CO, NMVOCs, NH_3) and particulate (PM_{10}, $PM_{2.5}$, BC and OC) air pollutants has been used to develop retrospective emission scenarios for the years 1970–2010 to quantify the effectiveness of emission reduction measures, change in fuel consumptions and technological developments on air quality emissions, and their impact on health, crops, and climate. Based on statistics and expert knowledge, EDGARv4.3.1 considers changes in activity data, fuel and air pollution abatement technology, as it has likely to have happened during the past 4 decades. Additionally, three retrospective scenarios are created. The first is simulating the complete stagnation of technology (STAG_TECH: lack of abatement measures and no improvement in emission standards). The second is assuming a constant fuel mix and consumption as they were in 1970 (STAG_FUEL: no change in human activities). The third is considering unchanged energy consumption since 1970, but assuming the technological development, end-of-pipe reductions, and fuel mix and energy efficiency of 2010 (STAG_ENERGY). Reference (REF): EDGAR v4.3.1 data represents our best estimate of the development of emissions (activity levels, emission factors, technology) for 1970–2010 (Crippa et al., 2016; *(edgar.jrc.ec.europa.eu/pegasos/index.php)*.

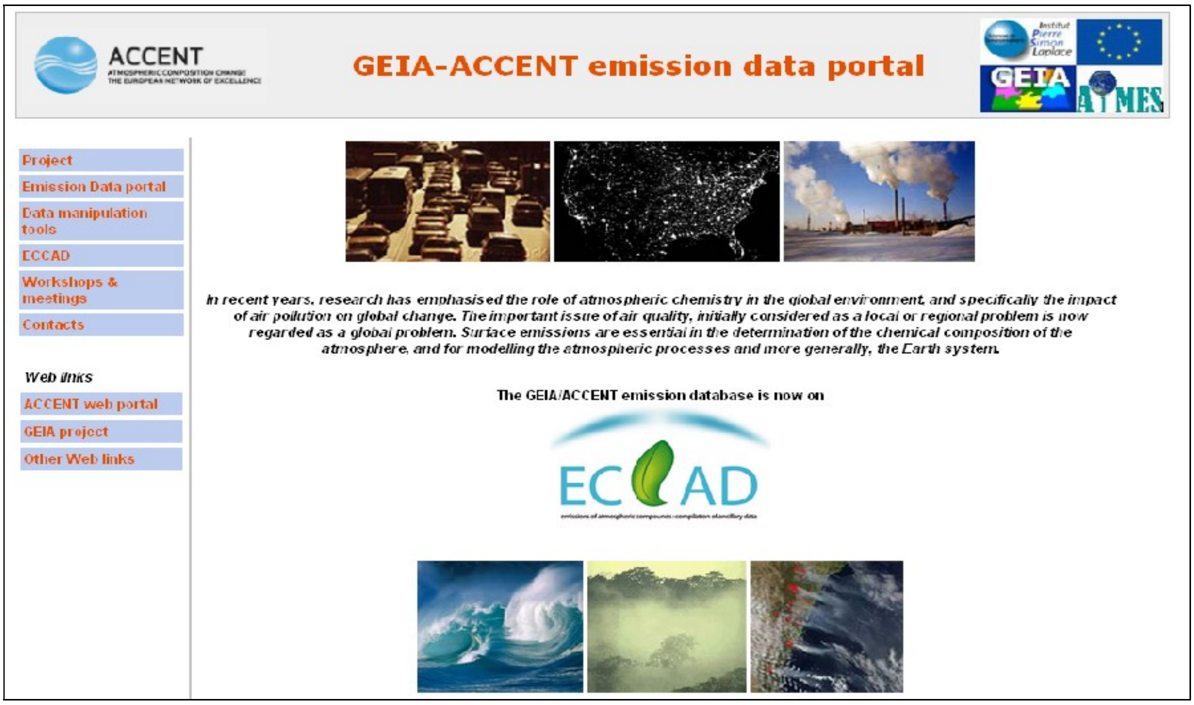

Figure 15: The main page of GEIA-ACCENT emission portal (accent.aero.jussieu.fr/index.php). (GEIA – Global Emission InitiAtive, ACCENT – Atmospheric Composition Change European Network of Excellence).

Summary

Emission inventories are comprehensive listings of the sources of air pollution and an estimate of their emissions within a specific geographic area for a specific time interval. They are generally identified as key inputs in the air quality modelling chain, especially when they are used to support regulatory decisions, such as air quality planning or the assessment of concentration levels over a given territory.

Nowadays high-resolution gridded emission inventories are expected by the air quality modelling communities. Generally, it can be said that finer spatial resolution of the emission data is needed in order to improve the results of air quality models.

4.7. Perception of populations, urbanisation

More than one third of the EU population lives in regions most affected by climate change, with a total population of 170 million. Regions under the highest pressure are generally located in the south and east of Europe. This is mostly due to changes in precipitation and an increase in temperature, which have an impact on vulnerable economic sectors, with river floods also contributing to the overall effect in Hungary, Romania and Serbia. Limited impacts are expected for northern and western Europe, apart from lowland coastal regions around the North and Baltic Seas, but with high exposure to costal erosion through extreme weather events.

Urban climate research seems to be inevitable today as the world is experiencing a tremendous demographic transition from rural to urban. Nowadays the majority of the population (60–70% in Central Europe) lives and works in cities, however cities occupy only a small fraction of the continent. Considering climate warming, the highest CO_2 sources are located in cities. At the same time, urban agglomerations are particularly vulnerable to climate extremes, such as heat waves (*Figure 16*) and flooding.

Discussion

Diverse demographic changes have been observed in Europe at the city level. Whereas the population as a whole has been growing in northern, western and southern Europe, central Europe has experienced stagnation or decline. Some central European countries (Czech Republic, Slovakia, and Slovenia) reported a balanced overall population growth, whereas core cities decreased in population. In Romania, population losses in cities were lower than in the country as a whole. A more differentiated picture can be seen in other countries (Bulgaria, Hungary, Poland), where some cities have lost population to a greater extent than in the countries as a whole, while other cities have experienced little population decline or have even grown. In regions which lag behind, the outer zones of cities gained, while core cities lost population, but in a number of exceptions (notably Hungary and Romania), the situation was reversed.

The age structure of the population varies in the Pannonian Region and its surroundings within a wide range. A comparison of the age structure for central European countries is provided with similar information for each of their capital cities. The situation is split into two parts; identifying those capital cities where the population aged 20–54 accounted for a relatively high share of the total population, and those where the elderly accounted for a relatively high share. Younger and middle-aged adults are generally drawn to capital cities. The existence of greater opportunities for higher education and employment offered by most capital cities might lead to the assumption that capital cities have a higher share of younger and middle-aged adults. For example, in 2012, the younger and middle-aged adult populations of Sofia accounted for almost 6 percentage points more of the total population than their respective national averages. There were, however, some exceptions to this rule, as the proportions of younger and middle-aged adults living in Warsaw, and Bratislava were lower than the respective national averages for Poland and Slovakia. It is conceivable that older people (aged 65 and over) might be tempted to move away from capital cities for their retirement to avoid some of the perceived disadvantages often associated with big cities, such as congestion and crime. A low proportion of the elderly were living in cities in Bulgaria, Croatia and Romania. However, in Warsaw, Bratislava, elderly people accounted for a higher proportion of the total population than the national average. This means that this part of the population living in big cities is the most vulnerable to damage caused by extreme weather events like heat waves and flooding.

There were only three relatively large EU cities (with a population of at least 500 000 inhabitants) where the share of the native-born population rose above 95%: the Bulgarian capital of Sofia (98.1%) and the two Polish cities of Lódz and Poznan (both 98.8%). By contrast, there were nine cities (4 German, 2 Belgian, 1 Dutch, 1 British and 1 Swiss) in Europe with in excess of 500 000 inhabitants where more than 25% of the population had been born in another country. Projections at city level indicate that the share of people with foreign backgrounds will further increase since the Mediterranean countries have received large waves of young immigrants over the last 15 years. The young migrants settling down preferably in the centres of European cities increase the urban population.

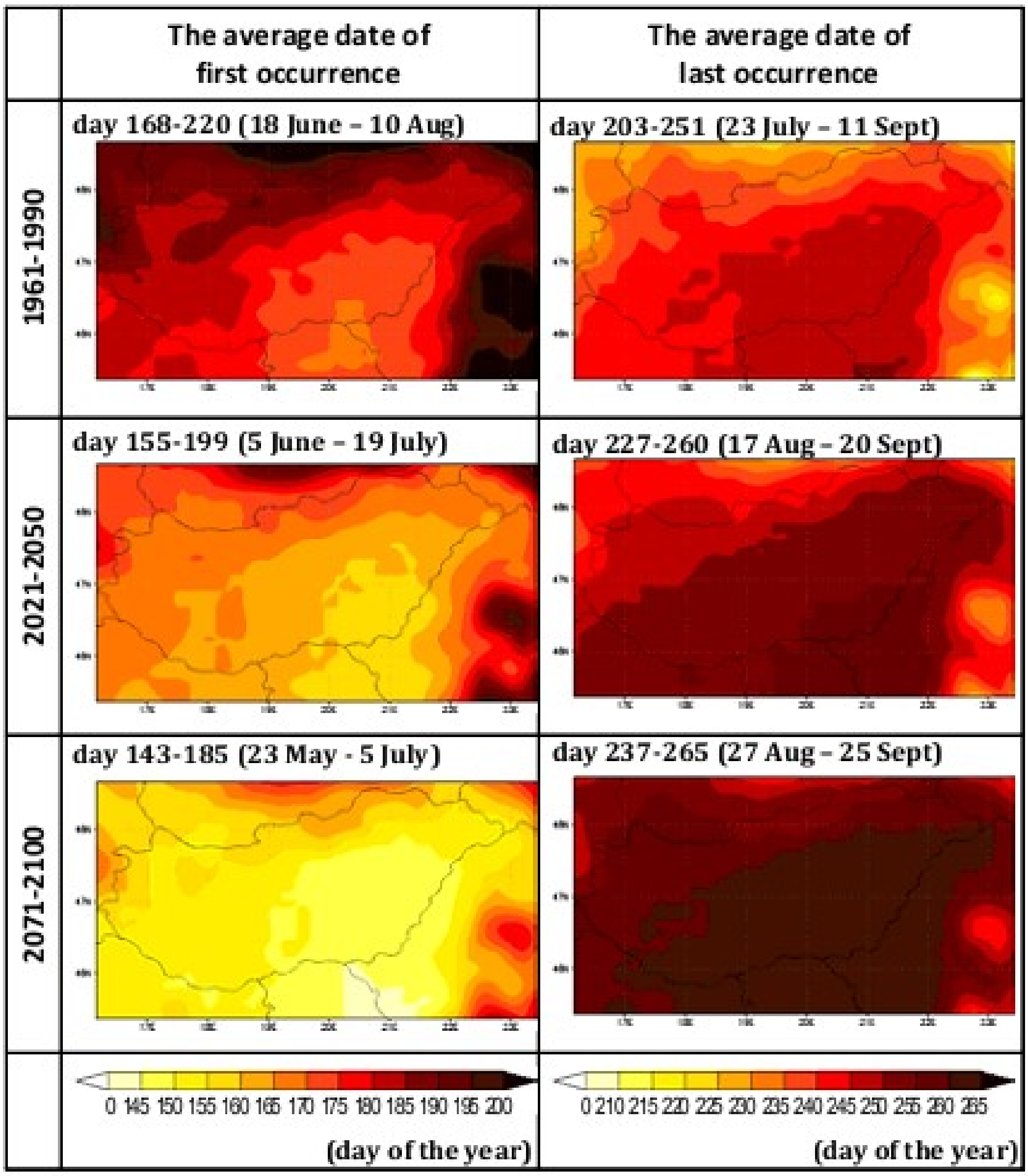

Figure 16: Average date of the first and the last occurrence of heat wave warning level 1 using the PRECIS simulations for 1961–1990, 2021–2050, and 2071–2100 (Pongrácz et al., 2011).
PRECIS (Providing REgional Climates for Impacts Studies).

In urban environments, due to growing rate of population, the built-up area is increasing, natural surface is decreasing, which lead to the formation of urban heat island phenomena. Compared to the rural surroundings, the air temperature in the city centre is on average 1–2 degrees warmer. The effect of climate change, sometimes reaching 2 ºC, can be added to this urban level. Considering the Pannonian region temperature changes on the basis of results of an EU funded project called CarpatClim, and the dataset from the Hungarian Weather Service the temperature increase from 1901 to 2014 is about 1 ºC. In south-eastern Europe the observed increase in maximum temperature translated into an increase in the number of hot days and, consequently, into an increase in the frequency of occurrence of heat waves (Tomczyk and Bednorz, 2016). Climate forecasts show that as this tendency continues, heat waves will not only be more frequent, but also longer and more intensive in the 21st century. (Pongrácz, et al., 2013; Zacharias et al., 2015).

Unfortunately, in Hungary – as in several other south-eastern European countries – with the increase of solid paved surfaces, the currently fashionable trends in planning open public spaces often not only fail to improve but actually contribute to the deterioration of climatic conditions in developed urban areas. In recent years urban research plans have been trying to find tools to mitigate the harmful effects of urban heat islands, to present examples of climate-conscious public area development in cooperation with urban architects and urban landscape-designers.

Summary

The Urban Heat Island effects are directly related to (and worsened by) climate change phenomena, where it is expected that a greater increase in the average temperature could be observed in a city than a rural, regional site. These extra signals of the urban environment can be filtered by statistical techniques. Homogenised data can be used for the temperature or precipitation maps or long-term time series for a description of characteristics of the urban climate. Heat waves are only one aspects of climate warming. In urban areas climate change causes storms with extreme precipitation, inland and coastal flooding, landslides, high level air pollution, droughts, water scarcity, sea level rises and storm surges having risks for people, assets, economies and ecosystems.

Investigating the formation of the local climate (outdoor and indoor), comparison studies among cities, future changes of pollutants, heat island intensity and health effects are also hot topics which require a common methodology in measurements (Unger et al., 2011), weather and climate modelling and environmental policy.

5. Concluding remarks

The scientific background, key issues and potential cooperation opportunities were reviewed in the field of air quality under the changing weather and climate in the Pannonian Basin.

The long term data from standard *meteorological measurements* including SYNOP, TEMP, and special surface and PBL measurements, such as radiation and energy budget components (*Fluxnet* for example, *fluxnet.ornl.gov/fluxnetdb*), sodar and windprofiler measurements, etc. are available. *The air pollution measurement network* (regional background, rural and urban stations, etc.) for trace gases, aerosol particles, pollens and precipitation chemistry is also optimally dense for regional scale investigations. European scale cooperation (WMO region 6, EMEP, Horizon2020) is well developed and a priority in each country. *The harmonisation of regional scale country-specific measurements and the expansion of the common used dataset are important.*

Observatories (agrometeorological, aerological, etc.) and special measurement platforms especially for air pollution and nucleation (see BpArt *salma.web.elte.hu/BpArt/*; Salma et al., 2016b) provide possibilities for scientific and educational cooperation. *The development of experimental measurement capacity, especially for PBL profiles, direct fluxes, surface energy budget components, soil energy budget and evaporation from water bodies are in the common interest for scientific and practical purposes*.

A common methodology is needed not only for air pollution inventories (EMEP, IPCC), but for the development of regional scale surface and soil datasets. *Gridded high density datasets (similar to CarpatClim) are important for the SVAT (Soil–surface–vegetation–atmosphere), air pollution and NWP modelling at the Pannonian Basin scale.*

Regional weather, air pollution and climate models are used in a wide range and high quality model development experience also exists. But the common model products for the Pannonian region are missing. For resolving this issue, the first step is the development of ensemble forecasts (meteorological, atmospheric environmental, or climate) for modelling the overlapping Pannonian regions. An *important task is the construction of the region specific parametrizations (surface processes, radiation, PBL, etc.) and the verification with the measurement databases. One of the key questions is evaporation from soil and water surfaces (lake, wetland) based on the preliminary experiences* (see Ma et al., 2015; Szilágyi, 2015).

Measuring and modelling of deposition velocities and/or bidirectional fluxes for pollutants (ozone, reactive nitrogen, aerosol particles) and the development of regional specific parametrisations for different vegetation types is also an important topic (Czóbel et al., 2010). Further investigation of greenhouse gas emission and budget, reactive nitrogen compound and ozone formation are also topical questions.

Climatological studies into the relation between high pressure systems or winter cold air pools and air pollution episodes in the Pannonian Basin are envisaged. Further work would go beyond PM mass concentration and would include chemical analyses of the core elements in PM_{10}, which would undoubtedly identify the extent of natural source contribution.

The harmonisation and application of ecological models using gridded meteorological and climate change datasets is a potential topic for further cooperation in the region. Using satellite based information (see Eumetsat products, eumetsat.int) for the Pannonian Basin (soil information, vegetation, air pollution (Ozone & Atmospheric Chemistry Monitoring), cloudiness, etc.) also help for better understand the climate and air pollution system.

The regional scale, meteorological and coupled air pollution models are available for the Pannonian region, for studying environmental processes beside daily practical tasks. The harmonisation of measurements, datasets and modelling of emission of cross-border transport and deposition processes are also potential joint research topics.

Seven research directions were formed during the preliminary phase of the PannEx Program (2015 November during the 1st PannEx workshop in Osiek Croatia) for better understanding the air quality in the Pannonian region under different weather and climate conditions. These are the following:

- How does a warmer climate affect air quality and human health?
- How do the changes of interactions affect air quality and the water cycle?
- How can we describe the interactions of environmental processes with agricultural practices (soil, water and air) in the changing climate?
- How can we optimise regional parameterisations of surface layer processes (energy budget, fluxes, deposition, profiles, etc.)?
- How can we improve forecasts by the investigation of the physics and chemistry of the boundary layer?
- How can we refine and harmonise the emission inventories for environmental modelling in the Pannonian region?
- How can we estimate the impact of population and urbanization on air quality and the local climate?

A regional consensus is needed for the harmonisation of the measurement and modelling practices, and in the implementation of regional research goals. Developing research cooperation can help with regional educational cooperation too, which could assist in the harmonisation of qualifications mainly in MSc and PhD schools. For this, the potential financing background is available (see *Appendix 1*). Research into the Pannonian region's climate system, and understanding the environmental status of the air is of widespread interest.

On the basis of the present material and discussions during the 2nd PannEx workshop (1–3 June 2016, Budapest), the final FQ2 chapter of the White Book consists of 5 basic topics:

- *How does a warmer climate affect air quality and human health?*
- *Interactions with agricultural practices (soil, water and air)*
- *Physics and chemistry of the surface and boundary layer; improving forecasts*
- *Refinement of emission inventories*
- *Perception of populations, urbanisation*

Appendix

I. Potential Financial backgrounds:

International:

- *CEEPUS* – Central European Exchange Program for University Studies (*ceepus.info/default.aspx*). The legal basis for CEEPUS is an international Agreement signed by the Member States and those open for accession. The main activities of CEEPUS are university networks operating joint programs.
- *COST* (*cost.eu*) is the longest-running European framework supporting transnational cooperation among researchers, engineers and scholars across Europe. The main goal of the cooperation is closing the gap between science, policy makers and society throughout Europe and beyond. One of the main topics of the program is environmental science and the low carbon economy.
- *DANUBE-INCO.NET* (*danube-inco.net/about/danubeinconet*) is a coordination and support action funded under the 7th Framework Programme and addresses the official EU Strategy for the Danube Region (EUSDR) in the field of research and innovation (R&I) with a wide variety of priority areas. SCOPES (Scientific cooperation between Eastern Europe and Switzerland) (*snf.ch/en/Pages/default.aspx*) will be discontinued at the end of the current programme phase (SCOPES 2013–2016). Other opportunities for collaboration with Eastern European research partners will be offered; however, the details have not yet been determined.
- *EEA and Norway Grants* (*ngonorway.org/*) are Iceland, Liechtenstein and Norway's contribution to reducing economic and social disparities in the European Economic Area and to the strengthening of bilateral relations with the 16 beneficiary states in central and southern Europe. Grants are available for non-governmental organisations, research and academic institutions and the public and private sectors.
- *Interreg, Danube Transnational Programme* (*interreg-danube.eu/approved-projects*). The cooperation programme is structured across four priority axes that intend to develop coordinated policies and actions in the programme area reinforcing the commitments of the Europe 2020 strategy towards the three dimensions of smart, sustainable and inclusive growth. More information from the Danube Strategy is available at: groupspaces.com/CapacityandCooperation/pages/steering-group
- *Interreg Europe* (*interregeurope.eu/*) supports interregional cooperation projects. These are projects that involve partner policy organisations from at least three different countries in Europe who come together for three-five years to learn from each other and to address a regional policy issue of common concern.
- *The International Visegrad Fund* (*visegradfund.org/home/*) is an international organization founded by the governments of the Visegrad Group (V4) countries (Czech Republic, Hungary, Republic of Poland, and Slovak Republic). One of the purposes of the fund is to facilitate and promote the development of closer cooperation among institutions in the region as well as between the V4 region and other countries, especially in the Western Balkan and Eastern Partnership regions in the areas of science and research, youth exchanges, cross-border cooperation.
- *The NATO Science for Peace and Security Programme* (*nato.int/cps/en/natolive/78209.htm*) The Science for Peace and Security (SPS) Programme is a policy tool that enhances

cooperation and dialogue with all partners, based on scientific research, innovation, and knowledge exchange. The SPS Programme provides funding, expert advice, and support to security-relevant activities jointly developed by NATO members and partner countries. One of the topics is Environmental Security.

- *The South East Europe Transnational Cooperation Programme* (*southeast-europe.net/en/*)
  The South East Europe programme is a unique instrument which, in the framework of the Regional Policy's Territorial Cooperation Objective, aims to improve integration and competitiveness in an area which is as complex as it is diverse.

National:

Information from National Scientific Foundations is presented on the website of the USA Scientific Fund (*nsf.gov/od/oise/europe/science_funding.jsp*). The actual addresses are follows:

- Austria – Austrian Science Fund (FWF) (*fwf.ac.at/en/research-funding/fwf-programmes/*)
- Croatia – Croatian science foundation (*hrzz.hr/default.aspx?id=47*)
- Czech Republic – Czech Science Foundation (GACR) (*gacr.cz/en/*)
  – Technology Agency of the Czech Republic (TACR) (*tacr.cz/index.php/en/)*
- Romania – National Research Council (*cncs-nrc.ro/home/*)
  – Executive Agency for Higher Education, Research, Development and Innovation Funding (UEFISCDI) (*uefiscdi.gov.ro/)*
- Hungary – National Research, Development and Innovation Fund (NKFIA *nkfih.gov.hu/funding*)
- Montenegro – Ministry of Science (*mna.gov.me/en/ministry*)
- Serbia – Ministry of Education, Science and Technological Development (*mpn.gov.rs/sajt/?page=1*)
- Slovakia – Slovak Research and Development Agency (SRDA) (*apvv.sk/agentura?lang=en*)
- Slovenia – Slovenian Science Foundation (SZF) (*eusea.info/Members/The-Slovenian-Science-Foundation*)
  – Slovenian Research Agency (ARRS) (*culture.si/en/Slovene_Research_Agency_%28ARRS%29*)
- The Former Yugoslav Republic of Macedonia – Ministry of Education and Science (*mon.gov.mk/)*
- Ukraine – State Fund for Fundamental Research (DFFD) (*dffd.gov.ua/index.php?lang=ua*)

II. List of abbreviations

ABRACOS	–	Anglo Brazilian Amazonian Climate Observational Study
ACCENT	–	Atmospheric Composition Change European Network of Excellence
AgMIP	–	Agricultural Model Intercomparison and Improvement Project
AirBase	–	European Air Quality Database
ALADIN	–	Aire Limitée Adaptation Dynamique Développement International
AQ	–	Air Quality
AQMEII	–	Air Quality Model Evaluation International Initiative
AROME	–	Application of Research to Operations at Mesoscale
AWC	–	Available water capacity
BC	–	Black carbon
Biome-BGC	–	Terrestrial Ecosystem Process Model
BOREAS	–	The Boreal Ecosystem-Atmosphere Study
BpArt	–	Budapest Platform for Aerosol Research and Training
BSc	–	Bachelor of Science
BSRN	–	Baseline Surface Radiation Network
BTEX	–	Is an acronym that stands for benzene, toluene, ethylbenzene, and xylenes
CC	–	Cross cutting
CAMx	–	Comprehensive Air Quality Model with Extensions
CarboEurope IP	–	Integrated Project, Assessment of the European Terrestrial Carbon Balance
CarpatClim	–	Climate of the Carpathian Region
CENTURY	–	a general model of plant-soil nutrient cycling which is being used to simulate carbon and nutrient dynamics for different types of ecosystems including grasslands, agricultural lands, forests and savannas
CEEPUS	–	Central European Exchange Program for University Studies
CFD	–	Computational Fluid Dynamics
CHIMERE	–	A multi-scale chemistry-transport model for atmospheric composition analysis and forecast
CLRTAP	–	Convention on Long-range Transboundary Air Pollution
CMAQ	–	Congestion Mitigation and Air Quality
CORINE	–	Coordination of Information on the Environment
COST	–	European Cooperation in Science and Technology
COST ES 1006	–	COST Action ES1006 Evaluation, improvement and guidance for the use of local-scale emergency prediction and response tools for airborne hazards in built environments
COUP	–	Coupled heat and mass transfer model for the soil-plant-atmosphere system
CTM	–	Chemical Transport Model
DNDC	–	DeNitrification DeComposition; a process-based model of greenhouse gas fluxes from agricultural soils
DIC	–	Dissolved organic carbon
ECCAD	–	Emissions of Atmospheric Compounds & Compilation of Ancillary Data
ECLAIRE (FP7)	–	Effects of Climate Change on Air Pollution and Response Strategies for European Ecosystems – is a four year project funded by the EU's Seventh Framework Programme for Research and Technological

		Development
ECMWF	–	European Centre for Medium-Range Weather Forecasts
EDGAR	–	The Emissions Database for Global Atmospheric Research
EDMF	–	Eddy diffusivity mass flux approach
EEA	–	European Environmental Agency
EEA	–	European Environmental Area
Eh	–	Soil redox potential (abbreviation)
ELTE	–	Eötvös Loránd University, Budapest
EMEP	–	European Monitoring and Evaluation Programme
EMEP4HR	–	High Resolution Environmental Modelling and Evaluation Programme for Croatia
ESDAC	–	European Soil Data Centre
ETC/ACM	–	European Topic Centre for Air Pollution and Climate Change Mitigation
EU	–	European Union
EUMETSAT	–	European Organization for the Exploitation of Meteorological Satellites
EUrad	–	European Air Pollution Dispersion Model in Medical & Science Rheinischen Institut für Umweltforschung (EURAD) an der Universität zu Köln
EUSDR	–	EU Strategy for the Danube Region
ETC/ACM	–	European Topic Centre for Air Pollution and Climate Change Mitigation
EWE	–	Energy water and environment
FAIRMODE	–	Forum for Air Quality Modelling
FASSET	–	Farm ASSEssment Tool (is a whole-farm dynamic model)
FLake	–	One-dimensional freshwater lake model
FLUXNET	–	Integrating Worldwide CO_2 Water and Energy Flux Measurements
FQ	–	Flagship Question
FVCOM	–	The Unstructured Grid Finite Volume Community Ocean Model
GAW	–	Global Atmosphere Watch
GCM	–	Global Circulation Model
Geos-Chem	–	A global 3-D chemical transport model (CTM) for atmospheric composition driven by meteorological input from the Goddard Earth Observing System
GEBA	–	Global Energy Balance Archive
GEIA	–	Global Emission InitiAtive
GEWEX	–	Global Energy and Water Exchanges Project
GFS	–	Global Forecast System
GHG	–	Greenhouse gases
GIS	–	Geographic Information System
GLOBE	–	The Global Learning and Observations to Benefit the Environment (GLOBE) Program
GOS	–	Global Observing System
Graminae	–	GRassland AMmonia INteractions Across Europe, funded by Fourth Framework Programme of European Community
GreenGrass	–	Sources and sinks of greenhouse gases from managed European grasslands and mitigation scenarios funded by Fifth Framework Programme of European Community
hazmat	–	hazardous material

HM	– Heavy metal
HMS	– Hungarian Meteorological Service
HORIZON2020	– The EU Framework Programme for Research and Innovation
IIASA	– International Institute for Applied Systems Analysis
ICE3	– Three-class ice parameterization
IE	– Intercomparison Exercise
IFS	– Integrated Forecasting System
IPC	– International Planning Committee
IPCC	– Intergovernmental Panel on Climate Change
LES	– Large Eddy Simulations
LOTOS-Euros	– Regional chemical transport model (CTM) designed for the assessment of gaseous and particulate air pollutants
LTER	– Long Term Ecological Research
MACC	– Monitoring Atmospheric Composition and Climate
Meso-NH	– Non-hydrostatic mesoscale atmospheric model of the French research community
MHSC	– Meteorological and Hydrological Service of Croatia
MSc	– Master of Sciences
NATO	– North Atlantic Treaty Organization
NEAA	– Netherlands Environmental Assessment Agency
NitroEurope IP (or NEU for short)	– is an integrated project for integrated European research into the nitrogen cycle
NMVOCs	– Non-methane volatile organic compounds
NWP	– Numerical Weather Prediction
OI	– Optimal Interpolation
OP	– Organic carbon
PAH	– Polycyclic aromatic hydrocarbon
PannEx	– Pannonian Experiment
PAR	– Photosynthetically Active Radiation
PaSim	– Process-based grassland biogeochemical model
PBL	– Planetary boundary layer
PM	– Particle matter
POPs	– Persistence organic pollutants
PRECIS	– Providing REgional Climates for Impacts Studies
PROGRASS	– Securing the conservation of NATURA grassland habitats with a distributed bioenergy production
RC-LACE	– Regional Cooperation for Limited Area Modelling in Central Europe
RegCM, RCM	– Regional Climate Model
RHP	– Regional Hydroclimate Project
RM	– Receptor model
SA	– Source Apportionment
SBL	– Stable-stratified boundary layer
SCOPES	– Scientific co-operation between Eastern Europe and Switzerland
SNAP	– Selected Nomenclature for Air Pollution
SOC	– Soil organic carbon
SPS	– Science for Peace and Security
SSR	– Solar Surface Radiation
SURFEX	– Surface Externalisée is the surface modelling platform developed by Meteo-France

STSMs	–	Short-Term Scientific Missions
SYNOP	–	Surface synoptic observations (is a numerical code called FM-12 by WMO)
SVAT	–	Soil-surface Vegetation Atmosphere Transport
TEMP	–	Abbreviation of Latin tempore (Radiosonde data report in our case)
TKE	–	Turbulent kinetic energy
TNO	–	Netherlands Organisation for Applied Scientific Research (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek)
TRACE	–	Climatological-type model for the long-range transport computations a continental scale from the International Institute for Applied Systems Analysis (IIASA)
UTC	–	Coordinated Universal Time
V4	–	Visegrad Group
VOCs	–	Volatile organic compounds
WB	–	White Book
WFPS	–	Water filled pore space
WHOS	–	World Hydrological Observing System
WMO	–	World Meteorological Organisation
WRDC	–	World Radiation Data Centre
WRCP	–	World Climate Research Programme
WRF	–	Weather Research and Forecasting
3D-VAR	–	Three-dimensional Variational Assimilation

6. References

General

Andreae, M., Jones, C., Cox, P., 2005: Strong present-day aerosol cooling implies a hot future. *Nature,* 435: 1187–1190.

Anderson, P.S., 2009: Interpretation of CO and PM Emissions Data from TLUD Gasifier Cookstoves. A presentation for the 2009 conference of ETHOS, Seattle-Kirkland, WA, 23–25. January 2009 http://www.drtlud.com/?resource=prt09199.

Baccini, M., Kosatsky, T., Analitis, A., Anderson, H. R., D'Ovidio, M., Menne, B., Michelozzi, P., Beggeri A., and the PHEWE Collaborative Group, 2011: Impact of heat on mortality in 15 European cities: attributable deaths under different weather scenarios. *Journal of Epidemiology and Community Health,* 65(1): 64–70.

Baklanov, A., 2000: Application of CFD methods for modelling in air pollution problems: possibilities and gaps. In: *Urban Air Quality: Measurement, Modelling and Management* (181–189), Springer Netherlands.

Baklanov, A., Schlünzen, K., Suppan, P., Baldasano, J., Brunner, D., Aksoyoglu, S., Carmichael, G., Douros, J., Flemming, J., Forkel, R., Galmarini, S., Gauss, M., Grell, G., Hirtl, M., Joffre, S., Jorba, O., Kaas, E., Kaasik, M., Kallos, G., Kong, X., Korsholm, U., Kurganskiy, A., Kushta, J., Lohmann, U., Mahura, A., Manders-Groot, A., Maurizi, A., Moussiopoulos, N., Rao, S. T., Savage, N., Seigneur, C., Sokhi, R. S., Solazzo, E., Solomos, S., Sørensen, B., Tsegas, G., Vignati, E., Vogel, B., Zhang, Y., 2014: Online coupled regional meteorology chemistry models in Europe: current status and prospects. *Atmospheric Chemistry and Physics*, 14: 317–398.

Beheydt, D., Boeckx, P., Sleutel, S., Li, C., van Cleemput, O., 2007: Validation of DNDC for 22 long-term N_2O field emission measurements. *Atmospheric Environment,* 41: 6196–6211.

Beier, C., Skiba, U., Sutton, M. A., 2010: Greenhouse gas exchange with European ecosystems and their interactions with nitrogen - results from NitroEurope IP. *European Journal of Soil Science,* 61: 627–630.

Benkovitz, C. M., Scholtz, M. T., Pacyna, J., Tarrasón, L., Dignon, J., Voldner, E. C., Spiro, P. A., Logan, J. A., Graedel, T. E., 1996: Global gridded inventories of anthropogenic emissions of sulfur and nitrogen. *Journal of Geophysical Research,* 101(D22): 29239–29253.

Bonan, G. B., 1996: A land surface model (LSM version 1.0) for ecological, hydrological, and atmospheric studies: Technical description and user's guide. NCAR Tech. Note NCAR/TN-417+STR, 150 pp.

Bossard, M., Feranec, J., Otahel, J., 2000: CORINE land cover technical guide – Addendum 2000, Technical Report No. 40, Copenhagen: European Environment Agency.

CEIP, 2013: Officially reported emission data. (ceip.at/webdab_emepdatabase/reported_emissiondata).

Crippa, M., Janssens-Maenhout, G., Dentener, F., Guizzardi, D., Sindelarova, K., Muntean, M., Van Dingenen, R., Granier, C., 2016: Forty years of improvements in European air quality: regional policy-industry interactions with global impacts. *Atmospheric Chemistry and Physics,* 16: 3825–3841, doi:10.5194/acp-16-3825-2016.

Cuxart, J., Bougeault, P., Redelsberger, J.-L., 2000: A turbulence scheme allowing for mesoscale and large-eddy simulations. Quarterly Journal of Royal Meteorological Society 126, 1–30.

Cuxart, J., Weidinger, T., Wrenger, B., Matjacic, B., Simó, G., Martinez-Villagrasa, D., Bordas, Á., Tordai, Á., Torma, P., Nagy, Z., 2016: Nocturnal surface thermal inversions in the Pannonian Basin. *EMS2016-334*.

Dickinson, R. E., Shaikh, M., Bryant, R., Graumlich, L., 1998: Interactive canopies for a climate model. *Journal of Climate,* 11: 2823–2836.

Dolman, A., Noilhan, J., Durand, P., Sarrat, C., Brut, A., Piguet, B., Butet, A., Jarosz, N., Brunet, Y., Loustau, D., Lamaud, E., Tolk, L., Ronda, R., Miglietta, F., Gioli, B., Magliulo, V., Esposito, M., Gerbig, C., Korner, S., Glademard, O., Ramonet, M., Ciais, P., Neininger, B., Hutjes, R., Elbers, J., Macatangay, R., Schrems, O., Perez-Landa, G., Sanz, M., Scholz, Y., Facon, G., Ceschia, E., Beziat, P., 2006: The CarboEurope regional experiment strategy. *Bulletin of the American Meteorological Society*, BAMS 87(10): 1367–1379.

Durand, P., Breuer, L., Johnes, P. J., Billen, G., Butturini, A., Pinay, G., van Grinsven, H., Garnier, J., Rivett, M., Reay, D. S., Curtis, C., Siemens, J., Maberly, S., Kaste, O., Humborg, C., Loeb, R., de Klein, J., Hejzlar, J., Skoulikidis, N., Kortelainen, P., Lepisto, A., Wright, R., 2011: Nitrogen processes in aquatic ecosystems. In (Eds. Sutton, M. A., Howard, C. M., Erisman, J. W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., Grizzetti, B.) The European Nitrogen Assessment. Cambridge University Press, Cambridge, U.K., 126–146.

EEA (European Environment Agency) 2004: Impacts of Europe's changing climate. An indicator-based assessment. Luxembourg, Office for Official Publications of the European Communities, 107 p.

EEA (European Environment Agency) 2005: The European environment – State and outlook 2005. Copenhagen.

EEA (European Environment Agency) 2015 Air quality in Europe – 2015 report. Report No 5/2015.

European Air Quality Directive 2008/50/EC, 11.6.2008 EN Official Journal of the European Union, L 152/1, 44 p.

Gash, J. H. C., Nobre, C. A., 1997: Climatic effects of Amazonian deforestation: Some results from ABRACOS. *Bulletin of the American Meteorological Society*, BAMS 78: 823–830.

Giltrap, D. L., Li, C, Saggar, S., 2010: DNDC: A process-based model of greenhouse gas fluxes from agricultural soils. Estimation of nitrous oxide emission from ecosystems and its mitigation technologies. *Agriculture, Ecosystems and Environment*, 136(3–4): 292–300.

Giltrap, D, Ausseil, A. G., Thakur, K., Saggar, S., 2011: A framework to estimate nitrous oxide emissions at regional and national scale. Adding to the knowledge base for the nutrient manager. (flrc.massey.ac.nz/workshops/11/Manuscripts/Giltrap_2_2011.pdf)

Kaimal, J. C., Finnigan, J. J., 1994: Atmospheric Boundary Layer Flows: Their Structure and Measurement. Oxford University Press, 304 pp.

Grell, G., Baklanov, A., 2011: Integrated modeling for forecasting weather and air quality: A call for fully coupled approaches. *Atmospheric Environment,* 45(38): 6845–6851.

Harrison, R. M., Jones, M. R., Collins, G., 1999: Measurements of the physical properties of particles in the urban atmosphere. *Atmospheric Environment,* 33: 309–321.

Hussen, A., 2005: Principles of Environmental Economics. Economics, ecology and public policy. Taylor & Francis e-Library, 383 pp.

Jacob, D. J., Winner, D. A., 2009: Effect of climate change on air quality. *Atmospheric Environment,* 43: 51–63.

Jerez, S., Tobin, I., Vautard, R., Montávez, J. P., López-Romero, J. M., Thais, F., Bartok, B., Christensen, O. B., Colette, A., Déqué, M., Nikulin, G., Kotlarski, S., van Meijgaard, E., Teichmann, C., Wild, M., 2015: The impact of climate change on photovoltaic power generation in Europe. *Nature Communications*, 6. Article number: 10014, doi:10.1038/ncomms10014.

Jiang, Y., Liu, X., Yang, X.-Q., Wang, M., 2013: A numerical study of the effect of different aerosol types on East Asian summer clouds and precipitation. *Atmospheric Environment,* 70: 51–63.

Kinney, P. L., 2008: Climate Change, Air Quality, and Human Health. *American Journal of Preventive Medicine,* 35: 459–466.

Kong, X., Forkel, R., Sokhi, R. S., Suppan, P., Baklanov, A., Gauss, M., Brunner, D., Bar, R., Balzarini, A., Chemel, C., Curci, G., Jimenez-Guerrero, P., Hirtl, M., Honzak, L., Im, U., Perez, J. L., Pirovano, G., San Jose, R., Schlünzen, K. H., Tsegas, G., Tuccella, P., Werhahn, J., Zabkar, R., Galmarini, S., 2015: Analysis of meteorology–chemistry interactions during air pollution episodes using online coupled models within AQMEII phase-2. *Atmospheric Environment,* 115: 527–540.

Kukkonen, J., Olsson, T., Schultz, D. M., Baklanov, A., Klein, T., Miranda, A. I., Monteiro, A., Hirtl, M., Tarvainen, V., Boy, M., Peuch, V.-H., Poupkou, A., Kioutsioukis, I., Finardi, S., Sofiev, M., Sokhi, R., Lehtinen, K. E. J., Karatzas, K., San Jose, R., Astitha, M., Kallos, G., Schaap, M., Reimer, E., Jakobs, H., Eben, K., 2012: A review of operational, regional-scale, chemical weather forecasting models in Europe. *Atmospheric Chemistry and Physics,* 12: 1–87.

Lafore, J.-P., Stein, J., Asencio, N., Bougeault, P., Ducrocq, V., Duron, J., Fischer, C., Héreil, P., Mascart, P., Masson, V., Pinty, J. P., Redelsperger, J. L., Richard, E., Vilà-Guerau de Arellano J., 1998: The Meso-NH atmospheric simulation system. Part I: Adiabatic formulation and control simulations. *Annales Geophysicae,* 16: 90–109.

Law, K., 2010: Combined policies for better tackling of climate change and air pollution. Science for Environment Policy. *Air Pollution and Climate Change. Special Issue,* 24: 1–3.
Lefohn, A. S., Husar, J. D., Husar, R. B., 1999: Estimating historical anthropogenic global sulfur emission patterns for the period 1850–1990. *Atmospheric Environment,* 33: 3435–3444.
Le Moigne, P., 2012: SURFEX scientific documentation. Note de centre du Groupe de Météorologie a Moyenne Echelle, 87, Météo-France, CNRM, Toulouse, France, on-line available at: cnrm.meteo.fr/surfex/
Leip, A., Marchi, G., Koeble, R., Kempen, M., Britz, W., Li, C., 2008: Linking an economic model for European agriculture with a mechanistic model to estimate nitrogen and carbon losses from arable soils in Europe. *Biogeosciences,* 5: 73–94.
Li, C., 2000: Modeling trace gas emissions from agricultural ecosystems. *Nutrient Cycling in Agroecosystems,* 58: 259–276.
Li, C., Aber, J., Stange, F., Butterbach-Bahl, K., Papen, H., 2000: A process-oriented model of N_2O and NO emissions from forest soils: 1. Model development. *Journal of Geophysical Research* 105(D4), 4369–4384.
Liu, L., Solmon, F., Vautard, R., Hamaoui-Laguel, L., Torma, Cs. Zs., Giorgi, F., 2016: Ragweed pollen production and dispersion modelling within a regional climate system, calibration and application over Europe. *Biogeosciences*, 13: 2769–2786.
Luyssaert, S., Inglima, I., Jung, M., 2009: Global Forest Ecosystem Structure and Function Data for Carbon Balance Research. Data set. Available on-line [http://daac.ornl.gov/] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A.
Ma, N., Zhang, Y. S., Xu, C. Y., Szilagyi, J., 2015: Modeling actual evapotranspiration with routine meteorological variables in the data-scarce region of the Tibetan Plateau: Comparisons and implications. *Journal of Geophysical Research Biogeosciences,* 120: 1638–1657.
Moore, K. E., Fitzjarrald, D. R., Sakai, R. K., 1996: Seasonal variation in radiative and turbulent exchange at a deciduous forest in Central Massachusetts. *Journal of Applied Meteorology,* 35: 122–134.
Muhlbauer, A., Hashino, T., Xue, L., Teller, A., Lohmann, U., Rasmussen, R. M., Geresdi, I., Pan, Z., 2012: Intercomparison of aerosol-cloud-precipitation interactions in stratiform orographic mixed-phase clouds. *Atmospheric Chemistry and Physics,* 10(17): 8173–8196.
Neemann, E. M., Crosman, E. T., Horel, J. D., Avey, L., 2015: Simulations of a cold-air pool associated with elevated wintertime ozone in the Uintah Basin, Utah. Atmospheric Chemistry and Physics 15, 135–151.
Pergaud, J., Masson, V., Malardel, S., Couvreux, F., 2009: A parameterization of dry thermals and shallow cumuli for mesoscale numerical weather prediction. *Boundary-Layer Meteorology,* 132: 83–106.
Peters, U., Poole, C., Arab, L., 2001: Does tea affect cardiovascular disease? A meta-analysis. *American Journal of Epidemiology*, 154: 495–503.
Peterson, T. C. (corresponding Editor), 2012: Explaining Extreme Events of 2011 from a Climate Perspective. *Bulletin of American the Meteorological Society* BAMS, 1041–1067.
Pinty, J.-P., Jabouille, P., 1998: A mixed-phased cloud parameterization for use in a mesoscale non-hydrostatic model: Simulations of a squall line and of orographic precipitation. Preprints, Conference on Cloud Physics, Everett, WA, American Meteorological Society, 217–220.
Pope, C. A. III, Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K., Thurston, G. D., 2002: Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *The Journal of the American Medical Association* JAMA 287(9): 1132–1141.
Putaud, J. P., Raes, F., Van Dingenen, R., Baltensperger, J. P. U., Brüggemann, E., Facchini, M. C., Decesari, S., Fuzzi, S., Gehrig, R., Hansson, H. C., Hüglin, C., Laj, P., Lorbeer, G., Maenhaut, W., Mihalopoulos, N., Müller, K., Querol, X., Rodriguez, S., Schneider, J., Spindler, G., Brink, H., Tørseth, K., Wehner, B., Wiedensohler, A., 2004: A European aerosol phenomenology – 2: Chemical characteristics of particulate matter at kerbside, urban, rural and background sites in Europe. *Atmospheric Environment*, 38: 2579–2595.
Putaud, J.-P., Van Dingenen, R., Alastuey, A., Bauer, H., Birmili, W., Cyrys, J., Flentje, H., Fuzzi, S., Gehrig, R., Hansson, H. C., Harrison, R. M., Herrmann, H., Hitzenberger, R., Hüglin, C., Jones, A. M., Kasper-Giebl, A., Kiss, G., Kousa, A., Kuhlbusch, T. A. J., Löschau, G., Maenhaut, W., Molnar,

A., Moreno, T., Pekkanen, J., Perrino, C., Pitz, M., Puxbaum, H., Querol, X., Rodriguez, S., Salma, I., Schwarz, J., Smolik, J., Schneider, J., Spindler, G., ten Brink, H., Tursic, J., Viana, M., Wiedensohler, A., 2010: A European aerosol phenomenology – 3: Physical and chemical characteristics of particulate matter from 60 rural, urban, and kerbside sites across Europe. *Atmospheric Environment*, 44(10): 1308–1320.

Querol, X., Alastuey, A., Ruiz, C. R., Artiñano, B., Hansson, H. C., Harrison, R. M., Buringh, E., Ten Brink, H. M., Lutz, M., Bruckmann, P., Straeh, P., Schneider, J., 2004: Speciation and origin of PM_{10} and $PM_{2.5}$ in selected European cities. *Atmospheric Environment,* 38: 6547–6555.

Rees, R. M., Agustin, J., Alberti., G., Ball, B. C., Boeckx, P., Cantarel, A., Castaldi, S., Chirinda, N., Chojnicki, B., Giebels, M., Gordon, H., Grosz, B., Horvath, L., Juszczak, R., Klemedtsson, Å., Klemedtsson, L., Medinets, S., Machon, A., Mapanda, F., Nyamangara, J., Olesen, J., Reay, D., Sanchez, L., Sanz Cobena, A., Smith, K. A., Sowerby, A., Sommer, M., Soussana, J. F., Stenberg, M., Topp, C. F. E., van Cleemput, O., Vallejo, A., Watson C. A., Wuta, M., 2013: Nitrous oxide emissions from European agriculture; an analysis of variability and drivers of emissions from field experiments. *Biogeosciences,* 10: 2671–2682.

Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C., Boote, K. J., Thorburn, P., Antle, J. M., Nelson, G. C., Porter, C., Janssen, S., Asseng, S., Basso, B., Ewert, F., Wallach, D., Baigorrial, G., Winter, J. M., 2013: The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. *Agricultural and Forest Meteorology,* 170: 166–182.

Samoli, E., Analitis, A., Touloumi, G., Schwartz, J., Anderson, H. R., Sunyer, J., Bisanti, L., Zmirou, D., Vonk, J. M., Pekkanen, J., Goodman, P., Paldy, A., Schindler, C., Katsouyanni, K., 2005: Estimating the Exposure–Response Relationships between Particulate Matter and Mortality within the APHEA Multicity Project. *Environmental Health Perspectives,* 113: 88–95.

Samet, J. M., Zeger, S. L., Dominici, F., Curriero, F., Coursac, I., Dockery, D. W., Schwartz, J., Zanobetti, A., 2000: The National Morbidity, Mortality, and Air Pollution Study. Part II: Morbidity and mortality from air pollution in the United States. Cambridge, MA, Research Report of Health Effects Institute 94 (Pt 2), 5–70; discussion 71–96.

Seity, Y., Brousseau, P., Malardel, S., Hello, G., Bénard, P., Bouttier, F., Lac, C., and Masson, V., 2011: The AROME-France Convective-Scale Operational Model. *Monthly Weather Review,* 139: 976–991.

Sellers, P. J., Mintz, Y., Sud, Y. C., Dalcher, A., 1986: A simple biospherical model (SiB) for use in general circulation models. *Journal of Atmospheric Sciences,* 43: 505–531.

Sellers, P., Hall, F., Ranson, K. J., Margolis, H., Kelly, B., Baldocchi, D., den Hartog, G., Cihlar, J., Ryan, M. G., Goodison, B., Crill, P., Lettenmaier, D., Wickland, D. E., 1995: The Boreal Ecosystem-Atmosphere Study (BOREAS): An overview and early results from the 1994 field year. *Bulletin of the American Meteorological Society,* BAMS 76: 1549–1577.

Simpson, D., Benedictow, A., Berge, H., Bergström, R., Emberson, L. D., Fagerli, H., Flechard, C. R., Hayman, G. D., Gauss, M., Jonson, J. E., Jenkin, M. E., Nyíri, A., Richter, C., Semeena, V. S., Tsyro, S., Tuovinen, J.-P., Valdebenito, Á., Wind, P., 2012: The EMEP MSC-W chemical transport model – technical description. *Atmospheric Chemistry and Physics,* 12: 7825–7865.

Smith, W. N., Grant, B. B., Desjardins, R. L., Worth, D., Li, C., Boles, S. H., Huffmann, E. C., 2010: A tool to link agricultural activity data with the DNDC model to estimate GHG emissions factors in Canada. Agriculture. *Ecosystems & Environment,* 136: 301–309.

Soares, P. M. M., Miranda, P. M. A., Siebesma, A. P., Teixeira, J., 2004: An eddy-diffusivity/mass-flux parameterization for dry and shallow cumulus convection. *Quarterly Journal of Royal Meteorological Society*, 130: 3365–3384.

Sofiev, M., Berger, U., Prank, M., Vira, J., Arteta, J., Belmonte, J., Bergmann, K.-C., Chéroux, F., Elbern, H., Friese, E., Galan, C., Gehrig, R., Khvorostyanov, D., Kranenburg, R., Kumar, U., Marécal, V., Meleux, F., Menut, L., Pessi, A.-M., Robertson, L., Ritenberga, O., Rodinkova, V., Saarto, A., Segers, A., Severova, E., Sauliene, I., Siljamo, P., Steensen, B. M., Teinemaa, E., Thibaudon, M., Peuch, V.-H., 2015: MACC regional multi-model ensemble simulations of birch pollen dispersion in Europe. *Atmospheric Chemistry and Physics*. doi:10.5194/acp-15-8115-2015.

Srivastava, A., Rao, B. P. S., 2011: Urban Air Pollution Modeling, Air Quality-Models and Applications. Popovic, D. (Ed.), ISBN: 978-953-307-307-1, InTech, Available from: (intechopen.com/books/air-quality-models-and-applications/urban-air-pollution-modeling).

Sutton, M. A., Howard, C. M., Erisman, J. W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., Grizzetti, B., 2011: The European Nitrogen Assessment: Sources, Effects and Policy Perspectives. Cambridge University Press, p. 664.

Sutton, M. A., Howard, C. M., Nemitz, E., Arneth, A., Simpson, D., Mills, G., de Vries, W., Winiwarter, W., Amann, M. (coordinating lead authors), 2015: Effects of Climate Change on Air Pollution Impacts and Response Strategies for European Ecosystems. Final Report. Project Number 282910, ÉCLAIRE: Effects of Climate Change on Air Pollution Impacts and Response Strategies for European Ecosystems, Seventh Framework Programme, Theme: Environment Project Final Report (nora.nerc.ac.uk/513099/).

Tagaris, E., Liao, K.-J., DeLucia, A. J., Deck, L., Amar, P., Russell, A. G., 2009: Potential impact of climate change on air pollution-related human health effects. *Environmental Science and Technology,* 43(13): 4979–4988.

Thompson, R. D., 1998: Atmospheric Processes and Systems. Routledge, London and New York, 184 pp.

Thunis, P., Miranda, A., Baldasano, J. M., Blond, N., Douros, J., Graff, A., Janssen, S., Juda-Rezler, K., Karvosenoja, N., Maffeis, G., Martilli, A., Rasoloharimahefa, M., Real, E., Viaene, P., Volta, M., White, L., 2016a: Overview of current regional and local scale air quality modelling practices: Assessment and planning tools in the EU. *Environmental Science & Policy.* http://dx.doi.org/10.1016/j.envsci.2016.03.013

Thunis, P., Degraeuwe, B., Cuvelier, K., Guevara, M., Tarrason, L., Clappier, A., 2016b: A novel approach to screen and compare emission inventories. *Air Quality and Atmospheric Health*, DOI 10.1007/s11869-016-0402-7.

Viana, M., Pandolfi, M., Minguillo, M. C., Querol, X., Alastuey, A., Monfort, E., Celades, I., 2008: Inter-comparison of receptor models for PM source apportionment: Case study in an industrial area. *Atmospheric Environment,* 42: 3820–3832.

Walls, M., 2006: SCAR Foresight Group Agriculture and Environment. SCAR Foresight Group. Standing Committee on Agricultural Research (SCAR), p 22. (ec.europa.eu/research/scar/index.cfm?pg=home)

Zappa, G., Hawcroft, M. K., Shaffrey, L., Black, E., Brayshaw, D. J., 2015: Extratropical cyclones and the projected decline of winter Mediterranean precipitation in the CMIP5 models. *Climate Dynamics,* 45(7–8): 1727–1738.

From the Pannonian Basin and surrounding

Amann, M. (ed.), 2012: EC4MACS Modelling Methodology The GAINS Integrated Assessment Model. European Consortium for Modelling of Air Pollution and Climate Strategies – EC4MACS, IIASA, 44p.

Balczo, M., Balogh, M., Goricsan, I., Nagel, T., Suda, J., Lajos, T., 2011: Air quality around motorway tunnels in complex terrain – computational fluid dynamics modeling and comparison to wind tunnel data. *Időjárás,* 115: 179–204.

Barcza, Z., Haszpra, L., Somogyi, Z., Hidy, D., Lovas, K., Churkina, G., Horváth, L., 2009: Estimation of the biospheric carbon dioxide balance of Hungary using the BIOME-BGC model. *Időjárás*, 113: 203–219.

Bartholy, J., Pongrácz, R., Torma, Cs., Pieczka, I., Kardos, P., Hunyady, A., 2009: Analysis of regional climate change modelling experiments for the Carpathian Basin. *International Journal of Global Warming,* 1(1–3): 238–252.

Bartok, B., 2010: Changes in solar energy availability for south-eastern Europe with respect to global warming. *Physics and Chemistry of the Earth Parts A/B/C*, 35(1–2): 63–69.

Baumann-Stanzer, K., Langer, M., Krüger, B. C., 2015: A new ozone prediction system using operational ALADIN data. Central Institute for Meteorology and Geodynamics (ZAMG), Vienna, Austria. (zamg.ac.at/docs/forschung/umweltmeteorologie/11_Harmonisation.pdf).

Bottyán, E., 2015: Source regions for Hungarian precipitation events. MSc Thesis Eötvös University Budapest (In Hung.)

Bottyán, E., Czuppon, Gy., Weidinger, T., Haszpra, L., Kármán, K., 2017: Moisture source diagnostics and isotope characteristics for precipitation in east Hungary: implications for their relationship. *Hydrological Sciences Journal – Journal des Sciences Hydrologiques*. doi.org/10.1080/02626667.2017.1358450

Bozó, L., 2005a: Modelling studies on the concentration and deposition of air pollutants in East-Central Europe. Advances in Air Pollution Modeling for Environmental Security. (Editors: Faragó, I., Georgiev, K., Havasi, Á.) *NATO Sciences Series. IV. Earth and Environmental Sciences*, 54: 33–40.

Bozó, L., 2005b: Assessment of air quality and atmospheric deposition in Hungary. *WIT Transactionson Ecology and the Environment,* 82: 187–193. www.witpress.com, ISSN 1743-3541 (on-line)

Bubnová, R., Hello, G., Benard, P., Geleyn, J. F., 1995: Integration of the fully elastic equations cast in the hydrostatic pressure terrain-following coordinate in the framework of the ARPEGE/Aladin NWP system. *Monthly Weather Review,* 123: 515–535.

Cherenkova, E. A., Semenova, I. G., Kononova, N. K., Titkova, T. B., 2015: Droughts and dynamics of synoptic processes in the south of the East European Plain at the beginning of the twenty-first century. *Arid Ecosystems,* V.5, I.2.: 45–56.

Cindrić, K., Pasarić, Z., Gajić-Čapka, M., 2010: Spatial and temporal analysis of dry spells in Croatia. *Theoretical and Applied Climatology,* 102(1–2): 171–184.

Czóbel, S., Horváth, L., Szirmai, O., Balogh, J., Pintér, K., Németh, Z., Ürmös, Zs., Grosz, B., Tuba, Z., 2010: Comparison of N_2O and CH_4 fluxes from Pannonian natural ecosystems. *European Journal of Soil Science, Special Issue: Nitrogen and greenhouse gas exchange,* 61(5): 671–682.

Ferenczi, Z., 2013: Predictability analysis of the $PM_{2.5}$ and PM_{10} concentration in Budapest. *Időjárás*, 117(4): 359–375.

Gaál, M., Quiroga, S., Fernandez-Haddad, Z., 2014: Potential impacts of climate change on agricultural land use suitability of the Hungarian counties. *Regional Environmental Change,* 14(2): 597–610.

Gelencsér, A., 2005: Carbonaceous aerosol. Atmospheric and Oceanographic Science Library 30, Springer Science & Business Media, 347 p.

Grosz, B., Horváth, L., Gyöngyösi, A. Z., Weidinger, T., Pintér, K., Nagy, Z., André, K., 2015: Use of WRF result as meteorological input to DNDC model for greenhouse gas flux simulation. *Atmospheric Environment,* 122: 230–235.

Haszpra, L. (editor), 2011: Atmospheric Greenhouse Gases: The Hungarian Perspective. Springer Science & Business Media, 387 pp.

Hidy, D., Horváth, L., Weidinger, T., 2015: Evaluation and gap filling of soil NO flux dataset measured at a Hungarian semi-arid grassland. *Időjárás*, 119(1): 23–37.

Horváth, Á., Kerényi, J., Lakatos, M., Nagy, A., Németh, Á., Szenyán, I., 2012: Meteorological background of extremely heavy drought situation in Hungary in 2012. Hungarian Meteorological Service. (In Hung) met.hu/ismeret-tar/erdekessegek_tanulmanyok/index.php?id=379&hir=A_2012-es_rendkivuli_aszaly_meteorologiai_hattere

Horváth, Z., Liszkai, B., Istenes, Gy., Zsebők, P., Szintai, B., Rácz, É. V. P., Környei, L., Harmati, I., 2016: Integrated urban air pollution dispersion modelling framework and application in air quality prediction of the city of Győr. Proceedings of the 17th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes.

Horvath, K., Lin, Y.-L., Ivančan-Picek, B., 2008. Classification of cyclone tracks over Apennines and the Adriatic Sea. *Monthly Weather Review,* 136: 2210–2227.

Ivančan-Picek, B., Horvath, K., Ivatek-Šahdan, S., Tudor, M., Bajić, A., Stiperski, I., Stanešić, A., 2011: Operational and research numerical weather prediction applications in the Meteorological and Hydrological Service of Croatia. MIPRO, 2011 Proceedings of the 34th International Convention.

Jeričević, A., Kraljević, L., Vidič, S., Tarrason, L., 2007: Project description: High resolution environmental modelling and evaluation programme for Croatia (EMEP4HR). *Geofizika,* 24: 137–143.

Jeričević, A., Kraljević, L., Grisogono, B., Fagerli, H., Večenaj, Ž., 2010: Parameterization of vertical diffusion and the atmospheric boundary layer height determination in the EMEP model. *Atmospheric Chemistry and Physics*, 10: 341–364.

Jeričević, A., Ilyin, I. and Vidič, S., 2012. Modelling of heavy metals: study of impacts due to climate change. In *National security and human health implications of climate change* (pp. 175–189). Springer Netherlands.

Jeričević, A., Džaja, G. V., Telišman, P. M., Vidič, S., Bloemen, H., 2016: Analyses of urban and rural particulate matter mass concentrations in Croatia in the period 2006–2014. *Geofizika*, 33 (0352-3659).

Juda-Rezler, K., Reizer, M., Oudinet, J. P., 2011: Determination and Analysis of PM_{10} Source Apportionment during Episodes of Air Pollution in Central Eastern European Urban Areas: The Case of Wintertime 2006. *Atmospheric Environment*, 45: 6557–6566.

Juda-Rezler, K., Reizer, M., Huszar, P., Krüger, B., Zanis, P., Syrakov, D., Katragkou, E., Trapp, W., Melas, D., Chervenkov, H., Tegoulias, I., Halenka, T., 2012: Modelling the effects of climate change on air quality over Central and Eastern Europe: concept, evaluation and projections. *Climate Research,* 53: 179–203.

Jurković P., M., Mahović, N., S., Počakal, D. E., 2015: Lightning, overshooting top and hail characteristics for strong convective storms in Central Europe. *Atmospheric Research,* 161–162: 153–168.

Kelemen, F. D., 2016: Dynamical analyses and sensitivity studies of regional climate model results. *Ph.D dissertation.* Eötvös Lorand University, Budapest, 105 p.

Kovács, A. J., Nyéki, A., Milics, G., Neményi, M., 2014: Climate change and sustainable precision crop production with regard to maize (Zea mays L.). International Conference on Precision Agriculture. Sacramento, CA, USA.

Kovács, A., Mészáros, R., Leelőssy, Á., Lagzi, I., 2016: Air pollution modeling in urban environment using WRF-Chem model. Proceedings of the 17th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes.

Kraljević, L., Belušić, D., Bencetić Klaić, Z., Bennedictow, A., Fagerli, H., Grisogono, B., Jeričević, A., Mihajlović, D., Špoler Čanić, K., Tarrasón, L., Valiyaveetil, S., Vešligaj, D., Vidič, S., 2008: Application of EMEP Unified model on regional scale – EMEP4HR. Croatian Meteorological

Journal 43, Proceedings from a 12 HARMO conference Part 1: Oral Presentations, /Đuričić, Vesna (Ed.), Zagreb. harmo.org/Conferences/Proceedings/Cavtat/topicIndex.asp?topicID=0.
Kiss, M., Józsa, J., 2015: Wind profile and shear stress at reed-open water interface: recent research achievements in Lake Fertő. Pollack *Periodica: An International Journal for Engineering and Information Sciences*, 10(2): 107–122.
Krámer, T., Józsa, J., Torma, P., 2012: Large-scale mixing of water imported into a shallow lake. In: 3rd International Symposium on Shallow Flows. Iowa, USA, pp. 354–357.
Kugler, Sz., Horváth, L., Weidinger, T., 2014: Modeling dry flux of ammonia and nitric acid between the atmosphere and Lake Balaton. *Időjárás*, 118(2): 93–118.
Lalić, B., Eitzinger, J., Thaler, S., Vučetić, V., Nejedlik, P., Eckersten, H., Jaćimović, G., Nikolić-Djorić, E., 2014: Can Agrometeorological Indices of Adverse Weather Conditions Help to Improve Yield Prediction by Crop Models? *Atmosphere*, 5: 1020–1041.
Lázár, D., Weidinger, T., 2016: CMAQ (Community Multi-Scale Air Quality) atmospheric dispersion model adaptation for Hungary (H17-126), 17'HARMO, Hungarian Meteorological Service, Budapest, 9–2 May 2016.
Machon, A., Horváth, L., Weidinger, T., Pintér, K., Grosz, B., Nagy, Z., Führer, E., 2011: Weather induced variability of N-exchange between the atmosphere and a grassland in the Hungarian Great Plain. *Időjárás,* 4: 219–232.
Machon, A., Horváth, L., Weidinger, T., Grosz, B., Móring, A., Führer, E., 2015: Measurement and modeling of N-balance between atmosphere and biosphere over a grazed grassland (Bugacpuszta) in Hungary. *Water, Air, & Soil Pollution,* 126(3): Article 27.
Major, Gy., Nagy, Z., Tóth, Z., 2002: Climatological energy budget for Hungary. – Hungarian climate-energy Studies, Institute of Environment, Economical University of Budapest (In Hungarian).
Makra, L., Matyasovszky, I., Hufnágel, L., Tusnády, G., 2015: The history of ragweed in the world. *Applied Ecology and Environmental Research,* 13(2): 489–512.
Matyasovszky, I., Makra, L., Guba, Z., Pátkai, Z., Páldy, A., Sümeghy, Z., 2011: Estimating the daily Poaceae pollen concentration in Hungary by linear regression conditioning on weather types. *Grana*, 50: 208–216.
Micu, D. M., Dumitrescu, A., Marius, S. C., Birsan, V., 2015: Climate of the Romanian Carpathians: Variability and Trends. Springer Meteorology, Environmental Science, Climatology. ISBN-10: 3319028855, p. 213.
Mika, J., 2013: Atmosphere as risk and resource. e-book: tankonyvtar.hu/hu/tartalom/tamop412A/2011-0038_33_mika_en/ar01s02.html.
Mika, J., Razsi, A., Wypych, A., Ustrnul, Y., 2013: Objective weather classification for environmental applications. Editors: Šiška, B., Nejedlik, P., Hájková, L., Kožnarová, V.: Environmental changes and adaptation strategies. International Scientific Conference Environmental Changes and Adaptation Strategies, 9th – 11th September 2013, Skalica, Slovakia. cbks.cz/SbornikSkalice2013/pdf/Mika.pdf, ISBN 978-80-552-1066-7
Mikuš, P., Bedka, K., Strelec Mahović, N., 2011: Comparison and validation of satellite-based overshooting top detection methods. Proceedings – 6th European Conference on Severe Storms (ECSS 2011), Palma de Mallorca, Spain, 03–07 October 2011.
Mikuš, P., Telišman Prtenjak, M., Strelec Mahović, N., 2012: Analysis of the convective activity and its synoptic background over Croatia. *Atmospheric Research,* 104–105: 139–153.
Mile, M., Bölöni, G., Randriamampianina, R., Steib, R., Kucukkaraca, E., 2015: Overview of mesoscale data assimilation developments at the Hungarian Meteorological Service. *Időjárás,* 119(2): 215–239.
Molnár, A., Mészáros, E., Imre, K., Rüll, A., 2008: Trends in visibility over Hungary between 1996 and 2002. *Atmospheric Environment,* 42: 2621–2629.
Móring, A., Horváth, L., 2014: Long-term trend of deposition of atmospheric sulfur and nitrogen compounds in Hungary. *Időjárás,* 118(2): 167–191.
Németh, Z., Salma, I., 2014: Spatial extension of nucleating air masses in the Carpathian Basin. *Atmospheric Chemistry and Physics,* 14: 8841–8848.
Páldy, A., Bobvos, J., Vámos, A., Kovats, R. S., Hajat, S., 2005: The effect of temperature and heat waves on daily mortality in Budapest, Hungary, 1970–2000. "Extreme weather events and Public Health Responses" eds. Kirch, W., Menne, B., Publisher: Springer Verlag, 99–107.

Philipp, A., Bartholy, J., Beck, C., Erpicum, M., Esteban, P., Fettweis, X., Huth, R., James, P., Jourdain, S., Kreienkamp, F., Krennert, T., Lykoudis, S., Michalides, S. C., Pianko-Kluczynska, K., Post, P., Alvarez, D. R., Schiemann, R., Spekat, A., Tymvios, F. S., 2010: Cost733cat: a database of weather and circulation type classifications. *Physics and Chemistry of the Earth,* 35(9–12): 360–373.

Pongrácz, R., Bartholy, J., Bartha, E. B., Törék, O., Pieczka, I., Torma, P., 2011: Projected Changes of Regional Heat Waves in Central/Eastern Europe Using Climate Model Simulations. 91st American Meteorological Society Annual Meeting, 161–167.

Pongrácz, R., Bartholy, J., Bartha, E. B., 2013: Analysis of projected changes in the occurrence of heat waves in Hungary. *Advances in Geosciences,* 35: 115–122.

Prtenjak, M. T., Srnec, L., Peternel, R., Madzarevic, V., Hrga, I., Stjepanovic, B., 2012: Atmospheric conditions during high ragweed pollen concentrations in Zagreb, Croatia. *International Journal of Biometeorology*, 56(6): 1145–1158.

Salma, I., Németh, Z., Kerminen, V.-M., Aalto, P., Nieminen, T., Weidinger, T., Molnár, Á., Imre, K., Kulmala, M., 2016a: Regional effect on urban atmospheric nucleation, *Atmospheric Chemistry and Physics,* doi:10.5194/acp-2016-115.

Salma, I., Németh, Z., Weidinger, T., Kovács, B., Kristóf, G., 2016b: Measurement, growth types and shrinkage of newly formed aerosol particles at an urban research platform. *Atmospheric Chemistry and Physics,* doi:10.5194/acp-2016-239.

Sándor, R., Barcza, Z., Hidy, D., Lellei-Kovács, E., Ma, S., Bellocchi, G., 2016: Modelling of grassland fluxes in Europe: Evaluation of two biogeochemical models. *Agriculture Ecosystems and Environment,* 215: Paper 5126.

Semenova, I. G., 2013: Regional atmospheric blocking in the drought periods in Ukraine. *Journal of Earth Science and Engineering,* V.3(5): 341–348.

Strelcová, K., Matyas, Cs., Kleidon, A., Lapin, M., Matejka, F., Blazenec, M., Skvarenina, J., Holecy, J. (eds.), 2009: Bioclimatology and Natural Hazards. Springer Science, 297 p.

Szabóné Andre, K., Bartholy, J., Pongrácz, R., 2016: Synoptic climatological analysis of persistent cold air pools over the Carpathian Basin. *Geophysical Research Abstracts* 18, EGU2016-2928.

Szepszo, G., 2008: Regional change of climate extremes over Hungary based on different regional climate models of the PRUDENCE project. *Időjárás*, 12(3–4): 265–284.

Szepesi, D. J., Fekete, K. E., 1987: Background levels of air and precipitation quality for Europe. *Atmospheric Environment,* 21(7): 1623–1630.

Szepesi, D. J., Fekete, K. E., Gyenes, L., 1995: Regulatory models for environmental impact assessments in Hungary. *International Journal of Environment and Pollution,* 5(4–6): 490–507.

Szilágyi, J., 2015: Testing the Rationale behind an Assumed Linear Relationship between Evapotranspiration and Land Surface Temperature. *Journal of Hydrologic Engineering* (ASCE) 20(5), 04014073, 9 p.

Syrakov, D., Prodanova, M., Georgieva, E., 2015: Performance of the Bulgarian WRF-CMAQ modelling system for three subdomains in Europe. *Física de la Tierra,* 27: 137–153.

Szintai, B., Szűcs, M., Randriamampianina, R., Kullmann, L., 2015: Application of the AROME non-hydrostatic model at the Hungarian Meteorological Service: physical parameterizations and ensemble forecasting. *Időjárás*, 119(2): 241–265.

Tomczyk, A. M., Bednorz, E., 2016: Heat waves in Central Europe and their circulation conditions. *International Journal of Climatology,* 36(2): 770–782.

Torma, P., Krámer, T., 2016: Modelling wave action in the diurnal temperature stratification of a shallow lake. Periodica Polytechnica Civil Engineering (In press).

Unger, J., Savić, S., Gál, T., 2011: Modelling of the Annual Mean Urban Heat Island Pattern for Planning of Representative Urban Climate Station Network. Advances in Meteorology, Article ID 398613, 9 pages. doi:10.1155/2011/398613

Vörös, M., Istvánovics, V., Weidinger, T., 2010: Applicability of the Flake model to Lake Balaton. *Boreal Environment Research,* 15: 245–254.

Weidinger, T., Cuxart, J., Gyongyosi, A. Z., Wrenger, B., Istenes, Z. Bottyan, Z., Simó, G., Tatrai, D., Jericevic, A., Matjacic, B., Kiss, M., Jozsa, J., 2014: An experimental and numerical study of the ABL structure in the Pannonian plain (PABLS13). 21st Symposium on Boundary Layers and Turbulence; Leeds, United Kingdom; 9 June.

Žabkar, R., Honzak, L., Skok, G., Forkel, R., Rakovec, J., Ceglar, A., Žagar, N., 2015: Valuation of the high resolution WRF-Chem (v3.4.1) air quality forecast and its comparison with statistical ozone predictions. *Geoscientific Model Development,* 8: 2119–2137.
Zacharias, S., Koppe, Ch., Mücke, H.–G., 2015: Climate change effects on heat waves and future heat wave–associated IHD mortality in Germany. *Climate,* 3(1): 100–117.
Zaninović, K. (ed.), 2008: Climate atlas of Croatia 1961–1990, 1971–2000. klima.hr/razno/publikacije/klimatski_atlas_hrvatske.pdf, Croatian Hydrometeorological Institute, 200 pp.

Internet addresses

accent.aero.jussieu.fr/index.php – Main page of GEIA ACCENT emission portal. (GEIA – Global Emission InitiAtive, ACCENT – Atmospheric Composition Change European Network of Excellence)

accent.aero.jussieu.fr/TNO_metadata.php – GEIA-ACCENT emission data portal, metadata.

accent.aero.jussieu.fr/database_table_inventories.php – GEIA-ACCENT emission data portal, database tables

acmg.seas.harvard.edu/geos/ – Geos-Chem model

aqmeii-eu.wikidot.com/ – Quality Model Evaluation International Initiative (AQMEII)

atmosphere.copernicus.eu/ – Copernicus Atmosphere Monitoring Service (CAMS)

atmosphere.copernicus.eu/services/air-quality-atmospheric-composition – European Air Quality Monitoring and Forecasting Program

camx.com/ – Comprehensive Air Quality Model with Extensions (CAMx)

ceepus.info/default.aspx#nbb – Central European Exchange Program for University Studies (CEEPUS)

ceeip.at – Centre on Emission Inventories and Projections

chemicalweather.eu – COST ES0602, Chemical Weather Action ES0602: Towards a European Network on Chemical Weather Forecasting and Information Systems (ENCWF)

cmascenter.org/cmaq/ – Community Multi-scale Air Quality (CMAQ) Modeling System for Air Quality Management

cnrm-game-meteo.fr/aladin/ – ALADIN model (Aire Limitée Adaptation Dynamique développement InterNational)

copernicus.eu – Copernicus programme (Europe's eyes on Earth)

cost.eu – COST program

daac.ornl.gov/BOREAS/boreas.shtml – The Boreal Ecosystem-Atmosphere Study (BOREAS)

danube-inco.net/about/danubeinconet – DANUBE-INCO.NET

danube-region.eu/ – Danube Region Strategy

db.eurad.uni-koeln.de/index_e.html – European Air Pollution Dispersion Model, University of Cologne (EURAD)

dndc.sr.unh.edu/ – The DNDC (DeNitrification-DeComposition) model is a computer simulation model of carbon and nitrogen biogeochemistry in agro-ecosystems.

eccad.sedoo.fr/eccad_extract_interface/JSF/page_login.jsf – Emissions of atmospheric Compounds & Compilation of Ancillary Data

ecmwf.int – ECMWF (European Centre for Medium-Range Weather Forecasts)

ecmwf.int/en/research/projects/macc-iii – ECMWF Monitoring Atmospheric Composition and Climate III (MACC-III)

edgar.jrc.ec.europa.eu/datasets_grid_list_htap_v1.php#d – Emission Database for Global Atmospheric Research (EDGAR)

edgar.jrc.ec.europa.eu/pegasos/index.php – EDGAR Retrospective Scenarios: the EU air quality legislation in a global perspective

eea.europa.eu/data-and-maps/data/digital-elevation-model-of-europe – European Environmental Agency (EEA)

emep.int – European Monitoring and Evaluation Programme (EMEP)

emep.int/mscw/index_mscw.html – EMEP Air Pollution Model

emep.int/mscw/Projects/emep4hr/ – High Resolution Environmental Modelling and Evaluation Programme for Croatia (emep4hr)

esdac.jrc.ec.europa.eu/resource-type/datasets – European Soil Data Centre (ESDAC)

eumetsat.int – Monitoring Weather and Climate from Space

fairmode.jrc.ec.europa.eu/index.html – Forum for Air quality Modeling (FAIRMODE)

fairmode.jrc.ec.europa.eu/tools.composite.map.html – FAIRMODE composit maps

flexpart.eu – FLEXible PARTicle dispersion model (FLEXPART)

fluxnet.ornl.gov/fluxnetdb – FLUXNET, Integrating Worlwide CO_2 Water and Energy Flux Measurements

geba.ethz.ch/ – Global Energy Balance Archive, ETH Zürich

geiacenter.org/access – ECCAD - The GEIA Database (ECCAD Emissions of atmospheric Compounds & Compilation of Ancillary Data)

gmes-atmosphere.eu – Monitoring Atmospheric Composition and Climate (MACC)

globe.gov – The Global Learning and Observations to Benefit the Environment (GLOBE) Program

harmo.org – Initiative on "Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purpose

hirlam.org – HIRLAM model (High-Resolution Limited-Area Model)

interregeurope.eu/ – Interreg Europe

ipcc-nggip.iges.or.jp/public/2006gl – 2006 IPCC Guidelines for National Greenhouse Gas Inventories

land.copernicus.eu/pan-european/corine-land-cover – Copernicus Land Monitoring Service, CORINE Land Cover

levegominoseg.hu – Hungarian Air quality Network

lternet.edu/ – Long Term Ecological Research (LTER) Network

nato.int/cps/en/natolive/78209.htm – The NATO Science for Peace and Security Programme

nomads.ncdc.noaa.gov/data.php – GFS model (Global Forecast System)

nsf.gov/od/oise/europe/science_funding.jsp – Information from National Scientific Foundations are presented in the homepage of Scientific found of USA.

ready.arl.noaa.gov/HYSPLIT.php – Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT)

romair.eu/model-description.php?lang=en – WRF-CHIMERE model in Romania

salma.web.elte.hu/BpArt/ – Budapest Aerosol Platform snf.ch/en/Pages/default.aspx –Scientific co-operation between Eastern Europe and Switzerland (SCOPES)

southeast-europe.net/en/ – The South East Europe Transnational Cooperation Programme

umr-cnrm.fr/spip.php?article120&lang=en– AROME model

visegradgroup.eu/ – Visegrad Group

visegradfund.org/home/ – The International Visegrad Fund

wmo.int/pages/index_en.html – World Meteorological Organisation (WMO)

wmo.int/pages/prog/hwrp/chy/whos/index.php – WMO Hydrological Observing System (WHOS)

wmo.int/pages/prog/www/OSY/GOS.html – WMO Global Observing System (GOS)

wmo.int/pages/prog/arep/gaw/gaw_home_en.html – WMO Global Atmosphere Watch (GAW)

wrf-model.org/index.php – Weather research and Forecast model (WRF)

www2.acom.ucar.edu/wrf-chem – Weather Research and Forecasting (WRF) model coupled with Chemistry (WRF-CHEM)

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No. 21. Weidinger, T., Tarczai, K., Bartholy, J. (eds.), 2007: Measurements from local to global scale – Why? Proceedings of the Summer School of Undergraduate Research Circle of the Department of Meteorology, ELTE, 28–31 August 2006, Volume. II. (In Hungarian)

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