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A.A. Baklanov[1,2], *Prof., Dr. Sci.,* and **MEGAPOLI team**

[1]*Danish Meteorological Institute, Copenhagen*
[2]*Russian State Hydrometeorological University, St.-Petersburg, Russia*
[3]*The MEGAPOLI consortium consists of 23 full partners from 11 European countries, 12 international research non-funded partners from USA, Canada, Mexico, India, Chile and Thailand, and 9 end users/stakeholders*[1]*.*

INTEGRATED MULTI-SCALE MODELS OF INTERACTING URBAN METEOROLOGY/CLIMATE AND AIR QUALITY: OUTCOMES FROM MEGAPOLI

Integrated multi-scale modelling concept of urban environment, air pollution, climate change and human health interactions for megacities and overview of integrated modelling frameworks for global to street scale realized in European FP7 project MEGAPOLI and several following research projects, are described in this paper.

Keywords: *meteorological and chemical transport models, local-, urban-, regional and global scales, megacities, atmospheric pollution, urban climate, climate change, interactions, feedbacks*

Introduction. Processes involving nonlinear interactions and feedbacks between emissions, chemistry and meteorology require coherent and robust modelling approaches. This is particularly important where multiple spatial and temporal scales are involved with a complex mixture of pollutants from large sources, as in the case of urban areas, especially megacities. Numerical weather and air pollution prediction models are now able to approach urban-scale resolution, as detailed input data are becoming more often available. The European Union FP7 project MEGAPOLI (see: http://megapoli.info) suggested a comprehensive integrated modelling framework which was tested for a range of megacities within Europe and across the world to increase our understanding of how large urban areas and other hotspots affect air quality and climate on multiple scales. Integrated multi-scale modelling concept of urban environment, air pollution, climate change and human health interactions for megacities and overview of integrated modelling frameworks for global to street scale realized in MEGAPOLI is described in this paper.

Integrated Multi-Scale Modelling Methodology. Impacts of megacities on the atmospheric environment are tied directly to anthropogenic activities as sources of air pollution. These impacts act on street, urban, regional and global scales. Previously there were only limited attempts to integrate this wide range of scales for regional and global air quality and climate applications. Indeed, progress on scale and process interactions has been limited because of the tendency to focus mainly on issues arising at specific scales. However the interrelating factors between megacities and their impacts on the environment rely on the whole range of scales and thus should be considered within an integrated framework bringing together the treatment of emissions, chemistry and meteorology in a consistent modelling approach. As mentioned above modern models are now able to approach urban-scale resolution. As a result the conventional concepts of down- (and up-) scaling for air pollution prediction need revision along the lines of integration of multi-scale meteorological and chemical transport models. MEGAPOLI aims at developing a comprehensive integrated modelling framework which will be tested and implemented by the research community for a range of megacities within Europe and across the world to increase our understanding of how large urban areas and other hotspots affect air quality and climate on multiple scales [2].

The integration strategy in MEGAPOLI (Figure 1) is not focused on any particular meteorological and/or air pollution modelling system. The approach considers an open

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[1] *For further information on the MEGAPOLI consortium, please, visit the website* http://megapoli.info.

integrated framework with flexible architecture and with a possibility of incorporating different meteorological and chemical transport models (see model specifications in MEGAPOLI, 2008).

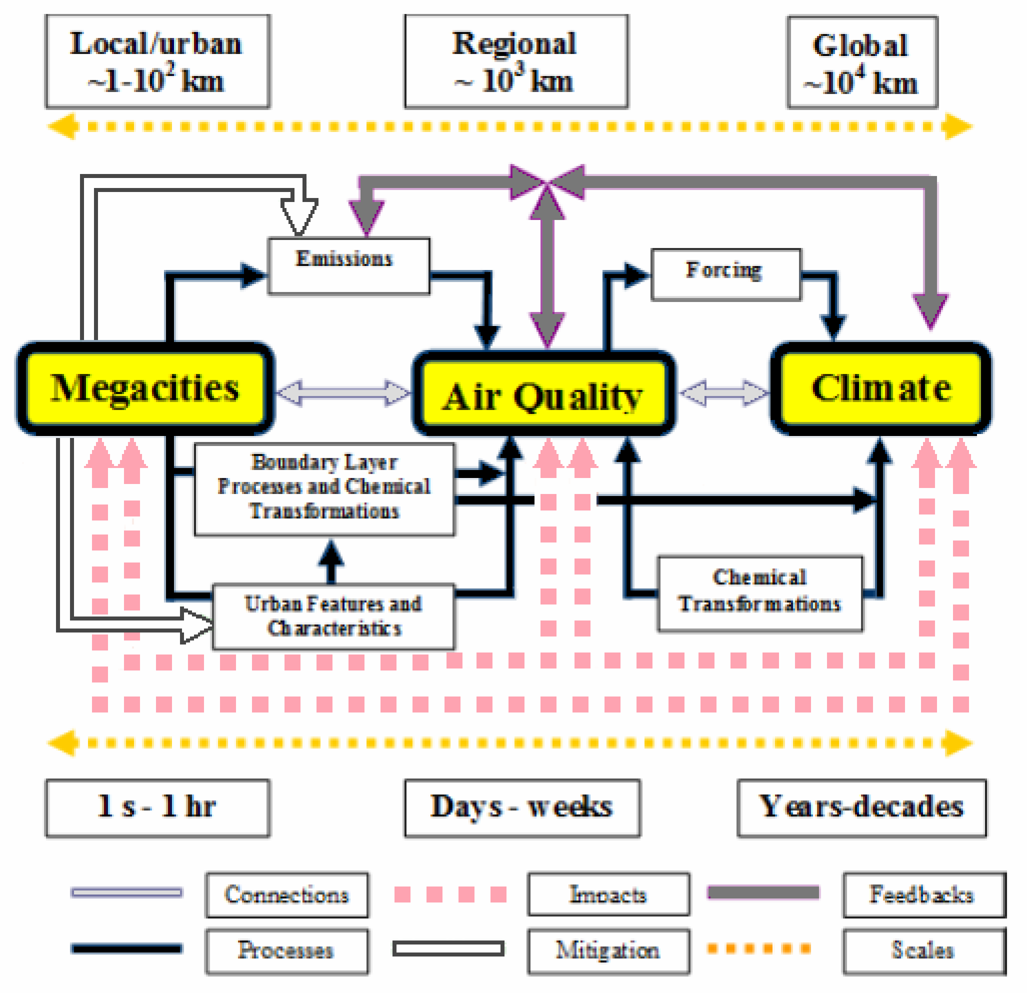

Fig. 1. Schematic showing the main linkages between megacities, air quality and climate. The connections and processes are the focus of MEGAPOLI. In addition to the overall connections between megacities, air quality and climate, the figure shows the main feedbacks, ecosystem, health and weather impact pathways, and mitigation routes which will be investigated in MEGAPOLI. The relevant temporal and spatial scales are additionally included. [12].

The following levels of integration and orders of complexity (temporal and spatial scales and ways of integration) are considered:

- Level 1 – Spatial: One way (Global -> regional -> urban -> street); Models: All.
- Level 2 – Spatial: Two way (Global <=> regional <=> urban); Models: UM-WRF-CMAQ, SILAM, M-SYS, FARM.
- Level 3 – Time integration: Time-scale and direction; Direct and Inverse modelling (Figure 2).
- Order A – off-line coupling, meteorology / emissions -> chemistry; Models: All.
- Order B – partly online coupling, meteorology -> chemistry & emission; Models: UKCA, DMAT, M-SYS, UM-WRF-Chem, SILAM.
- Order C – fully online integrated with two-way feedbacks, meteorology <=> chemistry & emissions; Models: UKCA, WRF-Chem, Enviro-HIRLAM, EMAC (former ECHAM5/MESSy).

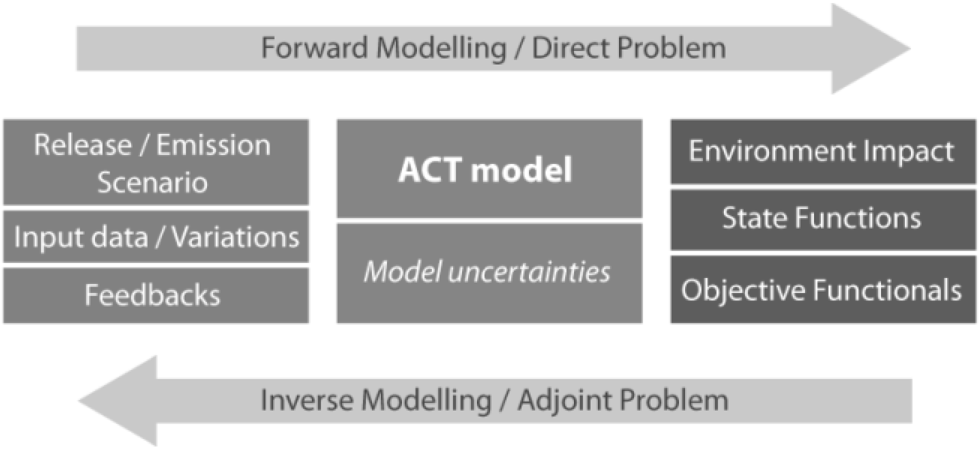

Fig. 2. Scheme of environmental risk assessment and mitigation strategy optimization basing on forward/inverse modelling [15].

A multi-scale modelling framework (Figure 3) for global to street scale includes nesting of (i) the land-use characteristics and scenarios, (ii) anthropogenic heat fluxes, (iii) emission inventories and scenarios, and (iv) the representation of atmospheric processes using two-way nesting [17,19], zooming, nudging, parameterizations and urban increment methodology [14]. The new or improved interfaces for coupling (direct links between emissions, chemistry and meteorology at every time step) can be implemented or developed and common formats for data exchange can be defined to ease the implementation and to help combine the different models via conventional data exchange protocols.

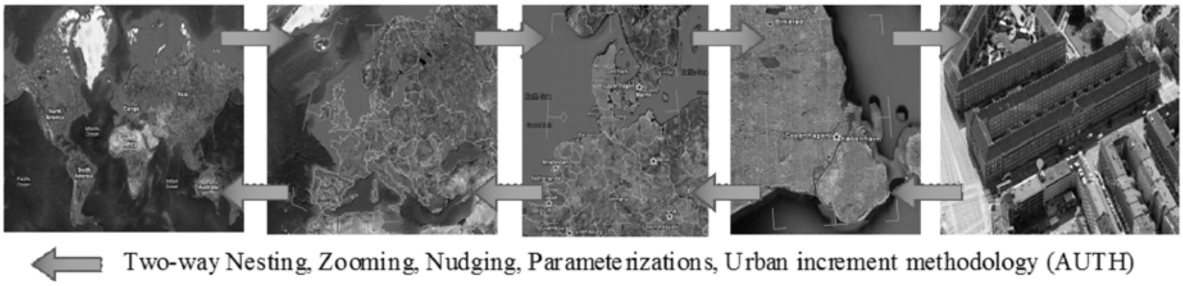

Fig. 3 Down-scaling of global and European-scale models to city and street scales and two-way nesting techniques including model up-scaling.

The current chemistry schemes were examined for their suitability to simulate the impact of complex emissions from megacities. The coupled model systems were applied to different European megacities during the project. The framework is used and demonstrated for selected models including UKCA (MetO), WRF-CMAQ (UH-CAIR), PMCAMx (FORTH), Enviro-HIRLAM (DMI), STEM/FARM (ARIANET), M-SYS (UHam) and EMAC (MPIC) on different scales. This part of the studies was linked also to the requirements and use of simpler tools for assessing air quality impacts within megacities (OSCAR - UH-CAIR, AIRQUIS - NILU, URBIS - TNO, EcoSence - UStutt).

The focus on integrated systems is timely, since recent research has shown that meteorology/climate and chemistry feedbacks are important in the context of many research areas and applications, including numerical weather forecasting, climate modelling, air quality forecasting, climate change, and Earth system modelling [6]. The prediction and simulation of the coupled evolution of atmospheric transport and chemistry will remain one of the most challenging tasks in environmental modelling over the next decades. Many of the current environmental challenges in weather, climate, and air quality involve strongly coupled systems. It is well accepted that weather is of decisive importance for air quality, or for the aerial transport of hazardous materials. It is also recognized that chemical species will 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 NWP, the dramatic increase in computer power enables us to use higher resolution to explicitly resolve fronts, convective systems, local wind systems, and clouds, or to increase the complexity of the numerical models. Additionally we can now directly couple air quality forecast models with numerical weather prediction models to produce a unified modelling system – online – that allows two-way interactions. While climate modelling centres have gone to an Earth System Modelling approach that includes atmospheric chemistry and oceans, NWP centres as well as entities responsible for Air Quality forecasting are only beginning to discuss whether an online approach is important enough to justify the extra cost. NWP and AQ forecasting centres may have to invest in additional computer power as well as additional man power, since additional expertise may be required. We are in favour of integrating weather and chemistry together, for both NWP and air quality and chemical composition forecasting. For NWP centers, an additional attractiveness of the online approach is its possible usefulness for meteorological data assimilation (Hollingsworth et al., 2008), where the retrieval of satellite data and direct assimilation of radiances will likely improve – assuming that the modelling system can beat climatology when forecasting concentrations of aerosols and radiatively active gases.

Urbanisation of Models. Urban air pollution (UAP) and atmospheric chemical transport (ACT) models have different requirements in terms of the way in which they represent urbanization (e.g., different importance of low-atmosphere structure details) depending on (i) the scale of the models (e.g., global, regional, city, local, micro) and (ii) the functional type of the model, e.g.:

- forecasting or assessment models,
- atmospheric pollution models for environmental and air quality applications (mostly for city scale),
- emergency preparedness models (mostly for city scale or micro-scale),
- integrated ACT and aerosol models for climate forcing,
- urban-scale research ACT models.

Incorporation of the urban effects into urban- and regional-scale models of atmospheric pollution should be carried out, first via improvements in the accuracy of meteorological parameters (velocity, temperature, turbulence, humidity, cloud water, precipitation) over urban areas. This requires a kind of “urbanization” of meteorological and numerical weather prediction (NWP) models that are used as drivers for urban air quality models or special urban met-preprocessors to improve nonurbanized NWP input data. In MEGAPOLI a hierarchy of urban canopy models/parameterisations for different type and scale models was developed [10]. In comparison with NWP models, the urbanization of UAP models has specific requirements, e.g., better resolution of the urban boundary layer (UBL) vertical structure; by themselves, the correct surface fluxes over the urban canopy are insufficient for UAP runs. Furthermore, for urban air pollution, from traffic emissions and for the modelling of preparedness for emergencies, there is a much greater need for vertical profiles of the main meteorological parameters and the turbulence characteristics within the urban canopy.

Other important characteristics for pollutant turbulent mixing in UAP modelling include the mixing height, which has a strong specificity and heterogeneity over urban areas because of the urban heat island (UHI), internal boundary layers, and blending heights from different urban roughness neighbourhoods [16]. For the modelling of preparedness for emergencies at local scale (e.g., biological, chemical, or nuclear accidental releases or terrorist acts) the statistical description of building structure is suitable only for distances longer than three or four buildings from the release, whereas for the first two to four buildings from the source, more precise obstacle-resolved approaches are needed [3].

Other specific effects of urban features on air pollution in urban areas, which cannot be realized via the urbanization of NWP models, include:

- deposition of pollutants on specific urban surfaces, e.g., on vertical walls, from different building materials and structure, vegetation, etc.
- specific chemical transformations, including increasing the residence times of chemical species (e.g., inside street canyons), the heterogeneity of solar radiation (e.g., street canyon shadows) for photochemical reactions, and specific aerosol dynamics in street canyons (e.g., from the resuspension processes).
- very heterogeneous emission of pollutants at the subgrid scale, especially from traffic emissions, which need to be simulated on detailed urban road structures with taking into account the distribution of transport flows, etc.
- the indoor–outdoor interaction of pollutants (not only via heat fluxes), which requires a more comprehensive description and modelling of emissions.

The effects of air pollution on health are the final and most important aim of UAP modelling. It is therefore important to combine the UAP with population exposure modelling, which includes high-resolution databases of urban morphology and population distribution and activity (Hanninen et al., 2004). One of the realisations of such an Urban Air Quality Information and Forecasting Systems (UAQIFS) was done within FUMAPEX (Baklanov, 2006). The improved UAQIFS is enhancing the capabilities to successfully describe and predict urban air pollution episodes through improvement and integration of systems for forecasting urban meteorology, air pollution, and population exposure based on modern information technologies. The UAQIFSs were implemented and demonstrated in seven European cities: Oslo, Norway (urban air quality forecasting mode), Turin, Italy (urban air quality forecasting mode), Helsinki, Finland (urban air quality forecasting mode + public health assessment and exposure prediction mode), Valencia/Castellon, Spain (urban air quality forecasting mode), Bologna, Italy (urban management and planning mode), Copenhagen, Denmark (urban emergency preparedness system), and London, UK (urban air quality forecasting mode).

MEGAPOLI Application of Models. Applications of integrated modelling systems for megacity air quality modelling were demonstrated for different megacities in Europe as we all other cities (Schlunzen, 2011b). In MEGAPOLI Francis and Sokhi (2011) describes a number of different integrated modelling systems applied to assess the impact of air quality of European and other megacities. These include RAMS-FARM, WRF-Chem, WRF-CMAQ, LOTOS-EUROS, M_SYS-METRAS-MECTM, MEMO-MARS, GRE-CAPS, Enviro-HIRLAM, MESO-NH, and ENSEMBLE. Examples of the use of integrated modelling systems over the European megacities (London, Paris, Po-Valley, and Rhine-Ruhr) and other cities (e.g., Vilnius, Lithuania; St. Petersburg, Russia) have been discussed.

For Paris, which was in the main focus of the project, many modelling systems (CHIMERE, Enviro-HIRLAM, LOTUS-EUROS, MEMO-MARS, MESO-NH, PMCAMx, WRF-CMAQ) have been applied to study the air quality over Paris. E.g., the results from LOTUS-EUROS [13] suggested that the model simulation around the Paris area clearly benefit from emission inventories based on nesting information from local inventories for the simulation of particulate matter. However, the average concentrations of PM predicted by LOTUS-EUROS over Paris are much lower compared to available measurements. Simulations with ‘nested’ emissions represented better diurnal cycles for PM when compared with observations. The online coupled modelling system MEMO-MARS has been used to study the feedbacks of direct aerosol effect on PM10 simulations over Paris. The difference field was produced by removing the control simulations from the online results. PM10 concentrations revealed a clear increase over almost the entire domain, reaching up to 2.5 µg m^{-3} in the central Paris area and the southern part of the computational domain, where higher pollution loads occur due to the prevailing wind flow during the simulation period (Douros et al., 2011 in [13]). This study indicates that feedback processes can be significant for air quality assessment and should form the basis of future studies. Similarly, PMCAMx has been employed to predict concentrations of PM and ozone during July 2009 and winter of 2010 [20]. The use of the volatility basis approach in PMCAMx has resulted in significant improvements in the ability to reproduce organic aerosol levels over Paris. MESO-NH has been used to predict primary and secondary aerosols components over Paris region.

Analysis of air quality over the Po valley with RAMS-FARM modelling system (Finardi et al., in [13]) has shown that the large urbanised areas contribute significantly to regional levels of pollutants such as PM2.5. The study also showed that the Po valley footprint, under prevailing anti-cyclonic circulation conditions, can extend well beyond the immediate region and can affect southern parts of continental Europe and northern Italy. On urban scales, a study with Enviro-HIRLAM for Vilnius [11] has indicated that modifications of the surface parameters can have significant impact on meteorological fields that affect air pollution. For example, it was found that the air temperature at 2 m height is typically higher in modified simulation runs.

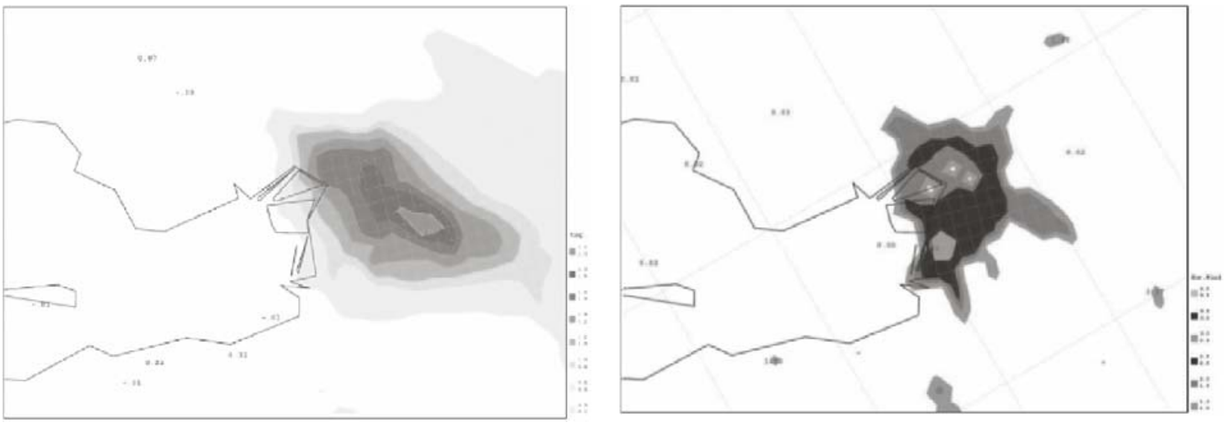

Fig. 4 Simulations of urban effects for St.-Petersburg by the Enviro-HIRLAM model [5] (by Gavrilova Yu., RSHU). Difference plots (between the control vs. urban runs) for: (left) the air temperature at 2 m and (right) the wind velocity at 10 m at 00 UTCs on 29 January 2009.

As an extension of this study, the effect of modified roughness, anthropogenic heat fluxes and the albedo (urbanization) in Enviro-HIRLAM modelling system has been studied for St. Petersburg (Russia). As it is demonstrated on Figure 4 results showed [5] that for winter the differences between control vs. urbanized runs over the metropolitan area and surroundings were the following: wind at 10 m up to 2 m/s (with a maximum up to 2.9 m/s, at nighttime) and air temperature at 2 m is more than 1ºC (with a maximum up to 2.7ºC, at nighttime)

The air quality over other non-European megacities like Mexico (PMCAMx and extended version of WRF-Chem), New York (PMCAMx), Phoenix (MM5-CMAQ), Shanghai (WRF-Chem and WRF-CMAQ) and New Delhi (SAFAR) has been also studied (see details in Francis and Sokhi, 2011).

Concluding remarks. Although these examples show successful application of suggested multi-scale integrated models to investigate air quality affecting megacities, a number of research developments are required. These include greater consistency in the use of data for megacities, moving towards online or coupled approaches and the need for dedicated and targeted data sets for model evaluation purposes. Prediction of PM remains a challenge for several models and is an important area for continued research.

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Совместные мультимасштабные модели взаимодействия метеорологических и климатических процессов и качества воздуха: результаты научного проекта "MEGAPOLI"

А.А. Бакланов и участники проекта "MEGAPOLI"

В статье на примере мегаполисов излагается концепция совместного мультимасштабного моделирования городской окружающей среды, которая рассматривает изменения климата, процессы, приводящие к загрязнению воздуха, и влияние всех этих процессов на здоровье человека. Представлен обзор совместных моделирующих систем для различных масштабов (от глобального до масштаба улицы), реализованных в европейском научном проекте "MEGAPOLI" в рамках FP7 и в некоторых последующих научно-исследовательских проектах.

Ключевые слова: *метеорологическая и химическая модели переноса, местный, городской и глобальный масштабы, мегаполисы, загрязнение атмосферы, городской климат, изменение климата, взаимодействия, обратные связи*

Сумісні мультімасштабні моделі взаємодії метеорологічних та кліматичних процесів та якості повітря: результати наукового проекту "MEGAPOLI"

А.А. Бакланов та учасники проекту "MEGAPOLI"

В статті на прикладі мегаполісів викладається концепція сумісного мультімасштабного моделювання міського довкілля, яка розглядає зміни клімату, процеси, що призводять до забруднення атмосфери, та вплив всіх цих процесів на здоров'я людини. Представлено огляд сумісних моделюючих систем для різних масштабів (від глобального до масштабу вулиці), які реалізовані в європейському науковому проекті "MEGAPOLI" в рамках FP7 та в деяких наступних науково-дослідницьких проектах.

Ключові слова: *метеорологічна та хімічна моделі переносу, місцевий, міській та глобальний масштаби, мегаполіси, забруднення атмосфери, міський клімат, зміни клімату, взаємодії, обернені зв'язки*