NOMTM1: Urban Canopy parameterizations I : Urban vegetation

A multi-layer urban canopy model for neighbourhoods with trees

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Addition of tall vegetation is a key design strategy for moderation of local urban climate, and many cities already boast extensive tree cover. Relative to shorter vegetation, urban trees have unique micrometeorological and climatic effects: they provide shade and shelter, interacting with buildings and streets to alter local climate and wind flow, affecting thermal comfort of residents, building energy demand, and pollutant concentrations in the canopy.

Urban canopy models (UCMs) predict neighbourhood-scale energy exchange and climate of the atmospheric layer between the buildings. Few UCMs represent the urban canopy with multiple layers, which permit more flexible and process-based representation of canopy physics. Most UCMs neglect vegetation, or incorporate its effects with a separate model, neglecting direct interaction between vegetation and built elements in the canopy.

We present BEP-Tree, the first multi-layer urban canopy model that explicitly includes trees and their interaction with buildings. It consists of an existing multi-layer UCM, a foliage energy balance model, and two major developments: firstly, a model that distributes solar and infrared radiation amongst tree foliage, road, roof, and wall elements at multiple heights, accounting for radiation 'trapping' and mutual shading; secondly, parameterization of building and tree foliage effects on flow, including generation and dissipation of turbulence, drag on the mean wind, and explicit consideration of sheltering. The combined model permits a wide range of building and tree configurations, and makes possible advanced assessment of impacts of trees on urban climate, air quality, human comfort and building energy loads.

BEP-Tree is compared with measurements from the Sunset neighbourhood in Vancouver, Canada. Urban trees principally channel sensible heat into latent heat (evaporation), shift surface-atmosphere energy exchange upwards, slow canopy wind, and dissipate turbulence more rapidly, especially if taller than nearby buildings. Effects of trees on neighbourhood-average canopy thermal climates are less clear; foliage clumping at the neighbourhood scale must be quantified with more fidelity, and we suggest this as an important future development for UCMs.

A new parameterization for surface heat fluxes in dense urban environments

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There is a large need to better understand and quantify surface latent/sensible heat fluxes partitions from urban environments and their specific nature, whether natural or anthropogenic. In this research, a hydrology parameterization was implemented in the multilayer urban canopy model (BEP) of the Weather Research Forecasting (WRF) model to quantify latent heat fluxes contributions from impervious surface evaporation at ground and roof levels during and after precipitation events, and evapotranspiration from street vegetation in the surface energy balance. A cooling tower scheme was also incorporated in the building energy model (BEM) to represent the anthropogenic latent heat released by this type of technology for commercial buildings. The new modeling schemes for latent heat flux was tested in New York City (NYC) during summer seasons. City Planning data for buildings were assimilated at 250 meters to improve the representation of the city morphology.

An evaluation with heat flux measurements from a limited field campaign in nearby Baltimore, Maryland, indicates that the new formulation properly represents sensible and latent heat daily cycle particularly during rainy days. A comparison with surface weather station data in NYC for summer 2010 shows overall seasonal improvement in the foresting when the new surface heat fluxes parameterizations are introduced, with small biases to overestimate daily maximum temperatures and underestimate moisture content at nighttimes. The hydrology scheme introduces a slightly higher amount of sensible heat in the late afternoon and night in dry days. Latent heat produced by surface evaporation during rain events exceeds amount of heat flux produced by evapotranspiration. Evaporative cooling technology from buildings diminishes between 80 and 90% the amount of sensible heat which is transformed into latent heat in commercial areas. Streets constitute the main source of sensible and latent heat in residential areas. The increase in environmental moisture content from streets and roofs influences the lower boundary layer leading to modifications of the atmospheric stability in commercial areas. The new surface heat flux parameterization allows for the effective exploration of mitigating alternatives to environmental impacts of urban fluxes. Exploration of green and white roofs is addressed for the case of NYC.

The influence of tree crowns on urban thermal effective anisotropy

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The three-dimensional surface structure of urban areas imparts an anisotropic character to the upwelling longwave radiation. Trees contribute to the three-dimensionality of the urban surface and are therefore expected to influence urban thermal effective anisotropy. In this presentation, the SUM sensor view model (Soux et al. 2004) is modified to include trees in order to assess their contribution to the anisotropy. A gap probability approach to estimate foliage view factors is used so that tree canopies are represented as volumes of turbid media and a simple energy budget model for leaf surface temperatures is added. The vegetated model (SUMVEG) is tested against airborne thermal observations from a treed residential study area in Vancouver, BC. The inclusion of trees in the model results in an approximate doubling of the effective thermal anisotropy near midday with a smaller increase in the morning. The vegetated model shows a statistically significant improvement over the original model.

The model is then used to assess the impact of trees on the thermal anisotropy of a range of urban geometries. A simple array of cubic elements is used to represent buildings and identically sized tree crowns are located a fixed distance from the buildings. Temperatures for buildings are estimated from the TUF3d canyon model of Krayenhoff & Voogt (2007). The temperature for surface patches that are partially shaded by tree crowns are estimated by weighting between a fully sunlit and fully shaded TUF3d modeled temperature based on the probability of gap for direct and diffuse shortwave radiation through the shading tree crown. Tests are made for tree heights both less than and greater than that of the buildings.

Results show that trees both increase and decrease anisotropy as a function of tree crown plan area fraction and building plan area fraction. In open urban geometries, the shadows cast by trees act to increase the urban thermal anisotropy while in more compact geometries trees reduce anisotropy as the plan area of tree crowns increases. Many urban geometries have a critical value at which the impact of tree coverage on the effective anisotropy reverses. Increases of tree coverage where the trees are taller than the buildings act to increase anisotropy for all plan area geometries.

VTUF: An urban micro-climate model to assess temperature moderation from increased vegetation and water in urban canyons

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With urban areas facing future longer duration heatwaves and temperature extremes, adaptation strategies are needed. Examining the role that increased tree cover and water availability can have on human thermal comfort (HTC) in urban areas as part of these strategies has been done using observations, but further work requires a modelling tool suited for this task. Sufficient model resolution is needed to resolve variables used to calculate HTC as well as the ability to model the physiological processes of vegetation and their interaction with water. The lack of such a tool has been identified as a research gap in the urban climate area and has impaired our ability to fully examine the use of vegetation and water for improved human thermal comfort.

A new model, VTUF (Vegetated Temperatures Of Urban Facets), addresses this gap by embedding the functionality of the MAESPA tree process model (Duursma & Medlyn 2012), that can model individual trees, vegetation, and soil components, within the TUF-3D (Krayenhoff & Voogt 2007) urban micro-climate model. An innovative tiling approach, allows the new model to account for important vegetative physiological processes and shading effects. It also resolves processes at sufficiently high resolution to calculate HTC and air and surface temperature, humidity, and wind speed across an urban canyon.

Model validations have shown performance improvements of the model and a suitability to use it to examine critical questions relating to the role of vegetation and water in the urban environment. Analysis using this model includes scenarios quantifying the impact each individual tree can have on temperatures in urban canyons as well the optimal arrangement and quantity of trees to maximize temperature moderation effects.

Modeling of Urban Vegetation as a Thermal Regulator and Management of Associated Water Resources for Neighbourhood to City-scale Applications

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Urban vegetation can influence urban climate to the scale of a whole city by its radiative, aerodynamic, thermal and moisture properties. In recent years, the urban canopy model TEB1 (Masson 2000; Hamdi and Masson 2008) has been improved to explicitly represent vegetation in urban areas, especially small-scale interactions between mineral surfaces, vegetation and atmosphere. The TEB model, in the TEB-Veg version, now includes parameterizations dedicated to low vegetation in urban canyons (Lemonsu et al. 2012), vegetated roofs (de Munck et al. 2013) which were each evaluated from experimental data point, and a more realistic description of urban basement.

Urban trees in particular constitute an alternative technique in the mitigation of Urban Heat Island (UHI) and improvement of local thermal comfort thanks to shading and shelter effects. However, few urban canopy models are currently taken into account vegetation, even less tree layer (Lee and Park 2008; Lee 2011; Krayenhoff et al. 2013), which alter radiative and energy balances within the urban canyon by intercepting and absorbing incident radiation, shadowing and increasing relative humidity of the air by evapotranspiration. They also have an impact on the local dynamics by modifying the air flow in the street.

In this work, we attempt to set up in TEB-Veg model a parameterization including the following key processes : (1) shading of tree crowns on ground vegetation, walls or mineralized surfaces like roads and (2) summed evaporation of bare ground and transpiration of leaves (both lawns and trees). For this purpose, we employ the Soil Biosphere Atmosphere Interaction (ISBA) model to represent all natural covers (high and low vegetation strata).

Modelling the impact of green infrastructures on local microclimate within an idealized homogeneous urban canopy

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Quantifying the impact of greening urban areas on urban meteorology, and therefore on human thermal comfort, is difficult due to the complex interaction between the energy fluxes coming from the various urban surfaces. Models give the opportunity to investigate this impact from local to regional scales. However, existing urban canopy models either represent the canopy through only one layer for city to regional scale applications or describe in detail buildings for only local scale applications. Single-layer canopy models may miss important mechanisms occurring within the canopy while detailed canopy models are too time consuming to be applied over several districts (neighbourhood scale). To overcome these limitations, we propose an intermediate approach with a multi-layer canopy model where meteorological fields are solved within and above the canopy and where the canopy roughness elements (building, vegetation) are represented through a drag approach. The model is further able to account for green infrastructures, such as, vegetation on building roofs and walls. The complete model, called ARPS-VUC, is thus applicable from neighbourhood to regional scale.

ARPS-VUC is used here to evaluate the impact of vegetation on the local microclimate of an idealized homogeneous urban canopy. To that purpose, we defined different canopy configurations with various degree of revegetation (small and high vegetation, green facades and roofs). Complete diurnal cycles were simulated for each configuration with meteorological conditions corresponding to a sunny summer day. Simulations show that the cooling effect of vegetation changes in amplitude and during the day following the type of vegetation.

Within the canopy, simulations reveal that trees induce a larger air cooling during daytime (-2 ºC) than small vegetation on ground (-1 ºC) and on building wall surfaces (-2 ºC). This is explained by the tree shadowing effect. This cooling is accentuated in presence of both trees and small vegetation on ground and building surfaces (-3 ºC). These first results are in agreement with recent studies (e.g., Leuzinger et al. 2010, Lindberg and Grimmond 2011, Hall et al. 2012).They further demonstrate the potentiality of our model to evaluate the impact of vegetation on local microclimate.

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Lindberg, F. and Grimmond, C.S.B. (2011) The influence of vegetation and building morphology on shadow patterns and mean radiant temperatures in urban areas: model development and evaluation. Theoretical and Applied Climatology, 105 (3-4). pp. 311-323. ISSN 1434-4483 doi: 10.1007/s00704-010-0382-8

Luzinger S., Vogt R. and Korner (2010) Tree surface temperature in an urban environment, Agricultural and Forest Meteorology 150, 56–62.

Modelling Radiative Exchange in a Vegetated Urban Street Canyon Model

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One of the key findings of the recent international urban land surface model intercomparison (PILPS-urban) was that models do not capture the magnitude and temporal variability of the latent heat flux relative to observations. This is despite many of the schemes including a vegetation component, which is typically represented by separate vegetation tiles or, in a limited number of models, explicitly within the urban scheme. The inability to reproduce the latent heat flux suggests that many schemes do not accurately represent urban vegetation and do not account for the impact of urban surfaces on vegetation physiology. PILPS-urban did however suggest that there was an advantage in using an integrated vegetation scheme as the range in performances of models using the separate tile was larger. This raises the following question; can we improve model accuracy of urban moisture fluxes by including vegetation explicitly within an urban land surface scheme? To address this question an integrated vegetation scheme is being developed for the Met Office – Reading Urban Surface Scheme (MORUSES) to explicitly include vegetation in the form of urban trees and natural surfaces (e.g. grass). The new vegetation scheme is tested within a 2D infinitely long street canyon, with the aim of improving urban weather forecasts and to provide a tool to test the mitigation of extreme heat events through urban greening. This study presents the theory and initial results for the first aspect of the new scheme, radiative exchange within a vegetated urban street canyon. An analytical method was developed based on existing relations and applied to determine the viewfactors for calculation of the longwave radiation budget between the surfaces within a non-turbulent street canyon, with a range of aspect ratios, containing a representation of an urban street tree. Unlike previous methods for modelling radiative exchange, which often assume that the wall and road surface have the same equilibrium temperature, this work investigates the non-trivial radiative exchange problem of vegetated (tree and grass) and urban surfaces that are likely not to be in equilibrium due to the impact of vegetation physiology on canopy temperature.

Wind velocity profile observations for roughness parameterization of real urban surfaces

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The logarithmic law is used widely in engineering practice to describe wind profiles. Vertical profiles of horizontally averaged wind velocity can be fitted by the logarithmic law even in built-up areas, allowing estimation of urban surface roughness based on parameters such as roughness length and displacement height. Such roughness parameterization of urban surfaces is very important, particularly for mesoscale weather simulation, because it is difficult to implement calculations incorporating fully resolved roughness elements in real urban areas.

Conventional roughness parameterizations for urban surfaces have typically used urban morphological parameters such as the building plan area fraction (i.e., the ratio of the plan area occupied by buildings to the total surface area) and the frontal area index (i.e., the total area of buildings projected into the plane normal to the approaching wind direction). It was noted in the previous research that the roughness height is related primarily to the frontal area index. However, the value of the frontal area index for a real urban area depends on the wind direction, implying that there is potential for the roughness height to vary with the wind direction. Although several previous studies have considered computational fluid dynamical or wind tunnel approaches to urban roughness parameterization, few have attempted to consider real urban areas, fewer still have considered the role of wind direction. In the present study, we conducted observation of the wind profile for 1 year above a high-density built-up area in Tokyo, Japan, using a Doppler lidar system. The observation results provide a database of the horizontally averaged turbulent statistics, from which we obtained roughness parameters for each wind direction. We compared our results with the roughness parameterizations of previous studies. The wind profiles were influenced not only by the above mentioned urban morphological parameters, but also by the maximum building height, the standard deviation of building height, and the plan area-weighted average building height. Future works will focus primarily on an empirical roughness parameterization based on these observation results.

Calculation method for outdoor air temperature of wooded architectural complex

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Developed by Hoffman and his group, the CTTC model is capable of calculating dynamic change of outdoor air temperature for architectural complex and the Green CTTC model is capable for complex with vegetations. However, the Green CTTC model was only tested in hot-dry cliamte in middle or high lattitude areas, and its validality for hot-humid climate in low lattitude areas is still remained unknown. Moreover, the Green CTTC model counted the convective heat flow of trees into ground, which is inconsistent with the fact that any convective heat flow can have direct impact on air temperature. Facing the above problems, this paper is aimed to propose and test an improved Green CTTC model in hot-humid area of China. The new model was established by directly counting the impact of convective heat flow of trees on rising of air temperature. In order to achieve the unknown factor, that is the ratio of convective heat flow to absorbed solar radiation for trees, several field experiments were conducted on various communities with trees in Guangzhou. The average outdoor air temperatures were measured in sunny summer day and the ration was determined for the improve Green CTTC model. The model was tested by using the experimental results of a commnunity and the results show that the improved model is more acurate and applicable for hot-humid area of China than the original model.

An intra-urban nocturnal cooling rate model

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Nocturnal urban heat island (UHI) and intra-urban heat island (IUHI) mainly develop through differences in cooling rates. The cooling process consists of two distinctive phases. In the first phase, around sunset, dense urban areas cool more slowly than more open sites, creating large intra-urban temperature differences that are preserved during the whole night. The intensity of this differential cooling is mainly determined by surface characteristics (geometry and material), prevailing weather conditions and season. On the other hand, the cooling during the rest of night, in the second phase, is independent of the surface characteristics.

In this study, we investigated how intra-urban cooling rates in the two phases are statistically related to prevailing weather conditions, season, and sky view factor using observation data from Gothenburg, Sweden. Based on the results, a simple statistical intra-urban nocturnal cooling rate model was developed. The model requires only commonly-used meteorological variables and sky view factor.
It was shown that the most intensive cooling rate at an open site, in the first phase, was chiefly dominated by the clearness of the sky and wind speed, i.e. the weather conditions. The cooling rate also had a linear relationship with maximum daily air temperature, which can be treated as the seasonal effect. Under clear sky condition, the magnitude of the cooling rate significantly decreased with lower sky view factor, but, under cloudy conditions, the cooling rate varied less or little. In the second phase, cooling rate seemed to linearly decrease as the night progressed and the slope of the decrease was determined by the clearness of the sky.
The model was evaluated using three additional datasets, one from Gothenburg, one from London, UK and one from Ouagadougou, Burkina Faso. Gothenburg and London are classified to have a marine temperate climate (Cfb) and Ouagadougou has a tropical steppe climate (BSh) according to Köppen climate classification. The model simulated cooling rates along a smooth profile statistically determined, while observed cooling rates often fluctuated through night. Nevertheless, the model estimated well the total amount of cooling during the whole night. This resulted in the well-simulated nocturnal air temperature. Modeled cooling rates were deviated from the observation at the sites where the large effects of anthropogenic heat and evapotranspiration were present. The effects were not included in this model yet but were found to be significant.

This model can be used for multiple applications such as nocturnal human thermal comfort estimation and climate-sensitive urban planning and design.

An empirical approach to estimate the biogenic components of CO2 flux over different ecosystems

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Carbon fluxes represent the net exchange between an ecosystem and the overlying atmosphere. In urban areas, it is due to the sum of biogenic components (ecosystem respiration and photosynthesis processes) and anthropogenic contributes (human and animal respiration, transportation, domestic heating/cooling).
Suburban areas, with typically a higher vegetation surface fraction than city centers, show a similar behavior to natural ecosystems and the diurnal carbon uptake by plants and lawns can help in reducing CO_2 emitted by human activities. This effect is particularly evident during the growing season.
Recent studies have shown that the natural cover fraction (obtained as the difference between total land cover and urban fraction) can be used as a proxy to estimate annual carbon exchange in urban sites.
Natural (vegetation and bare soils) and urban (buildings and impervious) cover fraction can therefore address to an estimation of carbon emissions.
The general aim of this work is the development of an empirical model to simulate the biogenic components of the vertical CO_2 flux based on environmental variables and vegetation cover fraction that can be applied over different ecosystems (natural, agricultural, urban, and suburban). In particular, in urban and suburban ecosystems it can allow to investigate the role of vegetation in acting as a carbon sink or source.
The advantage of such a model is that the estimation of CO_2 flux is based on a few and commonly measured variables, such as global radiation and vegetation cover fraction.
The empirical model simulates the soil and vegetation respiration and photosynthesis. It is developed using CO_2 flux measurements over different ecosystems, obtained with Eddy Covariance observations both in experimental sites and from literature.
A first validation, both over natural and suburban sites, is proposed here, and results will be shown.

NOMTM3: Computational Fluid Dynamics models

Thermal stratification and vegetation effects on the urban microclimate – a CFD case study

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Increasing urbanization renders both challenges and opportunities in myriad ways. While the job prospects, good living standards etc. belong to the latter category, the former include land scarcity, urban heat island phenomenon, meeting the needs such as infrastructure, resources etc. of increasing population. Of these, understanding urban microclimate, especially in densely populated cities is very crucial as it provides the basis for creating a highly liveable residential town. Although, several urban studies have been done in the past, most were conducted in mid-latitude regions and only very few in the tropics and sub-tropic regions.

Therefore, we aim to develop an urban microclimate – multi-physics integrated simulation tool (UM-MIST) that will enable town planners, architects, policy makers etc. to develop more sustainable cities, and which will provide better insights into the flow physics in a densely populated tropical city like Singapore. This multi-physics tool will incorporate the effects of thermal stratification, vegetation and solar irradiance on urban flows, and enable the whole master planning, urban design & environmental modelling to be carried out in a single urban digital platform.

The preliminary study will consist of CFD simulations for a small urban site (less than 0.5 km2) in Singapore. This urban site comprises of various complex features such as high-rise residential buildings of approximately 50m height, low-rise commercial buildings of approximately 10m height, courtyards, vegetation, roads etc. The objectives of this preliminary study are to (i) represent all the complex features of the geometry to the required detail, (ii) perform robust meshing, and (iii) analyse the effects of the presence and absence of vegetation in both neutral and unstably stratified flows. The steady-state RANS simulations will be carried out using Star-CCM and OpenFOAM and preliminary results will be presented in detail at the conference.

High resolution numerical study of wind, thermal effects and pollution dispersion in urban neighborhoods in Toulouse and Marseille

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Detailed, high resolution, 3D numerical simulation are used to study short episodes of local urban climate and pollution dispersion in the neighborhood of Bordelongue in Toulouse and Saint Marcel in Marseille in the framework of the French ANR project EUREQUA. These urban areas consist of various types of buildings and obstacles: house districts, tower blocks, highway, some local streets, vegetation areas, etc. The 3D geometry of this urban area was constructed with an in house tool developed around the open-source geometry and mesh generator SALOME, based on the available geophysical data SIG from the French geographical institute (IGN). The open-source computational fluid dynamic (CFD) code Code_Saturne, with the atmospheric option developed at CEREA, was used to carry out the simulations. The atmospheric model already implemented by solving the Navier-Stokes equation with a k-epsilon turbulent model is used to compute the air flow in the urban area. It is coupled with a newly implemented heat transfer and radiative model, which is able to take into account the effects of solar and atmospheric radiation, local traffic, as well as the heat transfer at the solid surfaces (building walls, ground, roads, etc). The vegetation area, principally composed with trees, is considered as a porous layer which induces a drag force to the air flowing through it. The pollutants of the local traffic emissions are considered as passive scalars, which are solved by the transport equations, transported by local winds and dispersed by local turbulence. The global meteorology condition is taken into account by using the measurement data at the meteorological station installed in the area during the different campaigns of 72-hour measurements in the framework of ANR project EUREQUA or by using results from mesoscale simulations performed over the region using the Meso-NH code. The simulation results of the air flow, heat transfer, and pollution dispersion are compared with the various measurements obtained both with a mobile station circuiting along a trajectory through several regularly spaced observation points in the neighborhood and fixed stations especially set up in the area during the campaigns. These validation results will also be compared with sociologically analyzed results based on the subjective perceptions of the environment by the local residents during the campaigns. The numerical tool and collected results can be used for the future studies of urban renewal scenarios.

Numerical study of the influence of albedo on the microclimate of Bergpolder Zuid, Rotterdam

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The rapid trend towards urbanization has increased the popularity of studies investigating urban microclimates. Factors such as the Urban Heat Island (UHI) effect and summer-time heat waves can have a significant influence on outdoor thermal comfort levels and building energy demand. For the investigation of urban microclimates, historically, observational approaches (such as field measurements) have been employed and lately, with the advancements in computing power, computational methods are becoming more popular because of the possibility to conduct scenario analysis. Computational Fluid Dynamics (CFD) is one of these computational methods which has proven to have the potential to accurately predict urban microclimate. Compared to other computational methods employed to investigate urban microclimate (i.e. Energy Balance Models), CFD has the capability to couple flow field with the temperature field at the cost of more computational resources. In this study, CFD simulations are performed to predict urban temperatures in the Bergpolder Zuid region, located in Rotterdam. The area is planned to be renovated and one of the aims is to increase its climate resilience. Based on the municipal drawings of the Bergpolder region, a high-resolution computational domain is generated. The computational domain has a hexagonal shape with an edge length of 2.4 kilometer and a height of 400 meter. In total, the grid consists of 6,610,456 hexahedral cells. The simulations are performed using the 3D unsteady Reynolds-averaged Navier-Stokes (URANS) equations in combination with the realizable k-epsilon turbulence model. Several physical phenomena influencing urban microclimate such as wind flow and heat transfer (conduction, convection and radiation) are considered in the simulations. As for evapotranspiration, during morning (6:00 – 11:00 h) and afternoon (15:00 – 18:00 h) a constant and uniform sink value of 80W/m2 is imposed and during noon time (11:00 – 15:00 h) the sink value is specified as 130 W/m2 (at the ground level). Meteorological data used in this study is obtained from the hourly averaged dataset of the Royal Dutch Meteorological Institute (KNMI) by the Rotterdam weather station, which is located near Rotterdam airport, 4 km northwest of Bergpolder Zuid. In the first part of this research, resulting surface temperatures on the region were validated using experimental data from high-resolution thermal infrared satellite imagery, which were recorded during the heat wave of July 2006. The resulting average surface temperatures showed a deviation of 7.9% with the satellite imagery data. In the second part, the investigation focused on the effect of different physical parameters, such as thermal diffusivity and albedo on outdoor thermal comfort, considering the validated time range. Preliminary results show that changing the thermal diffusivity of the building materials and albedo value of the ground cover can influence the average surface temperatures in an urban environment significantly. Complete results regarding the effect of physical parameters on outdoor thermal comfort are still being evaluated and the results will be available in the full paper.

Advanced numerical analysis on sensible heat flux from building external surfaces to the surrounding atmosphere using a heat balance simulation and CFD

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Sensible heat flux from building external surfaces is one of the essential factors warming the atmosphere around buildings and causing urban heat island effect. Field measurements are difficult to cover the whole sensible heat fluxes from the building external surfaces with complex geometries and the scales of wind tunnel experiments are different from that of reality. Therefore numerical analysis is considered to be effective method for grasping the sensible heat flux from the whole building surfaces. Although surface temperature, air temperature and air flow near the building surfaces, all of which dominate the sensible heat flux should be considered in the prediction, previous studies did not deal with these mutual and detailed relations.

This study applies the 3D CAD-based heat balance simulation, which was developed by the authors' group and can calculate the detailed surface temperature distribution taking into account the building geometry, and a CFD simulation. By using Low Reynolds number k-ε model (Low-Re) for the CFD simulation, we can simulate air temperature and wind speed distribution inside the wall boundary layers. The purpose of this study is to examine the method to predict the sensible heat flux from the building external surfaces by using coupled analysis of the heat balance simulation and the CFD (Low-Re) simulation. And this study is also implemented to figure out the appropriate prediction formula for CHTC (Convective heat transfer coefficient) that can be used for the prediction of heat fluxes by high Reynolds number k-ε model (High-Re), in order to apply this method to the analysis of urban block scales.

Firstly, we used High-Re and Low-Re to predict CHTC and compared these results with the result of a wind tunnel experiment. It is shown that the Low-Re showed the similar result as the wind tunnel experiment. Then we used coupled analysis of the heat balance simulation and CFD (Low-Re) to predict the sensible heat flux from the building external surfaces of a house complex. We confirmed that with considering the building geometry, wind speed attenuation inside veranda spaces and undeveloped boundary layer on the edge affect the prediction of sensible heat flux. Finally we found out that the correlation between CHTC and the effective wind speed near the building surface was high in forced convection dominant cases. The experimental approximation formula obtained from the analysis is considered to be appropriate for the heat flux prediction using High-Re for urban block scales.

Large eddy simulation of internal boundary developments over a huge urban area with 2m resolution

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We conducted Large eddy simulations (LES) of internal boundary layer developments over a huge urban area, i.e., 19.6 km in stream-wise and 4.8 km in span-wise, with 2m spatial resolution. The domain is a densely built-up urban area in Tokyo coastal region, including the Pacific Ocean at the inflow boundary. All the individual buildings without vegetation are explicitly resolved thanks to its high spatial resolution. A new LES technology using the lattice Boltzmann method has advantages in utilizing parallelized GPU computations, and contributes to realize such huge and detailed turbulence analysis of realistic urban boundary layers. The spatial development of internal boundary layer along the fetch from the coastal line are simulated and compared with the previous theories. Very large scale motions of longitudinally-enlarged streaky pattern are visible everywhere within the internal boundary layer, and increase the length (a few kilometers) and distance (several hundred meters) in accordance with the fetch. The similar streaky patterns are observed by a Doppler rider conducted in the same region. High buildings or building clusters are likely to trigger streaks.

Spatial Distribution of the Gust Index over an Urban Area in Tokyo

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The wind flow over an urban area induced the gusty condition due to its heterogeneous landscape. It might lead to the unpleasant events either towards the pedestrian or any structure within the area. It motivates a study to represent the situation by an indicator called gust index. Therefore, a feasible and realistic large eddy simulation (LES) paired with the lattice Boltzmann method (LBM) over a 2 m resolution of a huge urban domain of Tokyo was conducted. This paper also proposed an appropriate definition of the gust index that characterized the level of gustiness of the urban area. The gust index was calculated by normalizing the maximum wind speed, umax in 10 minutes time duration to the freestream velocity, $U\infty$. An understandable gust index map was prepared for an urban area in Tokyo. It can be referred to point out the area that creates the high gust occurrence. The potential factors such as the ratio of the open space to the building plan area, building height and size that contribute to the high gust index also will be discussed.

Key Words : Gust index, urban area, huge domain, LES, LBM

Large eddy simulation and bulk parameterization of momentum and heat transport in urban canopies: challenges and applications

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Understanding the turbulent transport of both momentum and scalars in urban environments is important for urban climatologists, boundary-layer meteorologists, and fluid dynamicists. Over such very rough surfaces caused in a large part by the buildings, the transport of momentum and scalars are dissimilar - form drag controls momentum exchanges with the surface while viscous exchanges continue to dominate for scalars. A numerical study is carried out using large-eddy simulations to investigate this dissimilarity. The development of key components of the code used in this study, and its evaluation will be presented in detail. Geometric parameters such as the frontal area index and the plan area index are then varied independently to examine their impact on turbulence and transport characteristics. The surface complexity is shown not only to increase the anisotropy of the flow, but also to modulate the efficiencies of momentum and scalar transport. Results suggest that distinctions between turbulent momentum and scalar transport make the parameterization of surface-air exchange over urban areas a non-trivial problem.

Generation of artificial inflow turbulence including scalar fluctuation for LES based on Cholesky decomposition

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In most attempts conducted to couple engineering computational fluid dynamics (CFD) models with mesoscale meteorological model (MMM), RANS approaches have been selected as turbulence models. Recently, several attempts to couple large-eddy simulation (LES) and MMM have already been reported due to growth of computer resources. In order to couple LES with MMM successfully, One of the biggest unresolved issues is the generation of inflow turbulencewhich satisfies not only turbulent statistics but also instantaneous turbulent structures. For this purpose, several techniques have been developed in the fields of wind engineering and building science. These pioneering techniques to generate inflow turbulence within neutral boundary layer are classified into two categories. The first, and also the simplest, is to store the time history of velocity fluctuations given from a preliminary recycling LES computation (e.g. Lund et al., 1998; Kataoka and Mizuno, 2002). The second is to generate inflow turbulence artificially which prescribes turbulent statistics without LES (e.g. Lee et al., 1992; Iizuka et al., 1999; Klein et al., 2003; Xie and Castro, 2008; Xuan and Iizuka 2013). In recent years, the non-isothermal LES within urban boundary layer have been carried out to investigated heat island phenomena and so on. When LES is applied to a non-isothermal field, not only inflow velocity fluctuation but also temperature fluctuation should be reproduced. About the generation of inflow turbulence considering temperature fluctuation, only a few studies have been conducted based on the method by using the recycling LES which mentioned above (e.g. Tamura et al., 2012; Jiang et al. 2012) in wind engineering field.

This paper aims to propose a new method to generate turbulent fluctuations of wind velocity and scalar quantities such as temperature and pollutant based on the Cholesky decomposition of time-averaged turbulent fluxes tensor of momentum and scalar. The artificially generated turbulent fluctuations satisfy not only the prescribed profiles of turbulent fluxes of wind and scalar but also the prescribed spatial and time correlations. Following the method proposed by Xie and Castro (2008), two-dimensional random data are filtered to generate a set of two-dimensional data with the prescribed spatial correlation. Then, these data are combined with those from previous time step by using two weighting factors based on an exponential function. The method was validated by applying it to a LES computation of contaminant dispersion in a half channel flow.

LES simulations of forced convective heat transfer at the surfaces of an isolated building using non-conformal grid

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The knowledge of external convective heat transfer coefficients (CHTC) is of great importance for many engineering applications. This is the case for building applications for example, where an accurate evaluation of CHTC is needed to calculate convective heat gains and losses from building façades and roofs. It is also important to evaluate the thermal performance of double-skin façades, solar collectors and greenhouses. Assessment of the CHTC can be performed by full-scale measurements, wind-tunnel experiments or Computational Fluid Dynamics (CFD) simulations. When CFD is considered, it can be a useful tool to determine CHTC in urban areas. In these cases, Large Eddy Simulation (LES) should be used because it can capture the complexity of the flow pattern much more accurately than Reynolds-Averaged Navier-Stokes (RANS) simulations. However, generating high-resolution high-quality computational grids for LES simulations of the CHTC is not straightforward. Ideally, LES grids, where the grid size is used as a filter, should consist of cubical cells. In addition, grids for assessing CHTC should have a very high resolution near the building surface in order to fully resolve the thin laminar sublayer (often only a few mm in thickness) which represents the largest resistance to convective heat transfer. In order to avoid a prohibitively high total number of cells and the need for excessive computational resources, we can resort to the development of a grid, consisting of cubical cells, that is refined gradually in all directions, i.e. a non-conformal grid. Nevertheless, the accuracy of this type of grid for the case of buildings in the highly turbulent atmospheric boundary layer still needs to be verified. Therefore, in this paper, the performance of non-conformal grids is evaluated. The evaluation is based on verification by a comparison between conformal and non-conformal grids and on validation with wind-tunnel measurements of surface temperature of a reduced-scale wall-mounted cube. The resulting number of cells for the conformal and non-conformal grid is 9.710.472 and 1.431.789 respectively, where both grids have the same near-wall resolution (y+ value). The results obtained by the non-conformal grid are in a very good agreement with the results by the conformal grid. In this case, the average difference between simulated surface temperatures on all surfaces of the cube is about 0.9% Moreover, the general agreement between the experimental results and CFD results using non-conformal grid is very good. For example, the average and maximum absolute deviation in surface temperature from the experiments are 2.0% and 5.5%, respectively. The verification and validation studies verify the accuracy of non-conformal grid for the investigation of CHTC for a wall-mounted obstacle. Finally, this means that the use of the non-conformal grid reduces the total number of cells by a factor 6.8, without compromising accuracy. To the best of our knowledge, LES CFD simulations of CHTC for a full-scale building have not been performed. In the second part of the paper, LES simulations of CHTC at the surfaces of a full-scale building are performed using a non-conformal grid. Further information concerning boundary conditions, solver settings and results will be presented in the full paper.

Analysis of wind turbulence in canopy layer at large urban area using HPC database

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In order to accurately predict the wind flow in canopy layer of large urban area, we introduce LES(Large eddy simulation) based on BCM(Building Cube Method) which is formulated on very fine Cartesian mesh system. Houses and buildings were not modelled and directly reproduced their shapes, because the wind profile parameterization requires the correct estimation of local flow field in the canopy layer close to the ground. Recent high-performance computing (HPC) technique has developed distinctly, so high-resolution computation becomes able to be applied to flows around a complicated configuration such as actual urban area. In this case we have to deal with buildings, vegetation and street etc. as a part of numerical model. Actually LES using the Cartesian coordinate encounters the incorrespondence of directions between the street lines and the discretized mesh lines. Very fine mesh system by BCM can solve this problen supported by the external forcing technque at the boundary named IBM(Immersed Boundary Method). Also, in this numerical scheme, computational process is so simple that the parallel algorithm and the memory access obtain the perfect efficiency. It is strongly expected that these advantages make it possible to efficiently simulate the flow around very complicated shapes with various scales consisting of a large variety of urban parts. In this study, we have applied LES by BCM to the wind flow estimation over the real complicated urban surface at straightforward and inclined wind directions to the main streets. Computational domain is several kim square with resolution of 1m for urban area. We also have exhibited the database of the wind turbulence in canopy layer among the buildings.

We examine the numerical model for the BCM and 3D contouring surfaces of Q values. We can recognize the 3D vortical structures in the wake of buildings. Conical vortex is recognized to be reproduced on the roof clearly. These local flow structures are expected to provide the appropriate turbulent characteristics in urban canopy layer. It can be found that, based on the present LES results using BCM, the turbulence structures at inflow and among a pack of tall buildings are effective in comparison with the other data obtained by experiment. We can confirm that the BCM model estimates the wind flow above and within urban canopy with sufficient accuracy even at inclined wind direction to the main streets.

Using the HPC database for LES of turbulent boundary layer flow over urban-like roughened surface, analysis of turbulent wind in urban canopy is performed. Actual buildings and houses, definitely larger effective height (height to boundary layer thickness) than those on conventional rough wall, are directly arrayed on the ground surface and above- and within-region equilibrium profiles of mean velocity and turbulent statistics are investigated. Also, the turbulence structures in the urban canopy are elucidated and urban canopy parameterization is discussed.

The stone forest as a small-scale field model for urban climate studies

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More than half of the world's population are now living in cities. Cities are hot areas which not only responsible for local and regional climate change, but also suffering a rigorous urban warming. Understanding, as well as stopping the urban warming phenomena are always vital in urban climate research. However, the major anthropogenic factors leading to urban warming are very complex, such as the complicate interactions of increased anthropogenic heat, heat storage, and solar radiation trapping, reduced evapotranspiration, and urban ventilation etc. Field measurements as well as physical and numerical models have been widely used to understanding the variety urban warming phenomena and energy transfer processes. Besides, the reduced-scale physical models, which are the simplified models of the real cities, can help to study the physical processes of urban climate.

Here, we present a field study in the stone forest as a small-scale field model of urban climate research. The field model was conducted in the Stone Forest Scenic Area (24.81N, 103.32E), which located in Yunnan Province, Southwest China. The stone forest is a set of limestone formations, range from 10-30m. The heights of the stones are similar with the heights of buildings in cities. Besides, the thermal properties of the stones in the stone forest and the concrete of the man-made structures within the cities are approximate. Thus, the thermal environment in stone forest can be considered to be a simulation of thermal environment in the city. We conducted the field studies and numerical analysis in the stone forest for 4 typical urban morphology and environment scenarios, including high-rise compact stone forest, low-rise sparse stone forest, garden stone forest and isolated single stone. This field measurement shows several common phenomena between the Stone Forest and cities. However, unlike cities, there are limit air pollution and anthropogenic heat in the Stone Forest. Thus, we believe that the stone forest can be a reasonable small-scale field model of urban climate studies.

Interaction of severe convective gusts and typical urban structures

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Severe convective gusts may reach wind speeds that exceed those related to synoptic-scale winter storms. Associated with this is a considerable damage potential for buildings and critical urban infrastructure. As reported in literature downwind speeds up to 200 km/h can be reached exceeding by far the design wind velocities in wind loading codes and national standards. Furthermore, wind loading codes presume a horizontal wind and do not consider a vertical component, which can become dominant in the case of convective descending gusts. Unfortunately, essential information concerning probability, spatial extent and maximum speed of convective gusts is rare. Furthermore, due to the fact that convective gusts are of local-scale nature, it is believed that they are underrepresented in wind statistics of meteorological stations. All this leads to a considerable lack of knowledge of the interaction of convective gusts with urban structures.

In the paper, results of an experimental wind tunnel project are presented, which aim at improving the basic knowledge of the interaction of convective gusts with typical urban built-up structures. Gusts of defined properties were generated by a jet tube connected to pressurized air. The pressurized air was controlled by a fast pneumatic valve. Thus, gusts of pre-defined duration, extent, and tilt could be simulated. The interactions of the gusts with scaled models of typical urban structures were analyzed. Flow quantities were measured by laser methods and parameters of influence were identified which are crucial for wind amplification in urban structures.

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Coupling of numerical weather prediction models and physical simulations for urban wind environment

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There are three ways to perform the parametrization of the urban environments in the NWP models: i) to vary the surface parameters in NWP model – slab models, ii) to couple an urban canopy layer model with NWP model, and iii) to couple microscale CFD model with NWP model. Slab models treat the urban environments as a flat terrain with a larger roughness length and smaller albedo compared to the rural areas. The urban canopy models can be divided into two groups: single-layer and multi-layer urban canopy models. In the single-layer urban canopy models, the urban geometry and all the physical processes that take place in the urban canopy layer are constrained within the first layer of the NWP model. Unlike the slab models, the single-layer urban canopy models can account for the interaction between the solar radiation and the urban geometry, as well as for the existence of an exponential wind profile inside the urban canopy layer. The multi-layer urban canopy models, being the most sophisticated models for parameterization of the urban environments, take into consideration the vertical distribution of the sources and sinks of momentum, heat (and moisture) within the urban canopy layer. Thus, the multi-layer urban canopy models interact with several NWP model levels. Yet another approach to investigate and parameterize the urban environments is to couple the NWP model with a CFD model. In this approach, the NWP model outputs in the form of velocity, turbulence (and sometimes temperature) profiles are used as the inputs for the CFD models. The CFD models are then used to resolve the flow and heat distribution in the urban environments in great detail. Afterwards, the CFD results can be fed in the NWP model as surface boundary conditions.

In this study, we propose another approach for the investigation of the urban boundary layer. Namely, instead of coupling the NWP and CFD models, the NWP models could be coupled with physical simulators. A 3D physical model of an urban environment can be placed inside of the new generation of large multi-fan wind tunnels or 3D and time–dependent testing chambers such as the WindEEE Dome at the Western University. Then, the incidence wind and turbulence profiles (i.e. profiles at the edge of the urban environment) determined by NWP modelling can be physically modeled as inflow boundary conditions. The advantage of the physical micro-scale modeling resides in their demonstrated capacity to simulate a large spectra of flow scales from the top of the urban layer to the level of the detailed flow patterns around buildings and structure. For instance, for wind engineering problems the physical (wind tunnel) simulators are preferred as they can model peak values of both flow and surface pressures which are essential for determining design loads. Pollution dispersion, pedestrian comfort and any other urban wind environment studies also benefit from the same capacity of reproducing a large spectra of scales.

The present research is aiming at correlating NWP models with large scale physical simulations in the WindEEE Dome at Western University. WindEEE is the world's first 3D wind chamber, consisting of a hexagonal test area 25 m in diameter and an outer return dome 40 m in diameter. Mounted on the peripheral walls and on top of the test chamber are a total of 116 individually controlled fans and 202 louver systems. Additional systems, including an active boundary layer floor and "guillotine" allow for further manipulation of the flow. These systems are integrated via a sophisticated control system which allows manipulation of the flow with multiple degrees of freedom. WindEEE can generate straight flows but with a variety of time and space correlations as well as translating tornadoes or downbursts as large as 5 meters in diameter. These flow capabilities coupled with large scale detailed urban orography models and the capacity of NWP models to predict inflow conditions opens a new avenue in mixed simulation of urban wind environments.

NOMTM6: Urban Climate measurement networks

Network optimization of urban heat island measurements -Effect of reduction of observation points

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Many cities have sensor network for heat island measurement and it is possible to observe the spatial pattern of meteorological data in detail. In the design and operation of a meteorological measurement network, a larger number of measurement points are better. But considering the labor and cost, a smaller number of them are better if the same result can be obtained. The effect of reducing observation points from an existing meteorological measurement network is considered in this study.

We consider the example of temperature data of the Tokyo metropolitan area (Extended METROS) which has about 200 measurement points. The effect of reducing observation points from an existing meteorological measurement network is considered, using sampling with clustering. The data obtained from May 2007 to October 2008 (18 months, every hour) were used for the analysis. 10% to 90% of the data were reduced and sampled from the original data in 10% interval. The sampled data and the original data were interpolated by using Inverse Distance Weighing method and the original and the sampled 2D images were made. The correlation between the original and the sampled 2D images are calculated and the correlation is used as an index of the similarity of the images.

The results indicated that the data with up to 30% reduction in measurement sites yield more than 0.9 correlations, which means the similar temperature patterns with the original data. The methods presented in this study can be applied in other meteorological measurement networks in evaluating the reduction of existing points of the networks.

Challenges and benefits from crowd-sourced atmospheric data for urban climate research using Berlin, Germany, as testbed

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Provision of atmospheric data from observational networks at high spatial resolution and over long time periods remains a challenge in urban climate research. Classical observational networks are designed for the detection of synoptic atmospheric conditions and rarely suitable for city-specific and intra-urban analysis. Therefore, using citizens as data provider offers huge potentials, especially in urban areas due to the high population density.

The concept of citizen science is not new, especially in the field of ecology (Dickinson et al. 2012). This concept relies on the active participation of citizens to contribute to research. A number of efforts have been made in recent years concerning atmospheric applications, e.g. mapping of atmospheric aerosols with smartphones (Snik et al., 2014) or involving citizens in observational networks such as “CoCoRaHS” (Community Collaborative Rain, Hail and Snow Network, http://www.cocorahs.org/) or the “Citizen Weather Observer Program” (http://wxqa.com). Another approach to acquire huge amount of data is the concept of crowd-sourcing, defined by Dickinson et al. (2012) as “getting an undefined public to do work, usually directed by designated individuals or professionals.” For instance, Overeem et al. (2013) took battery-temperature measurements from smartphones to derive urban air temperatures by using data from the smartphone application ‘OpenSignal’ (opensignal.com), while Mass and Madaus (2014) exploited air-pressure measurements from another application called ‘pressureNET’ (pressurenet.cumulonimbus.ca) to simulate an active convection event in the United States.

The netatmo system (www.netatmo.com) acts as an intermediate between active citizen science and crowd sourcing of passively acquired data. Netatmo is a private enterprise developing and distributing weather stations around the world for interested citizens to monitor their indoor and outdoor atmospheric conditions and sharing their records publicly. The netatmo weather station is cost-efficient and WiFi connection serves for data transfer, storage and visualisation via application software. Air temperature and relative humidity are measured both indoors and outdoors, the indoor device also records air pressure, CO2 concentration and noise level. While netatmo offers huge potentials due to the dense spatial coverage in many urban areas, the question remains if and how crowd-sourced data from this source can be suitable for urban climate research.

In a test phase during November 2014, we acquired public data (air temperature, relative humidity and air pressure) from more than 700 stations in Berlin and surroundings with a temporal resolution of one hour. Comprehensive analyses of quality and suitability of these crowd-sourced records includes the identification of problems that are user-specific, related to sensor accuracy, radiation shielding, and sensor set-up. This work will be based on meta-data analyses and own observations carried out with netatmo outdoor devices in comparison with standard scientific measurement equipment as well as statistical analyses and tests. If suitable, crowd-sourced atmospheric data can be used for evaluation of urban canopy models or spatio-temporal analysis of atmospheric characteristics of Local Climate Zones.
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First results of the data acquisition and analysis of microclimate conditions in Barranquilla, Colombia

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Urban climate conditions affect how cities will develop in the future, not only because of the impact on the energy consumption of buildings or on the environment, but also on human thermal comfort. For growing cities in tropical climates, urban microclimate becomes a relevant aspect for the design and planning of future developments. The aim of the overall research project is to establish the relationship between, microclimate data and building geometries using outdoor thermal comfort as an indicator, and to translate this knowledge into a parameterized design-feedback tool in order to explore 'design spaces' of urban forms in tropical climates [Tapias & Schmitt, 2014]. In this context, the goal of the first stage is a methodology to acquire local microclimate data with sensor technology for a period of one year in the tropical savanna climate of Barranquilla in Colombia.

The campus of the 'Universidad del Norte' is selected as the specific case-study area in Barranquilla. Within this urban settlement, four outdoor locations are identified for the data acquisition procedure. The selection is based on having four different orientations of pedestrian paths on a human scale. Additionally, one final location on a rooftop is selected in order to acquire general global data from the surrounding. For the acquisition of microclimate measurements, sensor technology in form of portable weather stations is used. One portable weathers station is installed for each of the preselected location. For the pedestrian scale locations, four of these mini portable weather stations are mounted at 1.2 meters high from the ground. These stations record measures of; temperature, humidity, rain fall, wind direction, wind speed (anemometer), and atmospheric pressure (barometer). For the location on the rooftop, an advanced portable weather station is mounted, which measures the same parameters plus solar radiation (pyranometer). The data are transferred permanently via internet. The data is being send to the web server (barranquilla.arch.ethz.ch/station1 - station5) and visualised through the WeeWx weather software.

The mini portable weather stations are successfully mounted and installed, recording data from different microclimate parameters. The wireless structure enables the long distance monitoring of the measurements from the weather stations. This measurement campaign is intended to last for one year, in order to acquire microclimate data for different weather periods. When the acquisition of the require data is finalised, the purpose of the next stage of the research project is to proceed with data processing and calculation of the outdoor thermal comfort based on the PET (Physiologically Equivalent Temperature) index using the RayMan model [Matzarakis: Rutz; Mayer, 2006].

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Climate moderation via green infrastructure – the potential to mitigate the UHI effect in Dar es Salaam

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Regulating urban ecosystem services can have an important role for offsetting the higher temperatures which tend to be associated with urban compared to rural areas. In the rapidly developing cities of sub-Saharan Africa, there is relatively little knowledge about phenomena like the Urban Heat Island effect and even less about intra-urban temperature variations. Similarly, evidence of the potential of regulating ecosystem services is also scarce.

This paper analyses temperature observations made at 64 fixed locations across two transects of northern Dar es Salaam, Tanzania. The city is situated on the eastern coast of Africa (6°48'S 39°17'E) and has a population over 4.3 million. Dar es Salaam's climate is generally hot and humid throughout the year, with an average temperature of 29°C and peak temperatures occurring during the austral summer (December-February). The city centre benefits from its coastal location but development can block the cooling effect of sea breezes.

Dar es Salaam can be characterised as having 11 high level Urban Morphology Types (UMTs). These, and 43 detailed UMTs, have been mapped for 2008 and 2002 for the wider administrative area (1502 square kms). Residential UMTs cover 46.5% of Dar es Salaam, followed by agricultural UMTs (40.4%) and a further 5.1% of the land area of the administrative zone is associated with other predominately vegetated UMTs. Important vegetation also exists outside predominantly green UMTs and proportional cover varies between classes. For example, condominium residential types contain 58% vegetation on average, compared to 42% in areas of mud/wood construction (often associated with low income settlements).

Air temperate data was collected using ibutton sensors over seven months (June 2012 - Jan 2013). This included the main dry season (June to September/early October), and the period of short rains termed "vuli" in Swahili (from October to December/ early January). Data were analysed against a rural reference point in Kibamba, located 24 km from the city centre (and at approximately 152m a.s.l). The results showed an elevation-adjusted nocturnal air temperature UHI intensity of up to 2°C in August 2012. Additional analyses were carried out in relation to urban morphological characteristics of the study sites, including the relative proportions of 11 different vegetated land cover types around the monitoring sites (such as large trees, small trees and shrubs, crops, bare ground, housing and other built surfaces). Development pressure is high and vegetation is rapidly being lost from both the peri-urban and urban core areas. Such changes have serious implications for enhancing the already evident UHI effect.

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High-resolution urban heat island measurements and electricity applications in birmingham, UK

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The Urban Heat Island (UHI) is one of the most well documented phenomena in urban climatology. Although a range of measurements and modelling techniques can be used to assess the UHI, the paucity of observations in urban areas is a significant limitation for many studies. As such, many UHI studies would benefit from high resolution air temperature data. Presently the only feasible way in which this can be achieved is by the use of dense sensor networks which are now becoming increasingly common in cities across the world. Indeed, this availability of such high resolution data is now enabling urban climate impacts to be investigated at an unprecedented granularity. This study investigates the spatial relationship between air temperature data obtained from the Birmingham Urban Laboratory, UK with electricity consumption data from across the city. In particular, the study highlights the added impact of the UHI during heatwave events on electricity consumption, when demand for fans and air conditioners is increased. The paper concludes by identifying the potential role of such networks in helping to forecast future electricity demand in cities.

Shanghai's Urban Integrated Meteorological Observation Network (SUIMON): case studies of applications

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Observations of atmospheric conditions and processes in cities are fundamental to understanding the interactions between the urban surface and weather/climate, improving the performance of urban weather, air quality and climate models, and providing key information for city end-users (e.g. decision-makers, stakeholders, public). Shanghai is one of a small group of cities with urban stations with long (>100 years) continuous records (Gherzi, 1950) (in Shanghai dating back to 1872). Today in Shanghai, there are a series of networks of different instrument types (e.g. automatic weather stations , weather radar, Met-towers, wind profilers, lightning mapping systems, remote sensing systems) that provide dense observations through a network of networks, referred to here as SUIMON (Shanghai's Urban Integrated Meteorological Observation Network). In this presentation, an overview of Shanghai's urban integrated meteorological observation network (SUIMON) will be presented, with examples of applications ranging (1) the heat island, sea breeze and convective weather, (2) photochemical and urban aerosol pollution, and (3) urban winds. The design and operation of the network, and the urban climate services it does and can support, are relevant to cities worldwide.

The Urban Heat Island of a middle-size French city as seen by high-resolution numerical experiments and in situ measurements – the case of Dijon, Burgundy

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This work aims at characterizing the spatio-temporal variability and features of the urban heat island (UHI) over the agglomeration of Dijon (north-eastern France; 260,000 inhabitants) under present-day conditions and during the boreal summer season (June through September). To that end, two complementary approaches are used:

• in situ measurements, using a network of 50 Hobo proV2 sensors measuring air temperature and specific humidity every 20 minutes, and implemented since June 2014 throughout the agglomeration;

• high-resolution (150m horizontal resolution) meso-scale atmospheric simulations performed using the WRF/ARW model coupled with the BEP-BEM urban canopy model.

Special attention was paid to the location of the thermometers. The sites were chosen to ensure a correct sampling of the various urban thermal environments such as described by the classification of Oke (2006). In order to ensure a representativeness of the neighbourhood and not merely the close environment, open locations are preferred, limiting shadows from the vegetation and nearby buildings. The sensors are fixed 3m above the ground surface, over the south face of public lampposts, with specific fixations designed to separate the measurements from the lampposts themselves. The density of our network enables us regionalizing in detail air temperature and humidity over the whole city.

Similar attention was also given to the static surface datasets used as surface boundary conditions for the climate modelling system (land-use maps, topography, urban morphology). Public and/or open databases developed by various French and European governmental services (Corine Land Cover, IGN, INSEE and OpenStreetMap databases) were used in order to obtain a generic and reproducible methodology, that can be used for any French city.

This presentation is the opportunity to first present the comparisons between both approaches and therefore quantify the capability of the climate modelling system (WRF/ARW - BEP+BEM) to simulate the main features of the UHI in Dijon during the 2014 summer period.

Urban climate monitoring system suitability for intra-urban thermal comfort observations in Novi Sad (Serbia) – with 2014 examples

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In 2014, urban climate monitoring systems were established in two neighboring European cities (Novi Sad, Serbia; Szeged, Hungary) based on Local Climate Zones (LCZ) classification system, GIS model calculations and field work. In the built-up area of Novi Sad (55 km2) 7 LCZ types and 2 LCZ land cover types in nonurban environment in the vicinity of the city were delineated.

Urban climate monitoring system in Novi Sad consists of 27 stations equipped with air temperature and relative humidity sensors distributed across all LCZs. This system provided 10-minute measured temperature and relative humidity data, as well as calculated human comfort (Psychologically Equivalent Temperature - PET) index values since June 2014.

Suitability of the developed monitoring system for human comfort observations in different built-up areas of the city and its surroundings was investigated. Preliminary results showed that during summer months heat waves PET index had surplus values (>6°C) in highest built-up types of the city (midrise LCZ type) compared to the nonurban areas (LCZ D – low plants), while human thermal comfort differences among other built-up LCZs were smaller. Also, largest differences occurred during evening and nocturnal hours.

Joint analysis of meteorology and air quality in Helsinki, using air-quality supersites and an observation network

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The over-arching objective of this study is to perform a substantially improved integrated assessment, regarding Helsinki's urban air quality and meteorology. For this aim, we will combine (i) the new, high-quality and extensive observations from both air-quality-measurement supersites in Helsinki, and additional AMS (aerosol mass spectrometer) and aerosol chemical speciation monitor (ACSM) measurements; with (ii) the drastically improved meteorological and climate measurement data that is available from "Helsinki UrBAN".

The FMI and the University of Helsinki have launched a state-of-the-art observational network for Helsinki's urban atmosphere, called Helsinki UrBAN (Urban Boundary-layer Atmosphere Network, http://urban.fmi.fi). The instruments within this network include a lidar, a ceilometer, weather stations, a sodar, eddy-covariance flux towers, a thermal camera, building surface thermometers and scintillometers. These measurements have not yet been used in an air-quality context.

The Kumpula air-quality supersite (Helsinki: SMEAR III) has been operational since 2004. Continuous measurements include particle size distributions, several gas phase compounds, and elemental/organic carbon (EC/OC). Since 2009, measurements have been with different aerosol mass spectrometers: AMS and ACSM. In this study, the AMS data from SMEAR III and downtown Helsinki will be used to characterize particulate matter. The latter is a monitoring station, in which measurements have already been conducted for one year using ACSM. AMS data will be used for source identification and for timing of certain types of pollution. Typical cases include long-range transport of particulate matter or formation of ground-level elevated concentrations of particles, due to temperature inversion.

Recently, AMSs have been used for better identification of particulate-matter emission sources. AMS-data benefits are: (i) fine temporal resolution (1s – 15min) allows superior comparison with modelling results, and (ii) detailed chemical composition (and for certain instruments also chemical size distributions) enable a more accurate identification of pollution sources.

We aim to improve and use the regional and urban-scale air quality models, the open road dispersion model CAR-FMI and the regional chemical transport model SILAM. The crucial meteorological quantities for dispersion will be assessed based on Helsinki UrBAN measurements, substantially better than has been possible previously.

In this presentation, we will show progress on this endeavour.

A novel approach for anthropogenic heat flux estimation from space

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How people live, work, move from place to place, what they consume and the technology they use, all affect the fabric, morphology and emissions in a city and in turn its climate. To understand the relations between urban form, energy use and carbon emissions an important challenge is to disaggregate urban areas into different spatial units and evaluate their impacts on energy fluxes and greenhouse gas emissions. There is a need in Earth system science communities for spatially disaggregated anthropogenic heat data, at local and city scales. The anthropogenic heat flux is the heat flux resulting from vehicular emissions, space heating and cooling of buildings, industrial processing and the metabolic heat release by people. Such information is practically impossible to derive by point in-situ flux measurements, while satellite remote sensing has proven a valuable tool for estimating energy budget parameters exploiting Earth Observation (EO) data. While EO data are widely used for urban studies, their main application area is limited to land cover mapping and similar applications. Nevertheless, currently available EO data and forthcoming satellite systems can considerably contribute to the study of urban climate. To this aim the recently launched H2020 project URBANFLUXES (URBan ANthrpogenic heat FLUX from Earth observation Satellites) investigates the potential of EO to retrieve anthropogenic heat flux, as a key component in the urban energy budget. The urban energy budget is considered in the context of a volume because of the three dimensional nature of the city, and includes the fluxes into, or out of, or the storage change within the control volume. URBANFLUXES advances existing EO-based methods for estimating spatial patterns of turbulent sensible and latent heat fluxes, as well as urban heat storage flux at city scale and local scale. Independent methods and models are engaged to evaluate the derived products and statistical analyses provide uncertainty measures. Optical, thermal and SAR data from existing satellite sensors are exploited to improve the accuracy of the energy budget components spatial distribution calculation. Synergistic use of different types and of various resolution EO data allows estimates in local and city scale. In-situ reflectance measurements of urban materials for calibration. The URBANFLUXES project prepares the ground for further innovative exploitation of EO data in scientific activities involving Earth system modelling and climate change studies in cities. The URBANFLUXES products will support system models to provide more robust climate simulations. Ultimate goal of the URBANFLUXES is to develop a highly automated method for estimating urban energy budget components to use with Copernicus Sentinel data, enabling its integration into applications and operational services. The improved data quality, spatial coverage and revisit times of the Copernicus data will allow support of future emerging applications regarding sustainable urban planning, with the objective of improving the quality of life in cities.

Land Surface and Climate Change Impacts on Temperature Variation in New York City

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The lack of evapotranspiration and radiative trapping which is caused by land surface modification in metropolitan areas can lead to Urban Heat Island (UHI) effect all year around in some cities like New York City. This phenomenon is known as Urban Heat Island. UHI refers to an increase in air and surface temperatures in urban centers as compared to surrounding suburban and rural areas. New York City is one of United States' most high densely populated cities with 27,000 people per Kilometer square and due to its different elevations and water bodies, the temperature is not uniformly distributed and some areas may heat up more than other. The urban heat island of a city can be subdivided into physically defined neighborhoods that can respond differently to large scale environmental forcing. The UHI effect can be amplified or reduced by land surface characteristics. Further more warming and increase in frequency of heat waves might increase the UHI effect and therefore factoring in the regional climate impacts are important. Therefore, to study the impacts of land surface characteristics and climate change in New York City UHI, field campaigns of temperature and relative measurements have been formed for the summer of 2012 and 2013.Two types of field campaigns have been done to complete temperature measurements. One is the suite of mobile sensors to measure temperature and relative humidity. The sensors are deployed by foot simultaneously for measuring street level environmental conditions. This measurement is high spatial resolution and it contains data from the hottest part of the day. Another field campaign measurement is done by 10 fixed sensors which were deployed to measure temperature, relative humidity and sunlight. These sensors were installed at select locations throughout New York City for high temporal resolution. The spatial and temporal variability sampled by these two campaigns provide complementary information that can help in predicting environmental variability throughout New York City. To understand the impact of UHI on New York City's land cover, this study has created high resolution neighborhood-scale data sets using three basic approaches; employing fixed stations, walking campaign data, and Landsat satellite data. This project is the first high resolution street level neighborhood study on a metropolitan city. To anticipate climate adaptation and mitigation at the neighborhood scale and to prepare the health community for climate induced increases in heat wave frequency/intensity, this project has been working to develop a neighborhood based temperature predictions using large scale measurements with down-scaling techniques for both near term and long term climate projections.

FluxSAP - A collaborative experimental campaign on water and energy fluxes in urban areas and the relation with the vegetation : the case of a Nantes district

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FluxSAP 2010 and 2012 urban hydrometeorology measurement campaigns were performed within the VegDUD ANR program that aimed at clarifying the role of vegetation in the climatology of urban areas. These experimental campaigns were devoted to heat and water fluxes over an heterogeneous urban area, and on the vegetation contribution to theses fluxes. They combined a ground-based experimental set-up with airborne remotely-sensed observations in 2010, and with a focus on latent heat observations in 2012. The scientific objectives of the FluxSAP campaigns were (i) to obtain heat and vapour transfer reference data allowing to assess urban hydro-climatological models, identifying their sources and separating the contributions from the bare and covered soils, from the buildings, and from the vegetated areas and (ii) to determine the spatial distribution of the observed latent and sensible heat fluxes in a district of Nantes, within the ONEVU long-term observatory area, during a spring period.

The current communication aims at presenting the Fluxsap2012 experimental set up and the first results qualifying the energy budget on this area. The experimental set up includes:

- meteorological variables and aerodynamic turbulent fluxes from 8 instrumented flux towers of 10 to 30 m, at open areas of the district ;
- wind profile observations,
- temperature and water content in the soil and at the surface at 8 points,
- temperature and humidity at 2-3 m above the surface at 14 points,
- mobile air and surface temperatures and humidity observations on streets,
- individual garden energy budget components,
- transpiration observations in green areas
- integrated heat fluxes from 5 large aperture and one small aperture scintillometers set on flat roofs of elevated buildings;
- spatial distribution of rainfall using radar data during rain events,
- passive tracer concentration horizontal and vertical dispersions along a mast and under a small tethered balloon.

This communication adresses the data quality and shows the coherence between the sensors (Li-COR and ultrasonic anemo-thermometers intercomparisons, scintillometry), the coherence between different observation averages (wind velocity and direction, soil temperature and humidity), and the variability of some other physical variables (heat fluxes, soil moisture…). The first analyses of this variability are discussed, and prove the complexity of urban climatology.

The TERRACES project - A collaborative work to understand the role of vegetative green roof in refreshing the urban ambiances

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Currently, different urban planning strategies are proposed to cool the micro-climate (especially in summer) acting on the temperature, wind and humidity. The frequently cited cooling devices are physical proceedings such as the vegetation cover expansion. The most prominent examples are the living walls and roofs. The proposed project intends to deeply develop the scientific analysis of the performance and impact of vegetative green roofs (VGR) on urban climate, environment and health.

The scientific approach aims to achieve three main objectives: task 1 is to assess the refreshing potential of a VGR; task 2 to develop relevant indicators dedicated to VGR environmental impacts; task 3 to establish a link between VGR performance and spreading potential in urban zones.

The task 1 is to qualify and quantify the changes in the urban energy balance induced by the introduction of vegetation. These modifications are associated with the physical properties of green surfaces and increased evapotranspiration. Estimation of evapotranspiration by VGR is important to assess the cooling potential of this system, in nowadays climate conditions but also under climate change GIEC projections. Several criteria will be used (vegetation type, substrate thickness, geographic context...).

The task 2 is to evaluate health and environment risks and benefits of VGR in their local urban context. These indicators can then help create an index that can be used by planners and decision makers. Analysis will be done specifically on water to evaluate potential metal and microbiological contamination.

The task 3 is to allow mapping the potential of VGR at the scale of an agglomeration using a building typology classification This latter will be based on land use database, technical characteristics of the buildings (roof slope, age, etc.) and urban data (PLU, architectural history, etc.). This representation will be coupled with the results of tasks 1 and 2 in order to obtain thematic maps.

This communication addresses the methodology selected, the experimental protocols developed and the first results on the three tasks.

TERRACES project (ImpacT of vEgetative Roofs on uRban Ambiances: Cooling effects, Environment and Spreading) consists of five partners (Cerema - Directions territoriales Est and Ile de France, CSTB, LEESU and GEMCEA) and is financially supported by the ADEME.

PROGRAM MCITY BRAZIL

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The Program MCITY BRAZIL is designed to assess the main features of the urban climate of the major Brazilian cities and to systematize this procedure of investigation to be easily extended to other Brazilian urban areas. The major focus of this program is to estimate the observationally the major components of the energy budget at the surface and associate them to the dynamic and thermodynamic properties of the urban boundary layer over urban areas. As an starting point it was set up a network of 4 micrometeorological towers in the Metropolitan Regions of São Paulo (3) and Rio de Janeiro (1) cities. They are the largest conurbations of Brazil corresponding, respectively, to areas of 8051 and 5682 km2, occupied by 19.7 and 11.9 million inhabitants, and by a fleet of 7.0 and 3.6 million vehicles. In this work the Program MICITY BRAZIL and major urban features of climate the São Paulo and Rio de Janeiro Metropolitan Regions are described. The seasonal evolution of major components of the energy and radiation balance at the surface, both estimated from observations carried out in the 4 micrometeorological towers in operation since 2012, are presented. Besides, the diurnal evolution of urban boundary layer observed during 4 field campaigns carried in 2013 where 3-hours interval radiosounding were carried out during 10 consecutive days provided the vertical dynamic and thermodynamic structure of the atmosphere in São Paulo and Rio de Janeiro during summer (2 campaigns) and winter (2 campaigns) seasons. The urban boundary layer height estimated from radiosounding are compared with LIDAR and WRF numerical estimates. The implementation of MCITY BRAZIL to other metropolitan regions in the Southeast of Brazil is analyzed.

Using stable carbon and oxygen isotopes to attribute measured carbon dioxide emissions in urban environments to different fuel sources

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The recent decade has seen a rapid adoption and advancement of methods to use and interpret eddy-covariance (EC) flux measurements of carbon dioxide (CO2) in urban environments. Although several studies demonstrate potential for using EC measurements to validate fine-scale emission inventories of CO2, a major challenge remains the source attribution of total measured mass fluxes of CO2 to specific emission sources. The EC-measured fluxes represent the sum of various fossil fuel combustion processes, respiration and photosynthesis. Information on the stable isotope composition of the CO2 could add promising additional information to complement EC flux measurements of CO2 in urban environments.

In this study, we measured the three most abundant CO2-isotopologues at high frequency directly in-situ in the urban atmosphere using a spectroscopy system (TGA 200, Campbell Scientific Inc., Logan UT) and calculated isotopic ratios d13C and d18O at high frequency. Every 10 minutes, the system is calibrated against three reference tanks of known d13C and d18O. Because d13C and d18O vary between representative fuel emission sources (gasoline, diesel, natural gas) and biogenic sources (human and ecosystem respiration) we can use mixing models to attribute sources based on excess concentrations and/or directly complement fluxes with isotopic information at high frequency. While d13C depends on the fuel type and origin (in our study: d13C gasoline 27.2‰; diesel -28.8‰; natural gas -41.6‰), d18O is fractionated in catalytic converters (d18O gasoline vehicles -12.5‰; diesel -18.6‰; natural gas -22.7‰) and exhibits higher variability between samples of biogenic sources to different source mixes of the oxygen.

We sampled air from the top of the 30-m flux tower at Vancouver-Sunset, located in between a busy intersection on one wind sector side, and a residential area characterized by emissions from natural gas furnaces in another sector. We explored how combining isotopic information with eddy covariance data allows us to partition fluxes from a specific wind direction. In a long-term ensemble we can separate between natural gas, gasoline and respiration sources. Results are independently tested against a fine-scale CO2 emission inventory via appropriate source area models, and a statistical-empirical partitioning approach developed for this site by Crawford and Christen (2014, Theor. Appl. Clim.).

A Mobile Sensor Network to Map Carbon Dioxide across Urban Environments

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There are a variety models and methods that can characterize and quantify the global increase in carbon dioxide (CO2) mixing ratios in the atmosphere and their links to anthropogenic emissions and terrestrial and oceanic sinks. However, mapping, visualizing and monitoring CO2 emissions and sequestration at policy relevant scales - the local to urban scale - remains a challenge. Emerging modular open source technologies are allowing for the miniaturization, mobilization and increasing accessibility of sensor systems and may be a promising way to observe and map CO2 mixing ratios across heterogenous and complex landscapes, including urban environments. These measurements can serve as either inputs for inverse modelling of emissions and for the visualization of urban emissions in the context of science-communication to public.

We present a system for monitoring CO2 mixing ratios in cities using a network of mobile CO2 sensors deployable on vehicles and bikes combined with geo-spatial analysis and visualization tools. We used components from Arduino (Arduino CC, Italy) coupled with the Li-Cor Li-820 infrared gas analyzer (Licor Inc, lincoln, NB, USA) to prototype a portable CO2 analyzer for possible future CO2 monitoring, and pollution mapping in general. We tested our experimental methodology by deploying a fleet of sensors in the city of Vancouver, Canada to determine excess urban CO2 mixing ratios (i.e. the 'urban CO2 dome') when compared to values measured at a fixed, upwind, remote background site. Sensors were deployed both in fixed locations and in a mobile campaign using bikes and volunteered vehicles. In the presentation we examine the strengths and weaknesses of such a mobile system to characterize CO2 mixing ratios across a complex urban environment and discuss the spatial biases of the two methods. The presentation will focus on lessons learned from the pilot study and discuss the methodology for processing and analyzing spatially and temporally discontinuous measurements using a web-based visualization tool.

Evaluating urban climate model simulations with low-cost air temperature measurements

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In recent years there has been an increasing interest to explore the potential of low-cost measurement devices and mobile measurements as alternative source of meteorological monitoring data, especially in the urban areas where high-density observations become crucial for appropriate heat load assessment. Non-standardized data collecting procedure, instrument quality, their response-time and design, variable device ventilation and radiation protection influence the reliability of the gathered data. We investigate what accuracy can be expected from the data collected through low-cost mobile measurements and whether the achieved quality of the data is sufficient for validation of the state-of-the-art local-scale climate model. Combining high-resolution urban climate model simulations and dense network of local air temperature measurements may help identify hot spots in urban areas and bring added value in heat warning systems.

We use the dynamical urban climate model MUKLIMO_3 (horizontal resolution of 100 m) to simulate the urban heat load during day-time conditions in the area of Vienna. The model is initiated with the vertical profile of temperature, relative humidity and wind from the operational weather forecast model ALARO-ALADIN (horizontal resolution of 4.8 km). Daily simulations for the entire summer seasons April-October 2011, 2012 and 2013 are performed. Maximum temperatures were evaluated against the monitoring data from the 9 operational weather stations showing an average error below 2°C. The mobile measurements took place on a clear-sky, dry and hot day in July 2011 by bicycles and in July, 2013 by car. Several low-cost devices were tested: Maxim iButton, OnsetHOBO UX100-003 and self-designed solar powered Arduino-based data loggers combined with the Sensirion SHT21 temperature and humidity sensor. The devices were calibrated and tested in stationary mode at the Austrian Weather Service showing accuracy between 0.1◦C and 0.8◦C. In mobile mode, the best response-time was found for self-designed device with Arduino-based data logger and Sensirion SHT21 sensor. The collected data were aggregated on a 100 m horizontal resolution grid and compared with the simulations initialized with the atmospheric conditions for the given day. Both measurement and modelling results show similar spatial gradients for distinct local climate zones. In case of bike measurements the average difference between the modelled and measured temperatures was 1.3°C and 1.1°C when compared to the operational monitoring stations.

Innovative observations and analysis of human thermal comfort in Amsterdam

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The Netherlands has a mild mid-latitude climate. Meteorological records for The Netherlands show that the number of hot summer days has increased, and future climate change projections predict the same trend. Heat stress is the major cause of weather-related urban human mortality. The urban heat island effect is significant for the Netherlands (summertime nocturnal UHI 95% >7 K) (Steeneveld et al., 2011, Heusinkveld et al., 2014) as more than 80% of the Dutch population live in cities and are thus subject to such added stress. For human thermal comfort during heat waves, shading is more important than wind according to Mayer and Höppe, 1987. However, for the Netherlands wind may also be relevant due to the proximity of the sea and large lake bodies. Here, measurements and analysis results are presented using an innovative mobile measurement system and a dense urban weather station network. The mobile measurements were used to assess the spatial variability of human thermal comfort (Heusinkveld, et al., 2010 & 2014). A key feature of the mobile measurement system is the direct measurement of mean radiant temperature and wind speed. To do so, a special cargo bicycle was equipped with 6 pyranometers, 6 pyrgeometers, 2D wind speed/direction, temperature, humidity, bicycle speed and GPS sensors. Mobile measurements can provide great spatial detail from a large set of sensors. However temporal resolution is limited and therefore a dense urban weather station network of temperature/humidity and wind speed was set up. Within a city the lower average wind speed increases the radiation induced temperature error of a thermometer screen. To minimize such errors, all air temperature/humidity sensors used on the mobile and urban weather stations were equipped with aspirated thermometer screens.

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Air temperature retrieval from crowd-sourced smartphone battery temperatures for Dutch cities and its application in mesoscale model validation

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Accurate air temperature observations are important for urban meteorology, i.e. to study the urban heat island and adverse effects of high temperatures on human health. Usually, the number of routinely available temperature observations is rather limited. We present a method to derive temperature information for the urban canopy from an alternative source: smartphones. Battery temperature data were collected by users of an Android application for smartphones (opensignal.com). The application automatically sends battery temperature data to a server for storage. A regression model, based on a physical model, is employed to retrieve daily air temperatures from battery temperatures. from a meteorological station of an airport located near the city and from an urban meteorological network in the city. In this study we apply this technique for rural and urban sites in and around Amsterdam (The Netherlands). The evolution of the retrieved air temperatures correspond well with the observations. The mean absolute error of daily air temperatures amounts to 1.4 K, and the bias amounts to 0.4 K. This shows that monitoring air temperatures employing an Android application holds great promise. Finally, we use temperature observations obtained from this technique to validate high resolution WRF mesoscale modeling results over Amsterdam for a warm summer period.

Statistical Partitioning Of Net Carbon Dioxide Fluxes Over A Heterogeneous Urban Landscape

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Eddy covariance measurements are increasingly used to quantify carbon dioxide fluxes in urban areas. The net carbon dioxide fluxes are the sum of anthropogenic emissions, biogenic carbon release from plant and soil respiration, and biogenic carbon uptake by plant photosynthesis. In natural environments, such as forests and grasslands, the partitioning of biogenic fluxes is well established. In contrast, the partitioning of net carbon dioxide fluxes in urban environments is more difficult due to the multitude of sources and sinks, and the spatial variability of emissions and uptake. Flux partitioning approaches that have previously been applied in urban environments include modeling fluxes based on surface fractions in the changing turbulent source area, and fusion with bottom up emission inventories.

Here, we present a statistical partitioning approach that uses filtering and empirical mode decomposition to quantify the components of the net carbon dioxide flux in a step-wise fashion. We applied the novel approach to a three year time series of measurements from a tall broadcast tower in a suburban neighborhood of Minneapolis-Saint Paul, Minnesota, USA. During winter, local vehicle counts were significantly correlated (r=0.68–0.91) with weekday net carbon dioxide fluxes over source areas that intersected roads, which enabled us to estimate vehicular emissions throughout the year. Modeled natural gas emissions from space heating based on hourly air temperature differences were significantly correlated (r=0.27) with the net carbon dioxide fluxes throughout the year and subsequently removed from the net fluxes. The above methods will give us a robust estimate of the anthropogenic flux which we can remove from the net carbon dioxide flux. The resulting biogenic flux is then partitioned with common methods of flux partitioning developed for natural environments. Soil respiration fluxes estimated in this way can be compared to modeled fluxes based on observations from a mobile tower over a turfgrass lawn within the footprint of the tall tower. The estimates of anthropogenic carbon emission components are needed to validate building energy and traffic models, while estimation of biogenic carbon release and carbon uptake are useful to identify areas with emission-reduction potentials and establish emission baselines.

Calculation of the CO2 storage term in an urban environment: results and guidelines from Central London

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Carbon dioxide storage and its governing processes in the urban environment are poorly characterised compared to vertical fluxes, potentially leading to under-estimation of emissions during periods of low turbulence. Some studies apply a flux correction using only data from the flux measurement height (zh), however the assumptions required are not valid during periods where measurements in the inertial sub-layer are likely to be decoupled from the ground. Although CO2 stored below zh can be calculated if the vertical CO2 concentration profile below zh is known, this is often not measured due to cost and access restrictions. In this presentation, guidelines are suggested for the required number and placement of sample points for CO2 storage measurements in a deep urban street canyon, developed using data collected between 2011 and 2014 in Central London, UK. Also considered are the effect of sensor response and sampling interval, and at the processing stage, three different temporal and spatial interpolation methods are evaluated against measured data. A method of independently benchmarking the quality of CO2 storage values using wavelet power spectra is proposed.

Instrumentation consisted of two open path gas analysers measuring at 10 Hz, one within the inertial sub-layer and one at half-canyon height, and a profile system of two closed path gas analysers connected to valve arrays which allowed air to sampled at 16 different locations sequentially. Co-located inlets were used to assess the stability of each closed path gas analyser with each other and the open path gas analysers. The vertical CO2 concentration profile was found to differ substantially from that typically reported in rural environments, requiring few measurements for accurate calculation of the CO2 storage, however calculated CO2 storage was sensitive to sampling interval. The power spectra of the CO2 storage time series varied according to a power law with frequency, and was anti-persistent with the majority of the energy in the signal at high frequencies.

Mixing height over London: spatio-temporal characteristics observed by Ceilometer networks

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Megacities are extensive, with large built surface, roughness, heat storage capacity and potentially immense anthropogenic heat emissions. These factors enhance turbulent surface fluxes and hence may have a profound impact on the structure of the urban boundary layer (UBL) and its mixing height (MH). This study combines ceilometer networks operated over several years within and around the megacity of London, UK, to evaluate the urban impact on the atmospheric structure, to analyse spatial variations within the city and to characterise the seasonal and diurnal variations based on a long-term climatology.

To obtain information about the depth of the mixed layer, profiles of attenuated backscatter data from several types of ceilometers were used: Vaisala CL31 and CT25K (Finland), and Jenoptik CHM15K (Germany). Calibrated attenuated backscatter backscatter profiles (vertical gradients and signal-to-noise ratio) obtained from the different systems are compared and analysed for strong changes in gradient to detect potentially significant internal boundary layers and MH. In addition, the strength of gradient and persistence in time are used to categorise different layers. Consideration is given to the implications of the strength and weaknesses of the observation techniques (e.g. performance under clear and cloudy conditions). The work confirms the importance of careful pre-processing of the attenuated backscatter profiles observed by the various instruments. Results further illustrate that, together with the day-time mixing height, ceilometer observations can also indicate the presence of potentially significant internal boundary layers, providing insight into the characteristics of the UBL under different synoptic conditions.

New York Metro-Area Boundary Layer Catalogue: Boundary Layer Height and Stability Conditions from Long-Term Observations

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The focus of this paper is to highlight the findings from an observational analysis of wind, temperature, and relative humidity vertical profiles for the estimation of stability conditions and boundary layer heights in the very dense city of New York. A microwave radiometer and a RADAR wind profiler jointly measured the measured thermal and momentum conditions for the determination of the atmospheric static stability. The measured values cover a period from 2010 to 2014. The analysis focuses on seasonal variations of observed temperature, wind speed and direction, relative humidity, and other derived quantities. Planetary boundary layer (PBL) heights were derived from three methods that consider the virtual potential temperature, the potential temperature gradient, and the relative humidity gradient. The three approaches show greater agreement in their estimations when highly unstable conditions are present than when stable conditions are present. Stability conditions were determined from the gradient of the virtual potential temperature. Observed summer maximum and minimum values for the near-surface (less than or equal to 200 m) gradient were 0.4904 K m-1 (stable) and -0.0409 K m-1 (unstable), respectively, with an average summer seasonal value of 0.0024 K m-1. The corresponding winter season values are 0.1618 K m-1 and -0.0733 K m-1, with an average seasonal value of -0.0101 K m-1. Finally, these observations are compared to corresponding values found using model results from the urbanized-Weather Forecast and Research model, or u-WRF.

Multi-point Doppler Lidar observation in urban area

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This study investigated vertical distributions of turbulent statistics at two different locations along a predominant wind direction. Two Doppler Lidars were used to observe the vertical profiles of mean wind velocity and vertical momentum flux at two locations along the predominant wind direction.

Doppler Lidars were installed at a top of I4-building in Tokyo Institute of Technology (Tokyo Tech), Tokyo, and a building top of Ota-ward office, Tokyo. A sonic anemometer was also installed at a top of M1-building in Tokyo Tech for compare with the Lidar observations. Ota-ward office is about 5.5 km away from the Tokyo Tech. Measurement was conducted for 2 months in Summer, 2013.

We estimated the internal boundary layer (IBL) height from the vertical momentum flux distribution as defined by a height where the momentum flux becomes zero. It resulted that the IBL height becomes about 300 m from the ground in the urban area irrespective of the atmospheric boundary layer height. Almost same value is estimated at both observation points. It is also shown that the IBL height increases with increasing mean wind velocity. This result has a potential to improve the surface parameterization of aerodynamic drag, and also modify the wall functions used in the mesoscale simulation model.

Measuring the real-world effects of urban heat island countermeasures: a case study of pavement-watering

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Typical countermeasures to urban heat islands (UHI) include the use of cool materials, urban greening or urban morphologies which favor regional winds. Such measures have been studied in the lab or on small-scale demonstrators for decades. Such tests have provided a basis for the simulation of larger scale implementations which provide assistance for decision-makers trying to reduce the impact of UHIs in cities. However, tools to validate predicted effects for larger scale field implementations are important to evaluate and follow-up on the effectiveness of anti-UHI policies put in place. Today, such tools mostly consist of direct comparisons between carefully-selected case and control sites.

Among UHI countermeasures, pavement-watering, which has been studied since the 1990's in Japan, has sparked recent interest in Europe. In Paris, it is viewed as a potential climate change adaptation tool against increasing and intensifying heat waves and has been field tested since 2012. Since July 2013, the rue du Louvre, located in the 1st and 2nd Arrondissements, has been continuously monitored. Two paired sites were selected, one watered and one control, to evaluate the field effects of pavement-watering.

Long-term measurements from this campaign have revealed that direct case-control comparisons are not suited to identifying the effects of pavement-watering. Case-control sites are never perfectly paired in the complex environments found in dense cities such as Paris, and thus measurements made at paired case-control sites are only rarely identical. In the general case, differences between case-control measurements depend on preexisting factors. If these are overlooked, they may be mistakenly interpreted as the effects of the UHI countermeasure being tested.

This paper proposes a field method for quantifying UHI countermeasure effects based on the evaluation of preexisting differences between paired case-control sites and on the comparison of test results with the obtained reference profile.

Interfacing the urban land-atmosphere system with a coupled UCM-SCM framework: model development and sensitivity

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Studies of impacts of urban land-use land-cover changes on the local hydrometeorology have been largely focused on the surface-layer dynamics. In this study, we aim to address the fundamental question: Can the influence of modified land surface processes in urban areas effectively "penetrate" into the overlying mixed layer via land-atmosphere interactions? Towards this objective, we couple a single column model (SCM) to a cutting-edge single-layer urban canopy model (UCM) with enhanced representation of urban hydrological processes. The land-surface transport of energy and moisture parametrized by the UCM provides realistic lower boundary conditions to the overlying atmosphere. The coupled UCM-SCM model is tested against field measurements of sensible and latent heat fluxes in the surface layer, as well as vertical profiles of temperature and humidity in the mixed layer under convective conditions. The model is then used to simulate urban land-atmosphere interactions by changing urban morphology, surface albedo, vegetation fraction and aerodynamic roughness. Results show that changes of landscape characteristics have a significant impact on the growth of the boundary layer as well as on the distributions of temperature and humidity in the mixed layer. In addition, we adopted an advanced stochastic procedure for analysing the model sensitivity, with uncertainties in input parameters characterized using prescribed probability distribution functions. In particular, results of sensitivity analysis reveal that the urban morphology, represented as the aspect-ratio between building height and street width in the UCM, exhibits a complex and non-linear effect on the evolution of the boundary-layer height. Overall, the proposed numerical framework provides a useful stand-alone modelling tool, with which the impact of urban land-surface conditions on the local hydrometeorology can be assessed via land-atmosphere interactions.

Improving the water budget in the urban surface scheme TEB for a better evaluation of green infrastructures for adaptation purposes

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Urban population grew fast these last decades and is expected to still increase during the future decades. Urban areas, due to artificial materials, impacts both urban climate and hydrology: urban heat island, more frequent floods, longer droughts… Furthemore, these modifications related to urbanization can go together with those due to climate change. City planning evaluation in both hydrological and climate terms becomes crucial. Numerical models are useful tools for such evaluations. Nevertheless, even if numerous models dedicated to urban areas are used, very few models are able to simulate both detailed energy and water budgets. Most of them are specialized in one topic and simulate roughly the other one.

Introduction of vegetation in cities is supposed to be one of the solutions to limit urbanization impacts as urban heat island and/or floods, by increasing water infiltration and favoring evapotranspiration. Thus, such green infrastructures impact both energy and water budgets. Our objective is then to develop a model dedicated to urban areas and able to simulate both energy and water realistic budgets.

This model is based on the Town Energy Budget scheme that has known different evolutions these last years: introduction of vegetation inside the canyon, simulation of the greenroofs. Its water budget has been improved by introducing soil and groundwater under buildings and roads (thanks to the SVAT ISBA) and the sewer network (combined or stormwater) that transfers the surface runoff and the drained groundwater to the outlet. The groundwater balance under the different surface types (building, road and garden) is performed and may impact the evapotranspiration flux from the garden surfaces.

This paper will present these last model evolutions related to the water budget as well as their evaluation. The hydro-climate evaluation of greening scenarios of a large part of the City of Nantes (France) using different green infrastructures (as greenroofs, trees, varying vegetation rates) will be discussed.

Adequately and Efficiently Representing Heat Conduction and Storage for Urban Surfaces

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When undertaking city-scale studies of weather and climate, the variability and complexity of urban surfaces presents a modelling challenge. In heavily urbanised sites, heat storage can consume around half of the net all-wave radiation. As heat takes time to diffuse through materials, the variation of heat storage is out of phase with net radiation. The delayed response, or thermal inertia, is often regarded as the key process in the genesis of the Urban Heat Island (UHI), and is clearly an important factor in accurately modelling urban climates through the diurnal cycle. Urban schemes often represent conduction using a discretised one-dimensional parameterisation where temperature nodes are located in the centre of layers of composite surfaces (the number of layers in urban models can range from one to over ten).

Here we will explore methods to adequately and efficiently represent heat conduction and storage in multi-layer urban surfaces. The number of temperature nodes required to adequately represent heat storage and conduction are examined. In addition, an alternative conduction paramaterisation that calculates temperature at layer boundaries (rather than layer centres) is introduced. Both methods were tested against half-hourly observations collected over 18 months for a medium density site in Melbourne, Australia using an urban canyon energy balance model modified from Masson (2000) Town Energy Budget approach (aTEB; Thatcher and Hurley, 2012).

For this site, the skin temperature conduction model was more successful in reproducing the observed cycle of heat storage and release, compared with the half-layer temperature conduction approach used in many urban schemes.

Integration of Urban Microclimate Models using the QUIC EnvSim GPU Framework

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Realistically simulating the urban climate is challenging. Increasing scale, generating realistic urban structure, or manipulating green infrastructure in urban domains all require efficient computational methods to process the complex interactions between the urban structures and the environment. Integrating different computational models together into a single simulation can often impart sophisticated data communication and software development interfaces. Moreover, the results of the simulations must be communicated to a diverse set of users and stakeholders using a variety of visualization techniques that afford exploration of and interaction with the data. Our efforts to create this software infrastructure have resulted in QUIC EnvSim (QES), a modular framework for simulating and visualizing radiative turbulent transport and radiative land-surface interactions in urban domains.

QES is implemented in a software development framework for creating coupled, high performance, urban microclimate simulations. It leverages efficiency by managing simulation data and computations on heterogeneous computing hardware to take advantage of both multi-core, graphics hardware (GPUs) and traditional CPUs. QES supports several models important for urban microclimate simulations including sky-view factor, radiative transport computations for direct diffuse and specular shortwave energy, and longwave emission and transport. Turbulent transport and land-surface model computations are also coupled into the QES framework to model the transfer of energy and moisture scalars between surfaces and through the air. Computational efficiencies are gained in QES by utilizing SPMD (Single Program Multiple Data) GPU programming with NVIDIA's OptiX and CUDA GPU programming interfaces.

The presentation will focus on the use and integration challenges addressed by QES in a multi-disciplinary software development setting in which computer scientists, engineers, and climate scientists contribute to coding the model. One of the key contributions provided by the QES infrastructure is a focus on managing the computational resources on the GPU that allow model data to be shared across models. The presentation will provide a technical description and demonstrations for how the QES software development interfaces afford coupling between models in a variety of contexts to simulate and visualize different urban domains.

Sensitivity analysis and optimization of an urban surface energy balance parameterization at a tropical suburban site

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Forecasting of the urban weather and climate is of great importance as our cities become more populated and considering the combined effects of global warming and local land use changes which make urban inhabitants more vulnerable to e.g. heat waves and flash floods. In meso/global scale models, urban parameterization schemes are used to represent the urban effects. However, these schemes require a large set of input parameters related to urban morphological and thermal properties. Obtaining all these parameters through direct measurements are usually not feasible. A number of studies have reported on parameter estimation and sensitivity analysis to adjust and determine the most influential parameters for land surface schemes in non-urban areas. Similar work for urban areas is scarce, in particular studies on urban parameterization schemes in tropical cities have so far not been reported.

In order to address above issues, the town energy balance (TEB) urban parameterization scheme (part of the SURFEX land surface modeling system) was subjected to a sensitivity and optimization/parameter estimation experiment at a suburban site in, tropical Singapore. The sensitivity analysis was carried out as a screening test to identify the most sensitive or influential parameters. Thereafter, an optimization/parameter estimation experiment was performed to calibrate the input parameter. The sensitivity experiment was based on the "improved Sobol's global variance decomposition method" . The analysis showed that parameters related to road, roof and soil moisture have significant influence on the performance of the model. The optimization/parameter estimation experiment was performed using the AMALGM (a multi-algorithm genetically adaptive multi-objective method) evolutionary algorithm. The experiment showed a remarkable improvement compared to the simulations using the default parameter set. The calibrated parameters from this optimization experiment can be used for further model validation studies to identify inherent deficiencies in model physics.

Using observations to improve modelled energy, water and carbon exchanges for urban areas

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Models are an essential tool for studying how our surroundings influence us and how we, intentionally or inadvertently, influence our surroundings. The Surface Urban Energy and Water balance Scheme (SUEWS) uses a basic meteorological forcing dataset and information about the surface cover to model components of the energy and water balance. The model was initially developed based on studies in North America and is now being run for multiple locations around the world. Here, we evaluate the model at two locations in the UK.

A network of micrometeorological observations exists across London, enabling comparisons between the city centre and suburbs. The central London study site is one of the most highly urbanised and densely populated to date. 120 km to the west is the typical suburban town of Swindon. At both of these locations, extensive observational datasets spanning several years have been collected, and work has been undertaken to classify the surface characteristics. However, as detailed land cover and socio-economic information may not always be available, we consider the impact on model performance of using only easily accessible data to provide the required inputs. SUEWS is evaluated against observations of energy and water balance components (including turbulent heat fluxes from eddy covariance and scintillometry techniques). SUEWS estimates evaporation using an adapted Penman-Monteith formulation with a variable surface conductance. Analysis of observed surface conductances suggests adjustments to improve model performance.

CO2 fluxes, closely linked to the surface conductance, are also examined. The central London and suburban Swindon sites behave differently, in terms of both the magnitude and temporal variability of CO2 exchanges. These differences are almost entirely a result of land use and land cover, and associated patterns of human behaviour. Simple models based on anthropogenic emissions inventories provide an indication of the magnitude of the CO2 release, however, at the suburban site vegetation plays an important role in CO2 uptake and must be incorporated too.

With improved modelling capability, the exposure of the population to risks such as thermal stress or flooding can be better estimated. Having validated the model, the impact of policy decisions and future climate scenarios on the wellbeing of the citizens can be assessed.

Seasonal comparison of three urban land surface schemes in a high-latitude city of Helsinki

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An offline comparison of three urban land-surface models (CLMU, SUEWS and SURFEX) was undertaken in Helsinki, Finland. The modeled net all-wave radiation, turbulent fluxes of sensible and latent heat and snow depth were compared against observations at two sites. One of the sites was highly built-up European city center with less than 10% of vegetation cover (Torni) whereas the other was semi-urban (Kumpula) with the plan area fraction of vegetation being over 50%. The model evaluation was made for 2012 (following a 6 month spin-up period) with particularly focusing on the seasonality, especially in snow which is a frequent feature of cold climate cities.

All models simulated the net all-wave radiation well and the largest uncertainties were related to the snow-melting period in spring when the fraction of snow on surfaces causes a bias to the outgoing short- and long-wave radiation. The largest uncertainties in the sensible heat flux seem to relate to the estimation of surface temperatures. Similarly to previous studies, the latent heat flux performance was most problematic for all models with a clear underestimation at both sites particularly in summer. Energy partitioning of the turbulent fluxes was better during the growing season than outside it.

All models simulated the snow depth well. However SUEWS and SURFEX delayed the complete snowmelt for Torni (> ten days) longer than for a vegetated surface. This had only a minor impact on the turbulent fluxes given the small fraction of vegetated surfaces at the site. No models outperformed the others, but rather the performances were season, site and flux dependent.

Atmospheric stability, an important parameter in applications like air quality forecasts, were compared against observations. Winter-time stability classes varied between the models. However, they were better simulated at the suburban site than at downtown. There, CLMU is unable to simulate stable atmosphere whereas SUEWS and SURFEX simulate more stable and neutral cases than the observations indicate. This emphasizes a need for correct description of the storage and anthropogenic heat fluxes.

Validation of a Lumped Thermal Parameter Model coupled with an EnergyPlus Model using BUBBLE Data

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Validation of an urban micro-climate estimation model requires the acquisition of a significant amount of accurate meteorological data. The BUBBLE experimental effort is undoubtedly one of the most significant scientific contribution in the field of urban climate data acquisition. For this reason, we decided to employ this dataset to demonstrate with which precision urban temperature can be approximated in a cold and humid environment using a lumped parameter urban canopy model coupled with an EnergyPlus model. Based on measurements of the Sperrstrasse (Basel, Switzerland) from November to December 2001, we calculated the frequency distribution and the average diurnal cycle of temperature. The similarity between these statistical outcomes and the ones assessed from the coupled scheme was computed in terms of Kolmogorov-Smirnov distance between two non-parametric distributions and root mean square error between two average hourly cycles. As a result, the coupled scheme estimates the urban temperature frequency distribution and average diurnal cycle of the Sperrstrasse with an accuracy of 45 in terms of Kolmogorov-Smirnov distance and 1.8 degrees Celsius in terms of root mean square error, respectively. A comparison between these results and the ones obtained in a complete different climatic environment (i.e. Masdar City, UAE) will be developed in a future study.

Modelling anthropogenic heat in urban climate models: capturing agency

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The importance of anthropogenic heat flux to the Urban Heat Island effect is recognised in literature, but understanding the true nature of anthropogenic influence on urban climatology is generally limited by a static representation of these sources when applied in urban climate models. Capturing spatial and temporal variability is often limited to use of daily profiles of behaviour that can be represented as some function of local meteorological conditions. This approach being a limited (if at all) representation of dynamic response to localised (spatial and temporal) conditions, with no way of determining how localised conditions may affect anthropogenic heat flux patterns. For example, flooding of roads causing a diversion in traffic that leads to a changed spatial pattern in transport related heat flux, and a possible change in overall heat flux due to increased traffic congestion. This type of human response to weather conditions seems intuitively to be a system feedback, but the significance of these anthropogenic responses to urban climate have not been robustly investigated.

To investigate the relevance of human response to climate conditions, SUEWS (Surface Urban Energy and Water Balance Scheme) has been developed further such that the anthropogenic heat flux component can be linked to an external model that calculates critical parameter values such as population density, metabolic rate, and activity type (commercial, residential, transport). To capture these values the movement of people and their response to local environmental conditions is modelled using an agent-based modelling approach. The decision-making behaviour of modelled agents will be dependent on their classification (e.g. groups of people classified by work, age, or economic status), which is yet to be fully explored. This paper presents a comparison between existing anthropogenic heat flux models and the early stage development of a more dynamically responsive model: the new approach is shown to remain representative in orders of magnitude of heat flux, whilst daily and annual profiles differ to existing model output.

Utilization of a mesoscale prognostic model in the modeling of experimental data within urban street canyons

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The mesoscale model, TAPM (The Air Pollution Model), is coupled to an integrated building-averaged urban surface scheme. This urban scheme is based on the so-called town energy balance (TEB) approach and simulates turbulent fluxes using a generic canyon geometry to resolve energy balances for walls, roads and roofs. The building energy budget is closed by the inclusion within the canyon of air ventilation, effects of recirculation, vegetation and turbulent fluxes. Boundary conditions for TAPM were provided by the low resolution Global Forecasting System (GFS) of NOAA. The model generates synoptic analyses files for every six hours and produces global meteorological predictions for 16 days ahead. Produced results have a horizontal spatial resolution of 0.5o and 1o degrees, at 64 vertically-averaged sigma-coordinates levels.

Air temperature and wind measurements were performed in urban street canyons, during summer period, in the center of Serres, Northern Greece. Experimental data were collected through extensive monitoring at different heights in the urban canyons. TAPM simulations were performed based on the orientation of the street, the geometrical characteristic of the street (Height/Width), surface properties (i.e. anthropogenic heat flux, urban albedo and conductivity) of urban surfaces such as asphalt/concrete/roofs. Forecast results for the specific period of experimental campaign were compared to field data in order to validate the accuracy of the TAPM.

Aim of the work was the comparison between measurements of temperature, net radiation and wind velocity inside different street urban canyons with the calculated ones by the mesoscale model TAPM.

Evaluation of building energy use: from the urban to the building scale

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A 1-D canopy interface model (CIM) has been developed recently and integrated in the meso-scale meteorological WRF v3.5 model in order to improve the surface representation. One of the objectives of such a model is to prepare for the coupling of micro-scale models with meso-scale models so as to improve building energy comsumption estimates at the urban scale as well as improve meteorlogical variables calculation in urban canyons.

The objective of the present study is to evaluate the value of the use of a module able to produce highly resolved vertical profiles of these variables. The coupling methodology is detailed here and its evaluation is done using a reference run based on a fine resolution WRF simulation. In order to keep both the CIM and the meso-scale model in coherence, a new methodology is developed and an additional term is added to the calculation of the CIM.

Two major conclusions can be drawn from this work: the coupling improves the simulations of the meso-scale model and the WRF-CIM system provides highly resolved vertical profiles while at the same time improving significantly computational time. The data from these preliminary results are very promising as it provides the foundations for the CIM to act as an interface between meso-scale and micro-scale models.

Additionally, we will discuss the strategy that will be used to couple the WRF-CIM system with the CitySim software. It is expected that on the one hand the feedback from the CitySim software would improve the meteorological variables calculations while on the other hand the WRF-CIM system can provide enhanced meteorological profiles to CitySim. This coupled sytem, could be used by urban planners or architects, as it would provide a significant advantage in the evaluation of building energy consumption and urban planning scenarios.

Keywords: building energy-use, canopy model, meso-scale models, micro-climate, multi-scale modelling, urban climate

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High resolution Numerical Weather Prediction of the urban boundary layer – a comparison with observations for London, UK

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The ability to accurately forecast local weather conditions in cities is important for a wide variety of applications. For example, alerting local authorities to low temperatures so that roads can be gritted, or issuing health-related warnings to vulnerable residents. Until recently, a lack of urban meteorological observations above roof height has meant that verification of numerical weather prediction models in urban areas can be difficult. This presentation reports results from a comparison of the UK Met Office forecast model with observations for a) a one-year comparison of the operational model at a resolution of 1.5 km, and b) preliminary results for runs with higher resolution (100m) for strong urban heat island cases.

Observations of the boundary layer of central London were carried out at the BT Tower (height 191 m) and at a rooftop (height 19 m a.g.l) from summer 2010 to spring 2013. A Doppler lidar was used over the same period to obtain profiles of wind and turbulence, and to determine mixing height, although the most significant overlap with model data was only for November 2011 to February 2012. Observations of surface meteorology and mixing height using Doppler lidar were also available at a rural site (Chilbolton, 125 km south-west of London). These observations have been used to evaluate the behaviour of the Met Office 1.5 km forecast model (UKV) over one year within the observational period. A focus was put upon days when a strong urban heat island was occurring, to test the model performance when the urban surface energy balance was having the maximum effect. For these days, both sensible and latent heat fluxes were underestimated at the BT Tower, and the timing of the diurnal cycle was delayed by two hours. The underestimate was also seen at the Chilbolton rural site, but not the delay. Nocturnal urban temperature was well modelled, whereas daytime urban temperatures were underestimated on average by 1-2°C. Daytime rural temperatures performed similarly, but night-time minima were too warm. For the shorter winter period available, the model did not capture the observed increase in urban boundary layer depth compared to the rural site. For the higher resolution simulations, the effect of resolution on resolved vs. sub-grid scale fluxes is demonstrated, and turbulent characteristics of the simulations are compared with Doppler lidar observations. It is tested whether increased resolution produces improved model performance in terms of fluxes and boundary layer depth.

Sensitivity of mesoscale models to scale-dependent UCP inputs

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Mesoscale weather and climate models are useful tools for providing important insights and improved understanding regarding climate change mitigation and adaptation in urban environments for institutional stakeholder and urban planner communities. For urban applications, the complexities of the urban fabric within each urban area require scale-dependent descriptions of the land use and activity pattern in order to account for the effects of subgrid scale urban surface cover and buildings. This enables improved predictions of the wind, turbulence, and concentration fields. A commonly used method is the inclusion of a set of urban canopy parameters (UCPs) into mesoscale meteorological models to parameterize building-induced drag and turbulence production and the building-modified surface energy balance. Current UCPs used in mesoscale models attempt to capture major struc¬tural and material features considered to control the momentum and ther¬modynamics of the flow. It is anticipated that through the WUDAPT (Ching et al., 2014), being initiated by IAUC, scale-dependent UCPs will soon become available for model applications.

In this presentation, we illustrate and explore the sensitivity of model outputs to scale-dependent UCP inputs to better understand and articulate their implication to model user communities. The MRA (Mouzourides et al, 2013; 2014) provides a powerful means to perform a weather and climate model scale-dependent sensitivity study for urban applications of models. The MRA is a method that can take into consideration the inherent information residing in urban landscapes, and convey this information to multi-scale modelling studies (without discarding redundant details) in a manageable coherent and structured way (Ching, 2012; Mouzourides et al., 2012). For example in a nested grid simulation over an urban area, the partitioning of the urban heterogeneity between the part resolved by the grid of the model and the subgrid part treated by the UCP must be derived in a consistent manner across all scales in order to obtain meaningful UCP values at all scales.

Given that the majority of the world's populations now reside in urban areas, we focus on demonstrating scale sensitivity in the context of energy usage and urban activities on climate, heat island intensity and other like issues. For this, scale-dependent energy-related attributes will be derived for the city of London using building energy data. It can be further shown how using this gridded data and the BEP-BEM urban option in WRF we can obtain predictions of anthropogenic heating from buildings, spatially resolved surface energy budget distributions, heat Island intensity and flows for London.

On the importance of horizontal turbulent transport in high resolution mesoscale simulations over cities.

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A common simplification of the conservation equations of momentum and heat in the Planetary Boundary Layer (PBL) used in mesoscale models consists in neglecting the horizontal component in the divergence of the turbulent fluxes. This is usually justified in two ways: 1) because the sink of momentum, and source/sinks of heat, located at the surface, induce stronger vertical than horizontal gradients of the atmospheric variables; 2) because the strongest turbulent motions are buoyancy driven (and so directed in the vertical). In addition, the horizontal resolution used in mesoscale atmospheric modeling until the last decade of the 20th century (when most of the PBL schemes were developed) was of several kilometers, something that, by itself, prevented the resolution of sharp horizontal gradients. These are the main reasons why standard PBL schemes are 1D in the vertical. These 1D PBL schemes were frequently tested/tuned/validated against LES with horizontally homogeneous surface fluxes. The main scientific question motivating the current work is: to what extent neglecting the horizontal divergence of turbulent fluxes is justified for PBLs over regions with strongly horizontally-heterogeneous surface fluxes, like cities? The answer to this question is particularly relevant if we consider that, thanks to the increase of computational power, we are now able to perform simulations with horizontal spatial resolutions of the order of several hundreds of meters, which creates the possibility of resolving sharp horizontal gradients. We use the NCAR Large Eddy Simulation (LES) model (Sullivan and Patton, JAS, 2011) to simulate turbulent flow over a 2.5 km wide hot and rough strip (surface heat flux of 360 W/m2 and roughness length of 1m), representing a city, surrounded by a colder and smoother (120 W/m2 and roughness length of 0.1m) strip of the same width, representing a rural area. The horizontal resolution is 20m, vertical is 8m, and the PBL is capped at 1000m. Mean fields are obtained by averaging over lines parallel to the direction of the stripes, and the turbulent fluxes are deduced from the perturbations from these means. Results are then averaged over time. Analysis of these results reveals that the horizontal divergence of the horizontal fluxes is found to be of the same order as the vertical divergence of the vertical fluxes, particularly close to the boundary of the city; therefore in the vicinity of city-induced horizontal heterogeneity, the horizontal divergence of horizontal fluxes cannot be neglected. A budget analysis of the horizontal and vertical turbulent fluxes is also performed to guide parameterization of such fluxes.

Impact of an Urban Land Surface Scheme on Local Climate Simulation for the Tokyo metropolitan area

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The land surfaces take an important role to provide dynamical and thermal energy to the atmosphere above. In order to forecast the appropriate amount of momentum, heat, and vapor fluxes, the MRI’s NHRCM (Non-Hydrostatic Regional Climate Model) selected a sophisticated vegetation scheme of the SiB (Simple Biosphere) as its land surface scheme. However, non-vegetation but urbanized grids became obvious as the resolution of the model became higher up to several km along with the rapid progress of dynamical downscaling technique and computational technology. Reproducibility of the climatology on urban area seems to be insufficient even if the model devises treatment of the SiB as dried bare ground to express the so-called urban deserts.

In this study, an urban canopy parameterization scheme, called SPUC (Square Prism Urban Canopy), will be applied to the 4km-resolution NHRCM in order to improve the representation of radiation and heat budgets of urban surfaces. Using the SPUC- and SiB-coupled NHRCM, present climate (from 2001 to 2006) experiments were executed and the impact of the SPUC scheme to the climatic reproducibility was evaluated.

The targeted area was Kanto-Koshin region including Tokyo metropolitan area, which is one of the most urbanized cities in Japan. The JMA’s regional analysis (RANAL) dataset was used as initial and boundary conditions of the simulation. The RANAL was downscaled once by NHRCM10km with SiB scheme for all land grids. The 10km resolution dataset was also downscaled by NHRCM4km. The 4km experiments were executed using SiB scheme for all land grids (NHRCM-SiB), and using both SiB for natural surface grids and SPUC for urban surface grids (NHRCM-SPUC). Time integration was continuously executed for about 5 years from August 1, 2001 to September 1, 2006.

The preliminary evaluation of the reproducibility can be concluded as follows. The five year mean surface temperature reproduced by NHRCM-SiB showed a certain level of minus biases in the Tokyo metropolitan area. The minus biases around Tokyo were changed to be plus when the SPUC scheme was applied there. Although the area averaged bias changed to be worse from 1.3 °C by NHRCM-SiB to 1.55 °C by NHRCM-SPUC, the correlation factor between the simulation and observation was improved from 0.73 (NHRCM-SiB) to 0.86 (NHRCM-SPUC) implying the better reproducibility of NHRCM-SPUC on horizontal distribution of temperature. On the other hand, few differences were seen in total amount of precipitation between the two experiments.

Sensitivity of different regional climate modeling techniques to study interactions between urban heat island and lake breeze

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This study explores the sensitivity of high-resolution mesoscale urban heat island (UHI) simulations and its relation with the lake breeze, focusing on the Chicago metropolitan area (CMA) and its environs with a series of climate downscaling experiments using the Weather Research and Forecasting (WRF) model at 1-km horizontal resolution. This study has the following research objectives: (i) perform a robust analysis of different urban physical parameterizations for the Chicago region and tune urban physics for the region; (ii) study the impact of urbanization and its relation to UHI and lake breeze; (iii) study the influence of land data assimilation for initialization of regional climate model; (iv) and study the impact of sub-grid scale land cover variability based on dominant and mosaic approach. Comparison of simulations with station observations and MODIS satellite data showed that WRF model was able to replicate the measured surface temperature and wind speeds with above numerical modeling improvements. It was found that numerical models need better representation of surface characteristics and correct initialization of land surface observational data to accurately capture near surface meteorology. In addition, changes in near surface temperatures were more significant during nighttime when urban heat island was high. Inclusion of the effects of sub-grid scale variability in sub-urban areas improved the near surface temperatures in those regions. Results have shown that the above objectives have helped to capture complex interactions between UHI and lake breeze and reduced uncertainties in numerical modeling techniques.

Simulation of the urban heat island under the background of urbanization around Guangzhou

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This paper simulated a heat wave event which occurred around Guangzhou during late July and early August, 2012 by a weather research and forecasting (WRF) model coupled with an urban canopy model (UCM) at a horizontal resolution of 1 km. Three numerical simulations with new land-use data representing different urbanization scenarios and an default simulation with Modis land-use data were performed. The land-use data of 2012 was extracted from the Remote sensing(RS) data of year 2012 produced by the Landsat-7 satellite,then based on satellite-measured night-time light data and the normalized difference vegetation index(NDVI), a human settlement index was used to represent the current urban land-cover and define three urban land subcategories in the UCM. Using up-to-date urban land use data,which obtained as described above, simulation results agreed well with observation. The coupled WRF/UCM model reasonably reproduced the best 2-m temperature evolution and the smallest minimum mean-root-square-error as compared other experiments. The experiments coupled WRF/UCM could capturing the temporal characteristics of UHI intensity more accurately.The UHI intensity is gradually increasing after midday and becomes strongest at night, while it graduallydecreases in the morning and even gets negative at noon.The result showed that UHI intensity peak reached a maximum value of 3.0 °C at 1900 LST around sunset. Research indicates that the land-use change have a great impact on the simulation result.Comparisons among the results of four sensitivity runs showed that classification of three urban land subcategories in the experiments coupled UCM contributed 0.58℃ to lift the maximum UHI intensities,and the maximum 1.58℃ to UHI intensities. Anthropogenic heat release respectively contributed maximum 0.89 °C to the simulated UHI effects.

The Impact of Land Use/Land Cover on WRF Model Performance in a Sub-Tropical Urban Environment

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Delhi, the capital city of India has witnessed immense urban growth in past few decades. Many agricultural and green areas have transformed into built-up areas. The default 24 category USGS land use data used in Weather Research and Forecasting (WRF) model for mapping land use to model domain is inadequate in terms of current land use representation. Consequently, there is a substantial mismatch between land use data that is inputted to the model and actual land use especially for Delhi region. An updated land use data, thus, provides a scope in improvement of model performance. Present study is aimed at analyzing impact of change in input land cover on model outputs of some surface meteorological parameters. Three different types of land use data have been applied to the model viz. USGS land use data, MODIS based land use data and user-modified USGS land use data. Model performance has been evaluated for surface meteorological parameters like temperature, wind speed and direction and relative humidity using statistical measures. Spatial urban heat island intensities (UHI) have also been analyzed with respect to those observed in a field campaign conducted earlier. The study highlights the significance of impact of land use/land cover in atmospheric processes and the need for updated LULC for meteorological modeling.

Urban heat island over northern Taiwan: Numerical study using WRF coupled with a 2-D urban canopy model

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Taiwan, especially Taipei (located in northern Taiwan), is experiencing a significant urban heat island effect due to its high population density and the uniqueness of the geographic structure. In order to evaluate the impacts of urbanization and UHI effect over northern Taiwan, a mesoscale model, Weather Research and Forecasting (WRF) model coupled with the Noah land surface model and a 2-D Urban canopy model (UCM2D), was used in this study.

The 2-D Urban canopy model was modified from original 1-D UCM (UCM1D) which already coupled in WRF model. The original UCM1D, the urban fraction (=0.7) and anthropogenic heat (50 watt/m2, in this study) are fixed in the simulation domain. We found the original UCM1D model has a tendency to underestimate air temperature in the city center during daytime while overestimated over the rural small town in northern Taiwan. In this study, we generated a new 2-D urban fraction in the simulation domain from a very high resolution of observed urban fraction (100 m resolution). Moreover, a new 2-D anthropogenic map is built from a 100 m resolution of building density in Taipei. By using this new WRF/UCM2D coupled model, it has significantly improved our simulation results for the diurnal variation during heat waves in Taipei.

Development of a fine-scale numerical weather prediction system for urban areas: Preliminary results

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In order to improve high-impact weather forecast for urban areas, a fine-scale numerical weather prediction system for urban areas (BJ-RUC-Urban), based on Weather Research and Forecasting (WRF) model, is developed with horizontal grid spacing of 1 km. BJ-RUC-Urban is nested into Beijing Rapid Update Cycle assimilation and forecasting system (BJ-RUC) with horizontal grid spacing of 9 km and 3 km. The main characteristics of BJ-RUC-Urban includes: 1) high-resolution urban land-surface dataset derived from Landsat-TM data; 2) enhanced modeling of latent heat flux from urban surfaces, e.g. irrigation and oasis effect for urban green areas; 3) using the combination of fractal dimension and fractional impervious surface to better characterize the heterogeneity of the urban morphological properties; 4) considering the release of sensible and latent heat from air conditioning system in the Build Energy Model (BEM) according to the ratio of various air conditioning types; 5) partial cycle of land surface variables; and 6) the outputs from Variational Doppler Radar Assimilation System (VDRAS) are used with the aid of four-dimensional data assimilation (FDDA). BJ-RUC-Urban is evaluated with automatic weather station (AWS) observations and quantitative precipitation estimation (QPE). Preliminary results show that BJ-RUC-Urban could well simulate urban heat island and spatial distribution of summer rainfall.

Urban weather and air chemistry forecasting using high resolution WRF model and Meteorological Temperature Profiler (MTP-5) data assimilation

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Moscow city is one of the largest megapolises in Europe with population of 15 million people but the meteorological conditions of this area are not well reproduced by global models. Therefore the goal of our work was to evaluate forecasting using WRF model and data assimilation of Meteorological Temperature Profilers (MTP-5). We present the results of several case studies of the urban weather and atmosphere composition forecasts over the region of Moscow city. The research has been performed with the use of the WRF model assimilating the temperature profiles obtained from the Meteorological Temperature Profiler MTP-5. The cases include several different weather condition types. Among the other cases we have investigated the situation of temperature inversions over Moscow region and its effect on the weather conditions and atmospheric composition.

Along with this the accuracy improvement of the WRF model after the temperature profile assimilation has been assessed. The observations from MTP-5 (vertical temperature profiles from 0 up to 1 km with 100 meter resolution) have been assimilated into the WRF in practical work for the first time thus making the research results of interest to the modeling community. We have designed a special experiment with several diverse measurement points of temperature profiles to evaluate the representation of the city heat island effect.

Using the atmosphere parameters inferred from WRF we have implemented the CFD airflow model working within the 3D urban terrain. The CFD model results were used to compute the chemical compounds propagation from the various sources such as traffic. The results of the chemistry modeling were compared to the independent measurements of the pollutants concentrations. The chemistry-related observations were made at 15 different sites around Moscow.