Megacities: meteorology, climate and air quality effects and interactions

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and FUMAPEX, MEGAPOLI, GURME and CEEH consortiums
(see: http://fumapex.dmi.dk, http://megapoli.info, http://ceeh.dk, http://mce2.org/wmogurme/, http://www.eumetchem.info/)

CAS TECHNICAL CONFERENCE ON
"RESPONDING TO THE ENVIRONMENTAL STRESSORS OF THE 21ST CENTURY"

Session V – Urbanization: Research and services for megacities and large urban complexes

WHY Megacities?

- **XXI century is called as century of urbanization**

- **Urban: > 50% of world popul. - < 1% land**
- **MCs: 10% of world popul. / < 0.2% land**
- **19 megacities > 10 Million people**
- **22 cities with 5-10 million people**
- **370 cities with 1-5 million people**
- **433 cities with 0.5-1 million people**

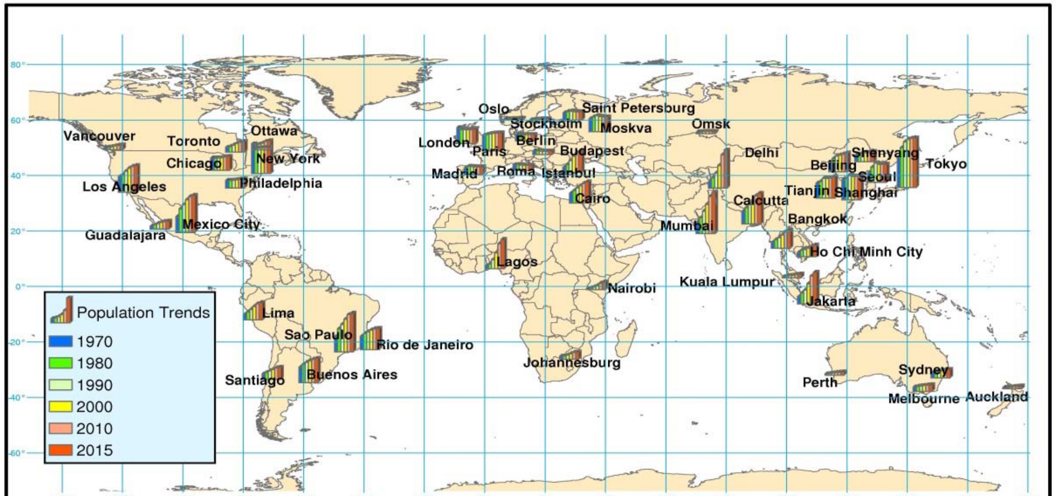
Source: UNCHS 2007

Fast growing MEGACITIES:

- 1950: 4, 1980: 28, 2002: 39, 2015: 59 megacities worldwide;
- 2/3 in developing countries, resp. South and East Asia
- 2002: 394 Mio. people, of these: 246 Mio. in developing countries, > 215 Mio. in Asia; in the year 2015: 604 Mio. worldwide
- Population data tripled between 1970 and 2000: e.g. Mexico City, São Paulo, Seoul, Mumbai, Jakarta, Teheran
- In 2050 urban population will be 66%

Urbanisation => Crisis? Or Solution?

- Driving forcers in economic growth (80%)
- Growing emissions and urbanisation => environment and climate on different scales
- Rapid and unbalanced growth
- Problems of fast growth: increasingly subject to crises
- Highest growth rates in medium size cities
- New urban population ≈ poor urban population
- Problems aggravated in developing countries by fin. crises



Population trends in megacities

Source: UN 2002

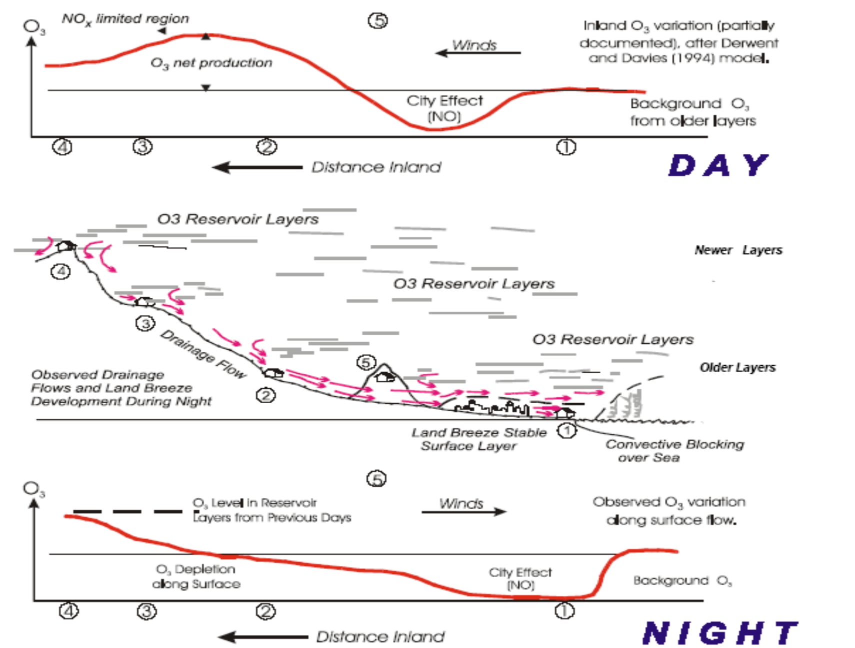
Mountains: Urban Climate & Air Pollution

- Most polluted cities – in mountain valleys
- Multi-scale effects: 2-way interaction of regional and urban scale processes
- Lower ventilation potential for cities in mountains: mountain valleys and circuses
- Nocturnal inversions leading to elevated air pollution episodes
- More vulnerable, significant impact on human health, visibility, ecosystem, climate
- Simplified AQ models fail to produce high pollution episodes in mountain and urban areas

Lanzhou urban pollution in a valley basin, Tibet, China

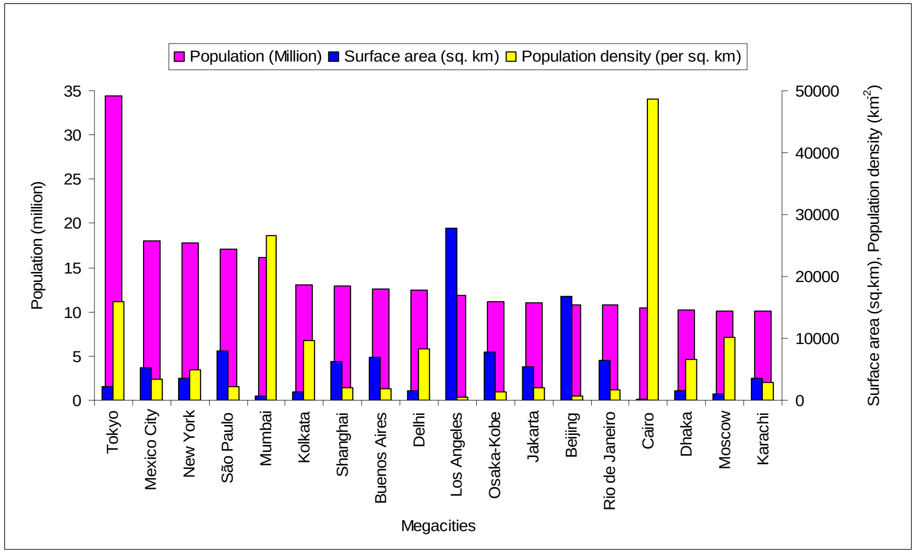
Many large and fast-growing cities situated in mountain regions, e.g. *Alma-Aty, Ankara, Bangalore, Dushanbe, Kabul, Kathmandu, Yerevan, Lanzhou, Santiago, Tashkent, Tbilisi, Tehran*

Climate change affects urban environment: *extreme weather, dry air & water problems, heat waves, pollution episodes, increases pollen season, forest fires, desertification, indirect costs, etc.*

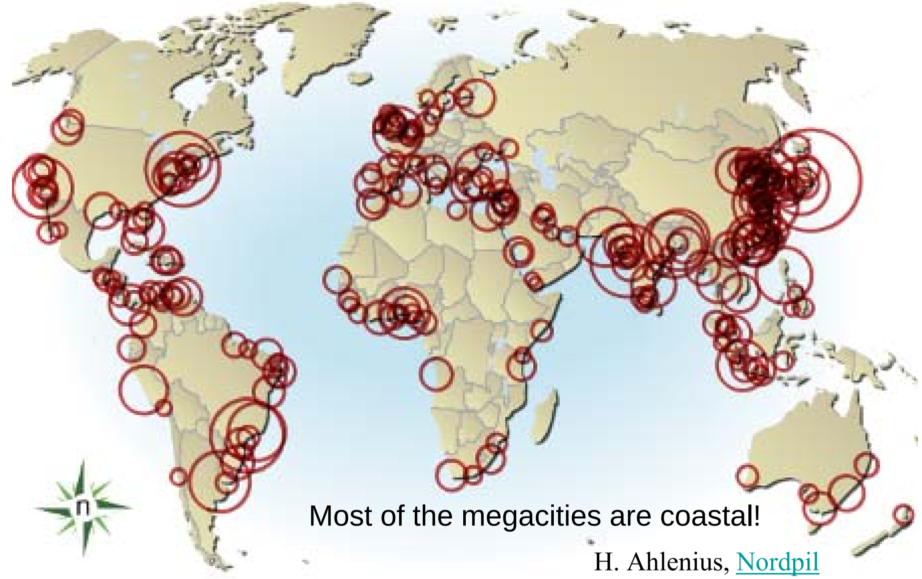


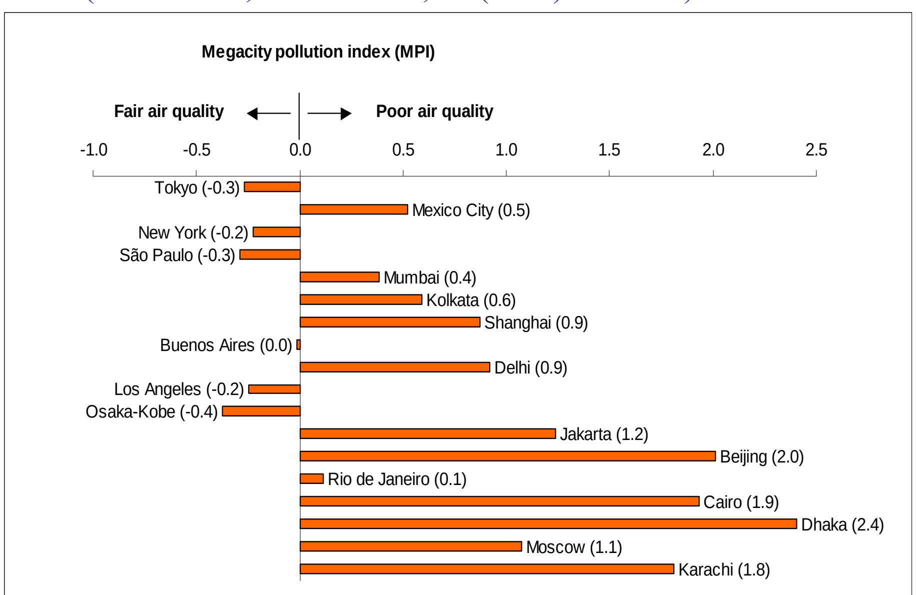
Urban effects on air pollution in Mediterranean region

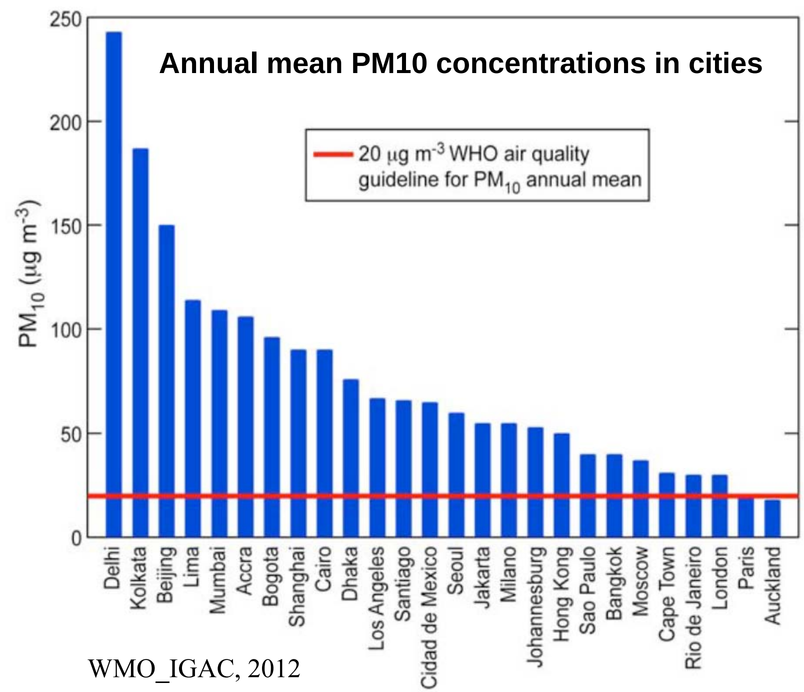
Megacity Characteristics and Pollution



(Butler et al., Atmos. Env., 42 (2008) 703–719)

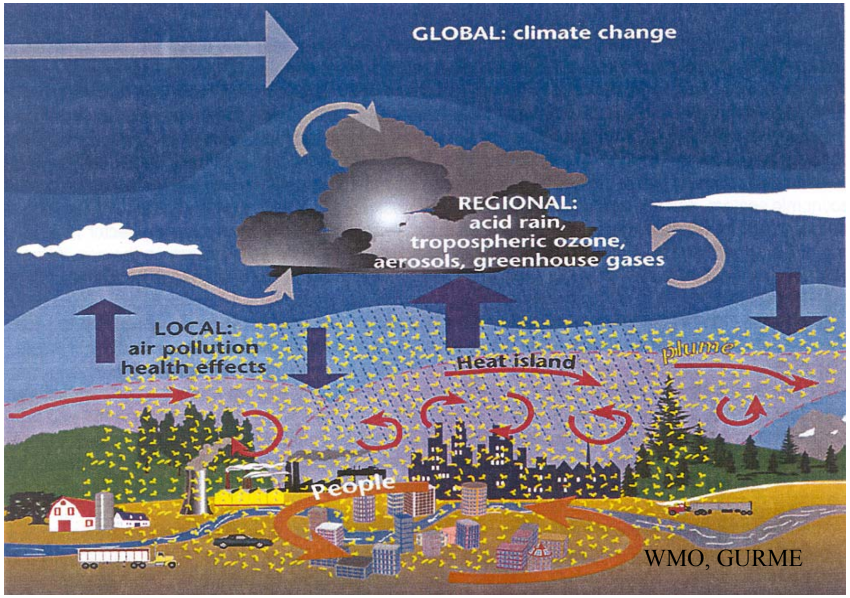




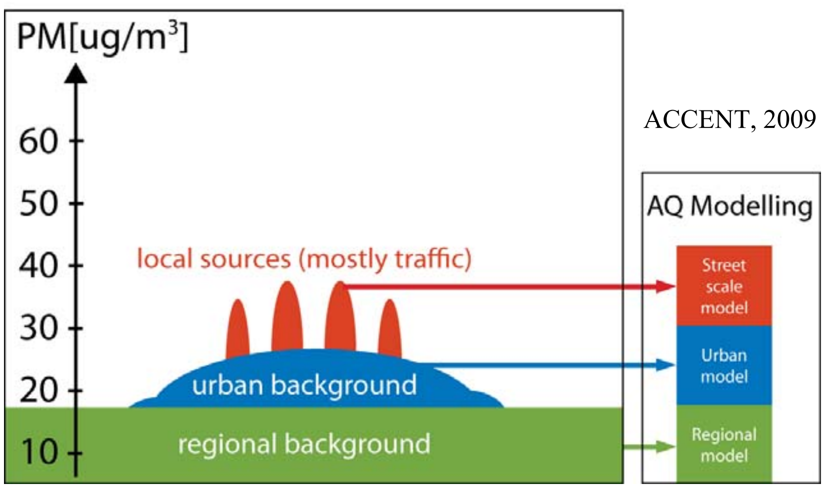


WMO_IGAC, 2012

Urban features in focus:



Why do cities have a different climate ?



…and air quality ?

- **Urban pollutants emission, transformation and transport,**
- **Land-use drastic change due to urbanisation,**
- **Anthropogenic heat fluxes, urban heat island,**
- **Local-scale inhomogeneties, sharp changes of roughness and heat fluxes,**
- **Wind velocity reduce effect due to buildings,**
- **Redistribution of eddies due to buildings, large => small,**
- **Trapping of radiation in street canyons,**
- **Effect of urban soil structure, diffusivities heat and water vapour,**
- **Internal urban boundary layers (IBL), urban Mixing Height,**
- **Effects of pollutants (aerosols) on urban meteorology and climate,**
- **Urban effects on clouds, precipitation and thunderstorms.**

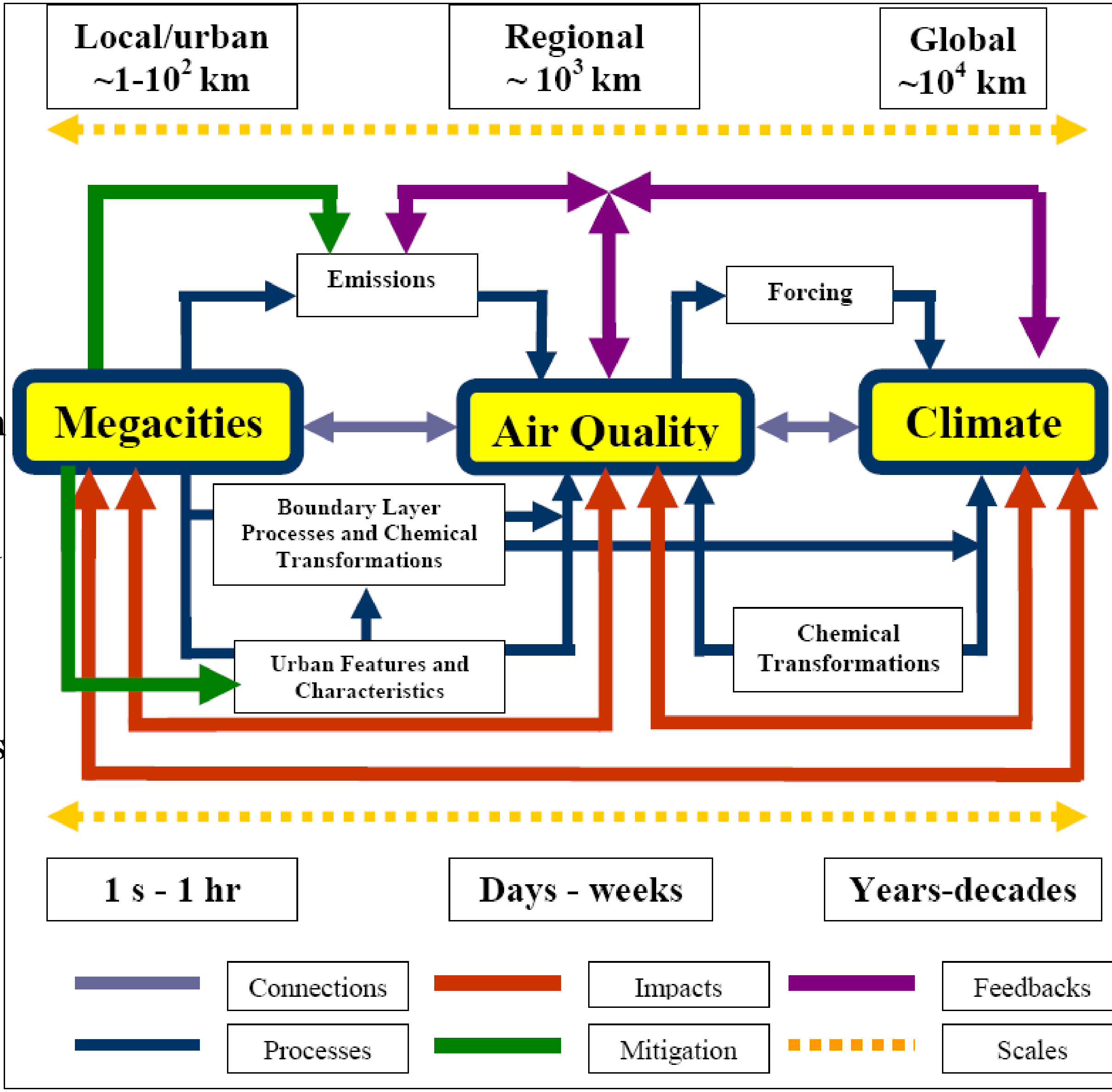
MEGAPOLI: Megacities: Emissions, Impact on Air Quality and Climate, and Improved Tools for Mitigation Assessments

Connections between Megacities, Air Quality and Climate:

The <u>main aim</u>:
(i) to assess impacts of growing megacities and large air-pollution "hot-spots" on air pollution and feedbacks between air quality, climate and climate change on different scales, and
(ii) to develop improved integrated tools for prediction of air pollution in cities.

- Science - nonlinear interactions and feedbacks between urban land cover, emissions, chemistry, meteorology and climate
- Multiple spatial and temporal scales
- Complex mixture of pollutants from large sources
- Scales from urban to global
- Interacting effects of urban features and emissions

see: Nature, 455, 142-143 (2008)

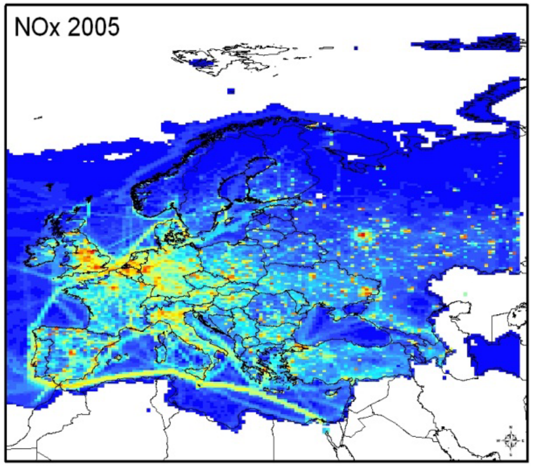


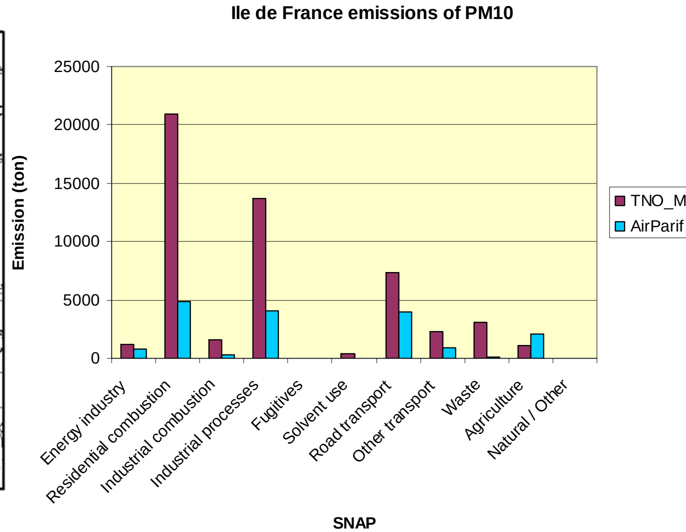
MEGAPOLI main scientific questions:

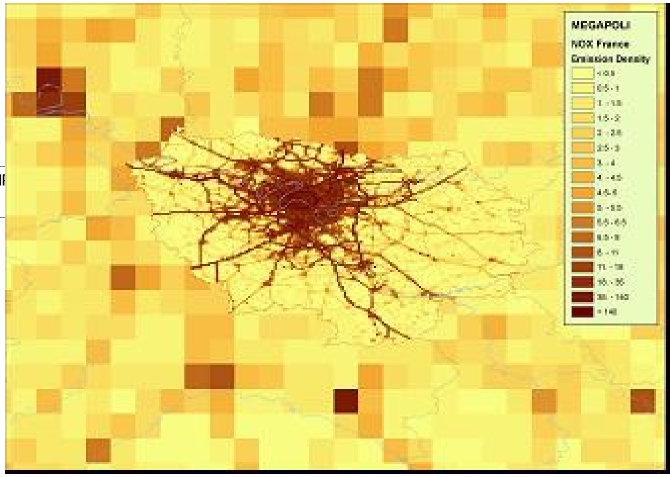
- Q1: What is the change of exposure of the overall population to the major air pollutants as people move into megacities? What are the health impacts of this exposure?
- Q2: How do megacities affect air quality on regional and global scales? What is the range of influence for major air pollutants (ozone, particulate matter, etc.)?
- Q3: What are the major physical and chemical transformations of air pollutants as they are moving away from megacities? What happens to the organic particulate matter, volatile organic compounds, etc?
- Q4: How accurate are the current emission inventories for megacities in Europe and around the world? What are the major gaps?
- Q5: How large is the current impact of megacities on regional and global climate?
- Q6: How will the growth of megacities affect future climate at global and regional scales?
- Q7: What is the impact of large-scale dynamic processes on air pollution from megacities?
- Q8: What are the key feedbacks between air quality, local climate and global climate change relevant to megacities? For example, how will climate change affect air quality in megacities?
- Q9: How should megacities (emissions, processing inside megacities, meteorology) be parameterised in regional and global models?
- Q10: What type of modelling tools should be used for the simulation of multi-scale megacity air quality - climate interactions?
- Q11: Which policy options are available to influence the emissions of air pollutants and greenhouse gases in megacities and how can these options be assessed?

How accurate are the current emission inventories for megacities in Europe and around the world? What are the major gaps?

MEGAPOLI Emission Inventories







- In MEGAPOLI a state-of-the-art (global and) regional European (6x7km) emission data base was combined and cross-checked with bottom-up emission inventories (1x1km) for Paris, London, Rhine-Ruhr area (Germany) and the Po-valley (Italy).
- The allocation of the emission in the regional down-scaled inventory can deviate substantially (up to a factor of 4) from the MC bottom-up inventories.
- The major discrepancies caused by e.g. residential combustion and industry sectors were documented and explained.
- Emission inventories are not consistent across scales and this is likely to have significant impact on predicted air pollution and exposure levels.
- New method for determination of megacity NOx emissions and lifetimes from satellite measurements was developed (*Beirle et al., Science, 333, 2011*)
- Anthropogenic heat flux (AHF) model was developed by KCL and used to compute the AHF inventories for globe, Europe and London.

H. Denier van der Gone, TNO

What are the major gaps in MC emissions?

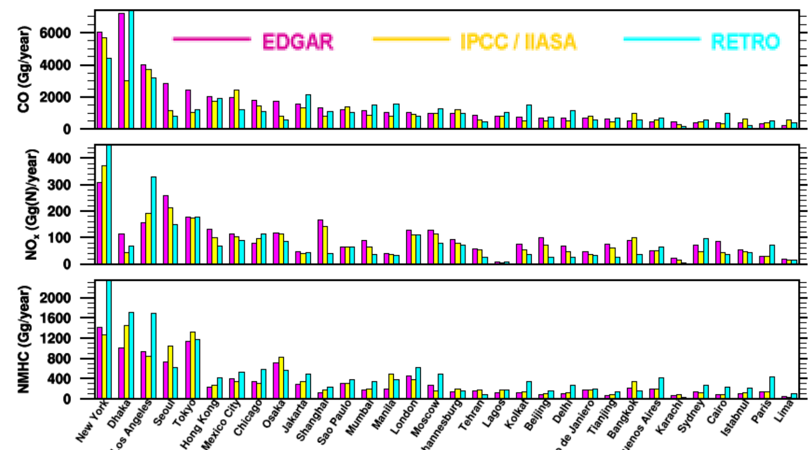
- Compared 3 global EIs and 2 city-level inventories: large differences (factor of 2)
- GEIs underestimate emissions from European and Chinese MCs and overestimate emissions in LA and in Asia (except China)
- MCs in Europe and N & S America, transport is dominating for CO and NOx; in Asia and Africa: CO - dominated by residential biofuel use, NOx - industrial emissions

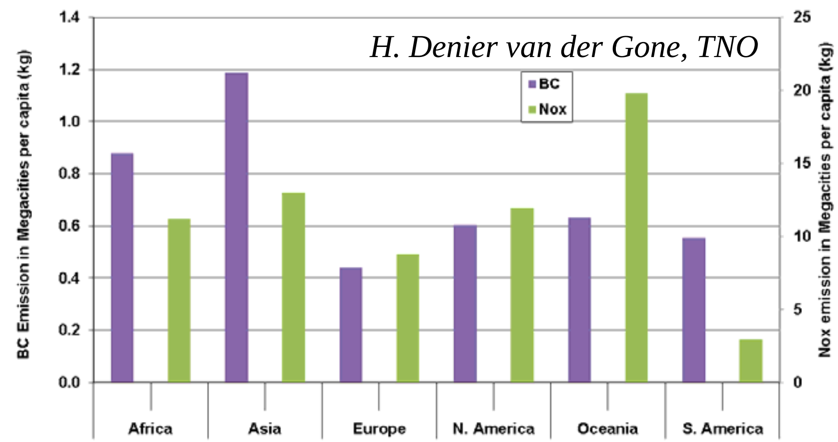
Key gaps in our knowledge:

- initial process of developing emissions databases
- variation in fuels, its quality and appliance types between MC and country
- identifying which emissions should be associated with MCs
- notable differences in per capita emissions from the various MCs: reasons?

=> Recommendations for how to reduce or minimize emissions in MCs

(Butler et al., Atmos. Env., 42, 2008)





Average emission of Black Carbon varies from 0.4 kg/capita in MCs of Europe to 1.2 kg/capita in Asian MCs, respectively

What are the major physical and chemical transformations of air pollutants as they are moving away from megacities?

What happens to the organic particulate matter, volatile organic compounds, etc?

Major transformations of air pollutants in MC plume

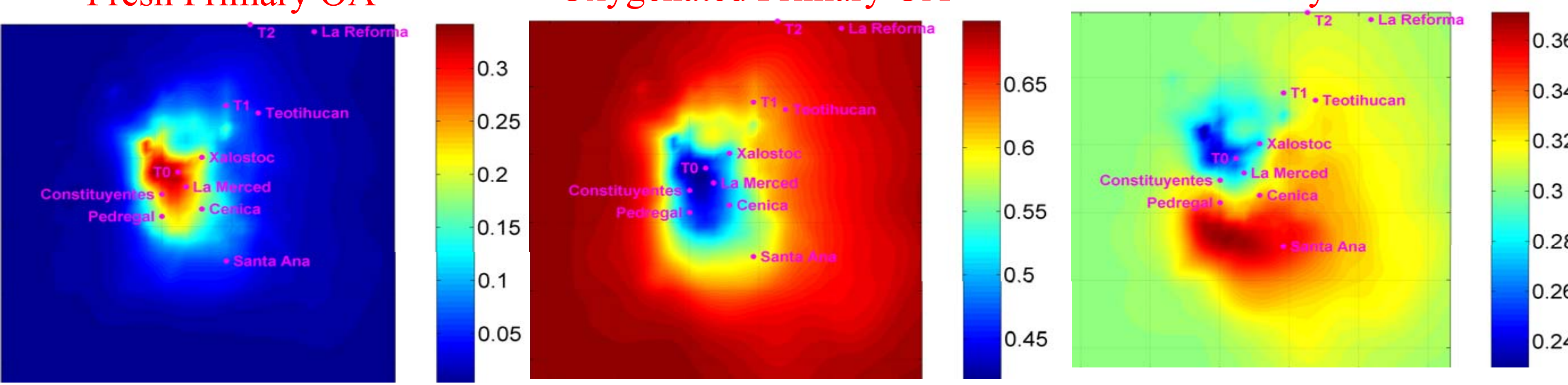
Physical changes:

- Dilution: reduces rapidly (10s km) passive concentrations; Paris plume for BC & VOCs up to 150 km
- UHI increases urban BL height and effects MC plume mixing
- Evaporation of semi-volatile particulate matter components
- Rapid dry deposition of nitric acid, etc.; wet deposition

Chemical changes:

- Formation of ozone, sulfates, and secondary PM; max O3 and SO4 downwind of MCs
- Organic PM exported by MCs is quite different chemically from that emitted by the sources inside MC
- Aged organic PM is a lot more hygroscopic and less volatile than the original PM
- PM-CAMx simulated oxygenated OA more abundant than fresh OA, even in the city center

Fresh Primary OA | Oxygenated Primary OA | Secondary OA



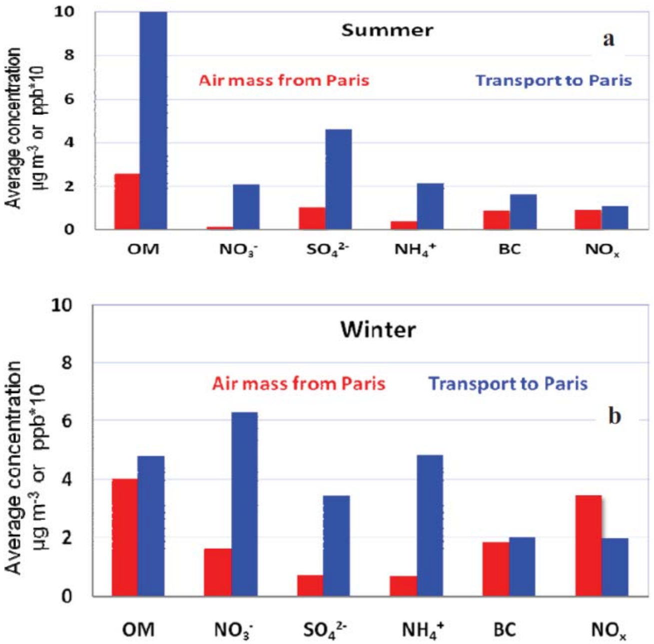
(Courtesy of FORTH: Spyros Pandis et al., 2012)

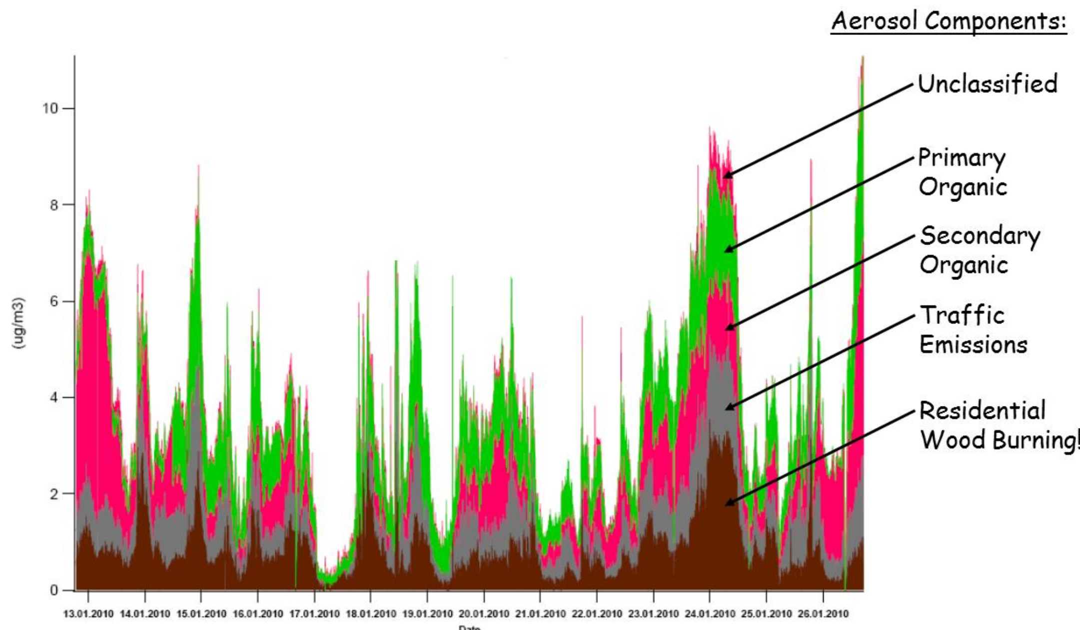
How do megacities affect air quality on regional and global scales?
What is the range of influence for major air pollutants (ozone, particulate matter, etc.)?

What is the impact of large-scale dynamic processes on air pollution from megacities?

MEGAPOLI Paris Measurement Campaigns

- Aim: Provide new experimental data to better quantify sources of primary and secondary carbonaceous aerosol in a megacity and its plume. Duration: Summer – 1-31 Jul 2009, Winter – 15Jan-15Feb 2010
- 30 research institutions from France and other European countries, MEGAPOLI Teams & Collaborators





(Courtesy of Monica Crippa et al.; PSI Team)

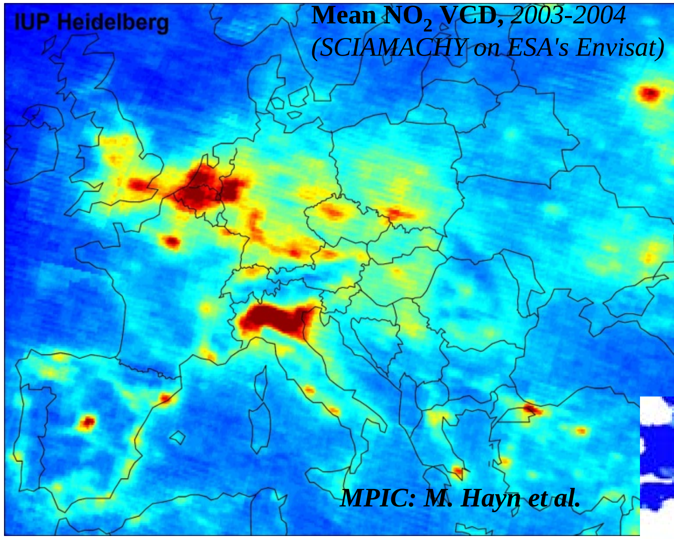
- Surprisingly low fine PM levels
- 70% of fine PM mass is transported into megacity from continental Europe
- Fossil fuel combustion contributes only little to organic fine PM
- Large fraction of carbonaceous aerosol is of secondary biogenic origin
- Cooking and, during winter, residential woodburning are the major primary OA
- BC concentrations are on the lower end of values encountered in megacities worldwide.

(Beekmann et al., 2013)

How large is the current impact of megacities on regional and global climate/meteorology?

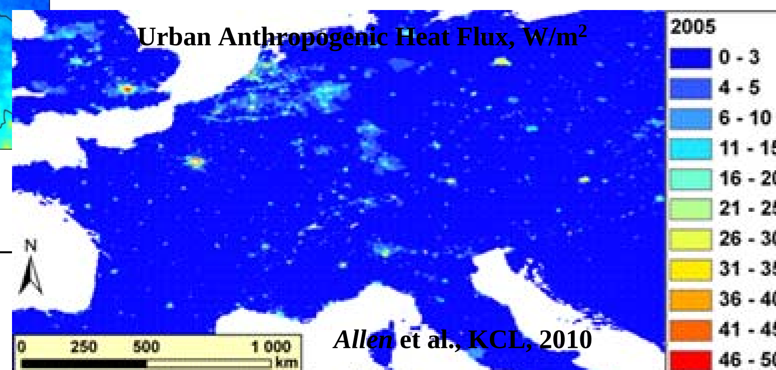
How will the growth of megacities affect future climate at global and regional scales?

Megacities: environment and climate change



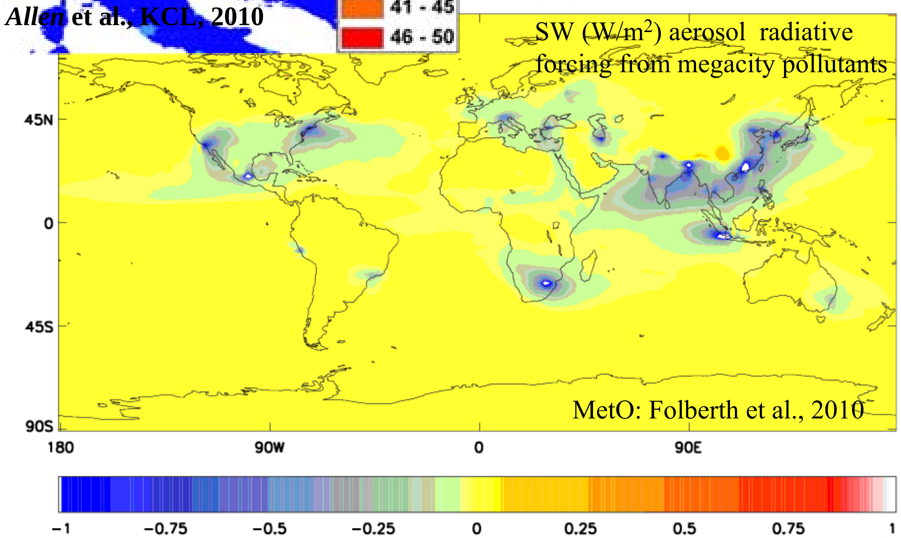
Are megacities to blame for climate change/global warming?

- On city- and meso-scales definitely 'Yes' (both via UHI and emissions), up to 10 K
- On regional and continental scale: UP extends up to thousands km, can affect CC,
- On global scale: probably 'No' due to UHI, but 'Yes' due to GHG emissions (anthropogenic CO_2, CFC, CH_4, N_2O and tropospheric ozone)
- Source of aerosols which have both direct and indirect cloud radiative effects (cooling or warming)
- MCs contribute a global warming of over 0.2 K after 100 years, with nearly 90% of this being due to CO2 emissions, and most of the rest due to methane



Measures to reduce urban drivers of climate change, e.g.:

- Reducing GHG and aerosol emissions
- Reducing traffic congestion
- Switch to fuels with less GHG side effects
- Conserving energy and water
- Greater use of passive heating and cooling technology
- More compact city design and greater use of mass transportation
- Intelligent use of trees to shelter or shade
- Increased use of light colored surfaces in hot cities.



What type of modelling tools should be used for the simulation of multi-scale megacity air quality – climate/meteorology interactions?

How should megacities be parameterised in regional and global models?

Methodology and Research Tools

Multi-scale modelling Chain / Framework: from Street to Global

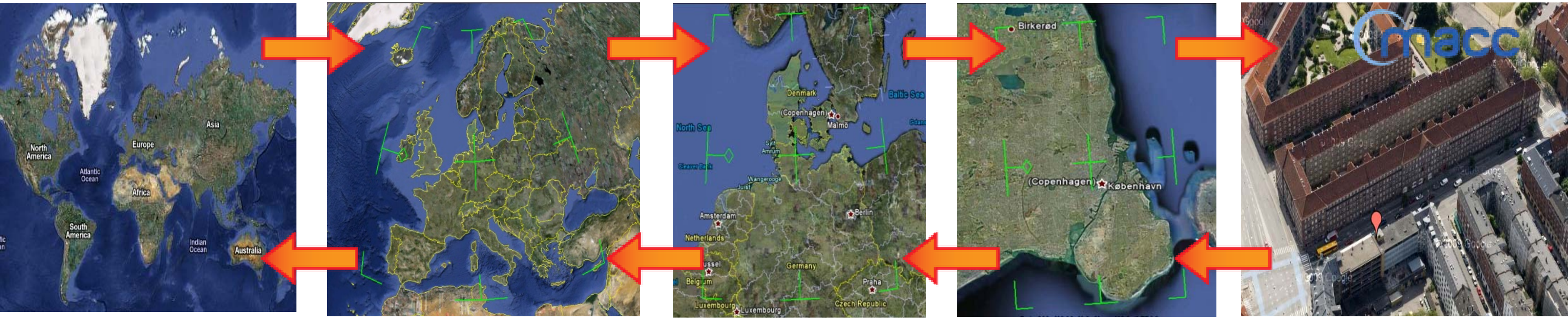
- Land-use characteristics and scenarios
- Anthropogenic heat fluxes
- Emission inventories and scenarios
- Atmospheric processes model down- and up-scaling

ACT, Meteorology, Climate Models

Global: ACT: MPIC, MACC; GCM: UKMO;
Regional: ACTM *Ensemble*, RCM: RegCM, ..
Megacity: Enviro-HIRLAM, MEMO, METRAS, PMCAMx, …;
Street: LES, M2UE, MIMO, MITRAS, …

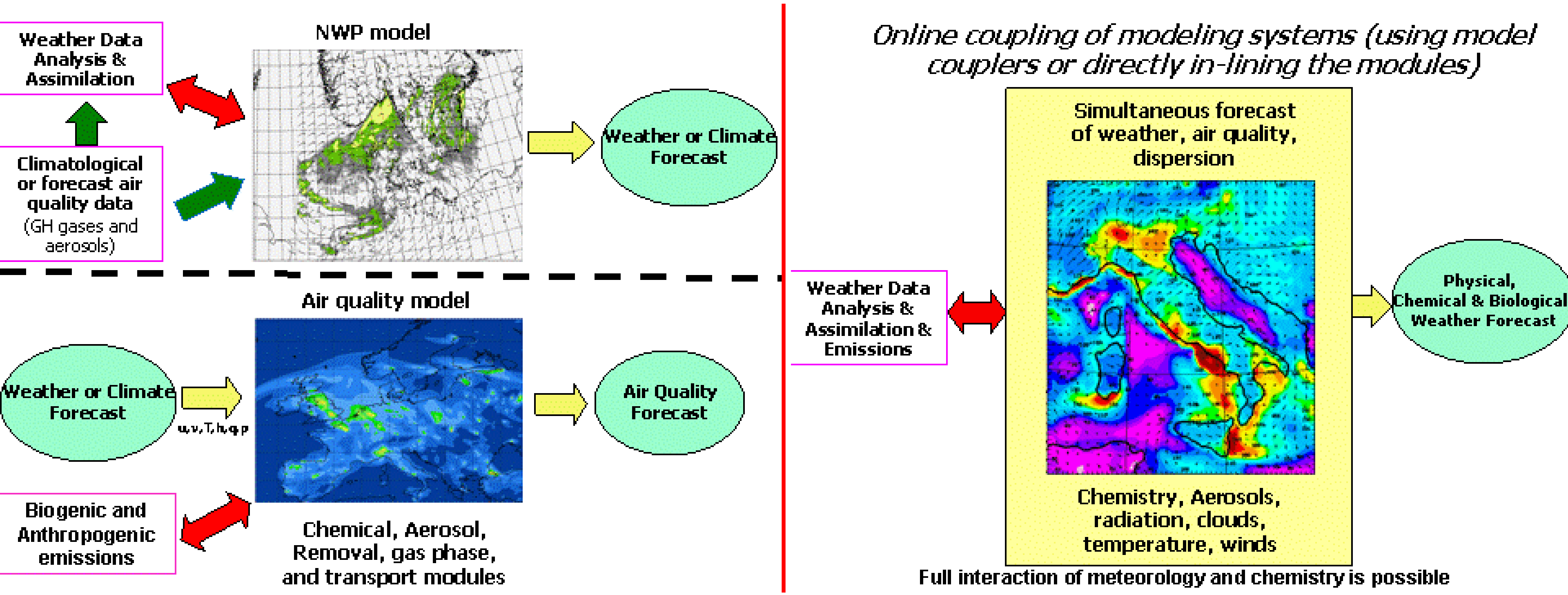
Temporal and spatial scales and ways of integration:

- Level 1 – Spatial: One way (Global -> regional -> urban -> street);
- Level 2 – Spatial: Two way (Global <=> regional <=> urban);
- Level 3 – Time integration: Time-scale and direction; Direct and Inverse modelling.



Two-way Nesting, Zooming, Nudging, Parameterizations, Urban increment methodology (AUTH)

Schematic diagram of the offline and online coupled ACT & NWP/CC modelling approaches



Online coupling can be archived through the use of various available coupling tools or through directly inlining the chemical and aerosol modules into the NWP models.

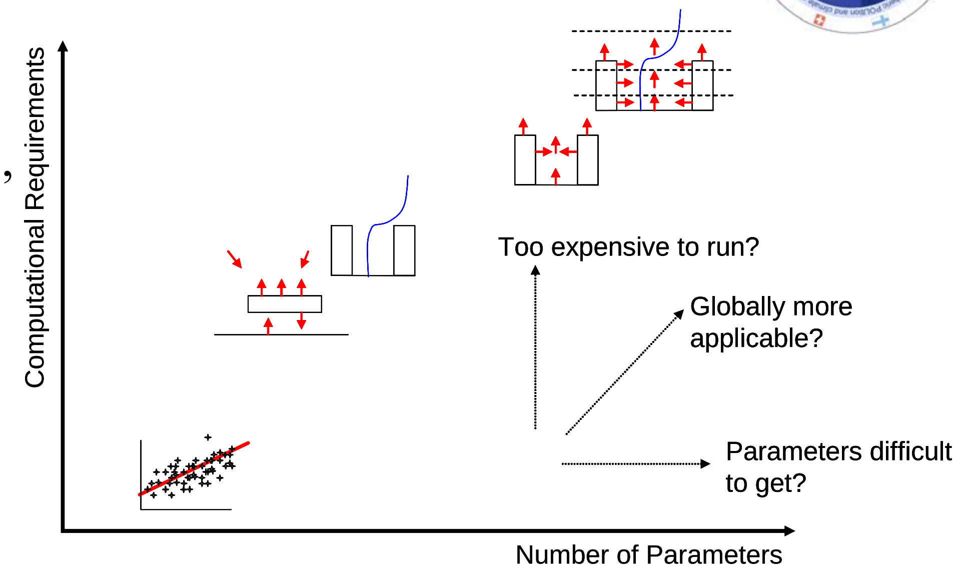
Order of integration and complexity:

- Order A – off-line coupling, meteorology / emissions -> chemistry; Models: All.
- Order B – partly online coupling, meteorology -> chemistry & emission; Models: UKCA, M-SYS, UM/WRFChem, SILAM.
- Order C – fully online integrated with two-way feedbacks, meteorology <=> chemistry & emissions; Models: UKCA WRF-Chem, Enviro-HIRLAM, EMAC (former ECHAM5/MESSy).

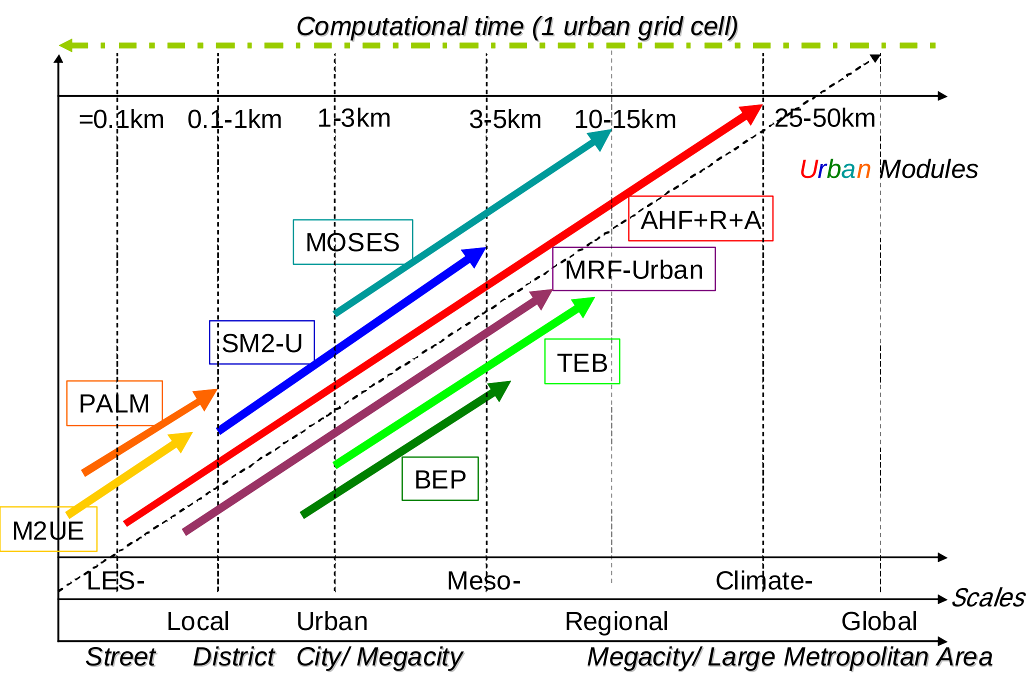
Strategy to urbanize different models

Main types of UC schemes:

- Single-layer and slab/bulk-type UC schemes,
- Multilayer UC schemes,
- Obstacle-resolved microscale models



MP hierarchy of urban canopy schemes for different type and scale models:



- Simple modification of land surface schemes (AHF+R+A)
- Medium-Range Forecast Urban Scheme (MRF-Urban)
- Building Effect Parameterization (BEP)
- Town Energy Budget (TEB) scheme
- Soil Model for Sub-Meso scales Urbanised version (SM2-U)
- UM Surface Exchange Scheme (MOSES)
- Urbanized Large-Eddy Simulation Model (PALM)
- CFD type Micro-scale model for urban environment (M2UE)

Mahura & Baklanov, 2011

FUMAPEX: Integrated Systems for Forecasting Urban Meteorology, Air Pollution and Population Exposure

FUMAPEX

http://fumapex.dmi.dk

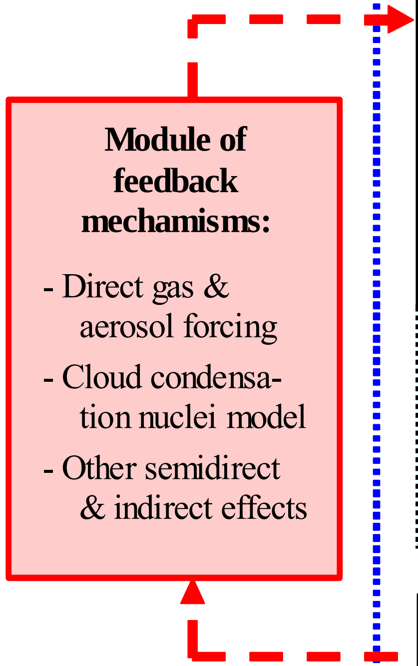
Goal: Improvements of meteorological forecasts (NWP) in urban areas, interfaces and integration with UAP and population exposure models following the off-line or on-line integration

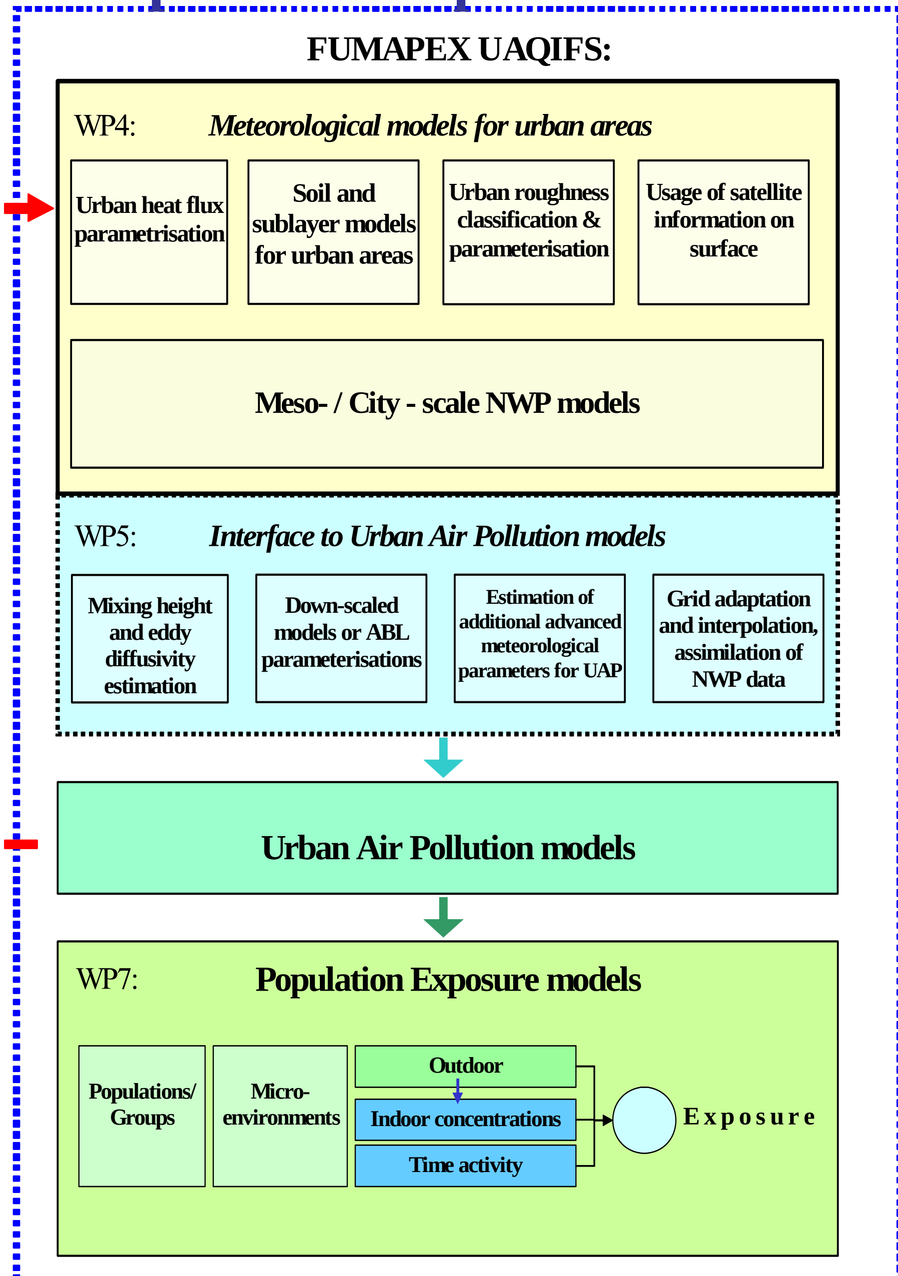
UAQIFS implemented in 6 European cities for operational forecasting:

#1 – Oslo, Norway
#2 – Turin, Italy
#3 – Helsinki, Finland
#4 – Valencia/Castellon, Spain
#5 – Bologna, Italy
#6 – Copenhagen, Denmark

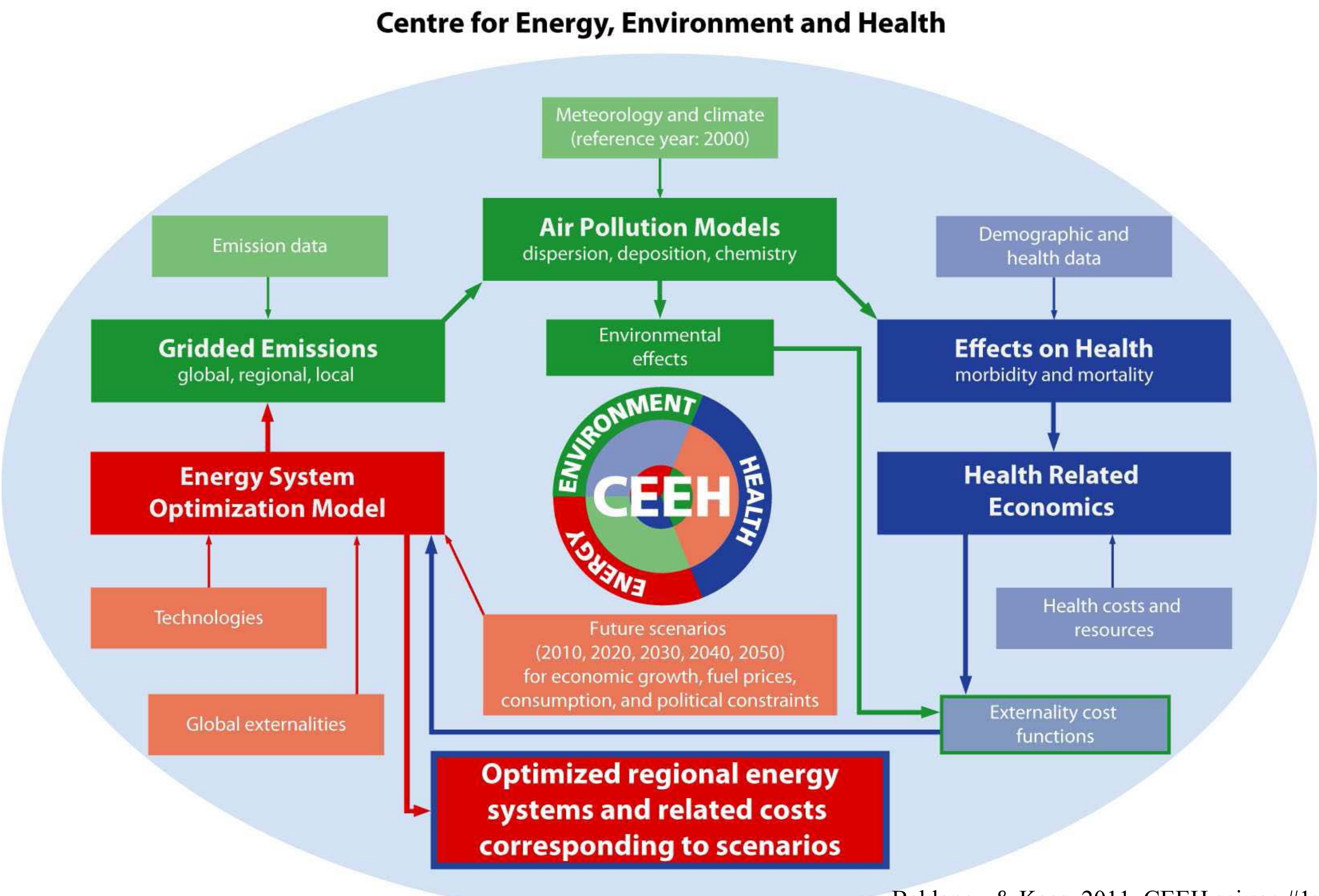
Different ways of the UAQIFS implementation:

(i) urban air quality forecasting mode,
(ii) urban management and planning mode,
(iii) public health assessment and exposure prediction mode,
(iv) urban emergency preparedness system.





CEEH modelling framework: Optimization of Energy System to minimise environmental and health impacts

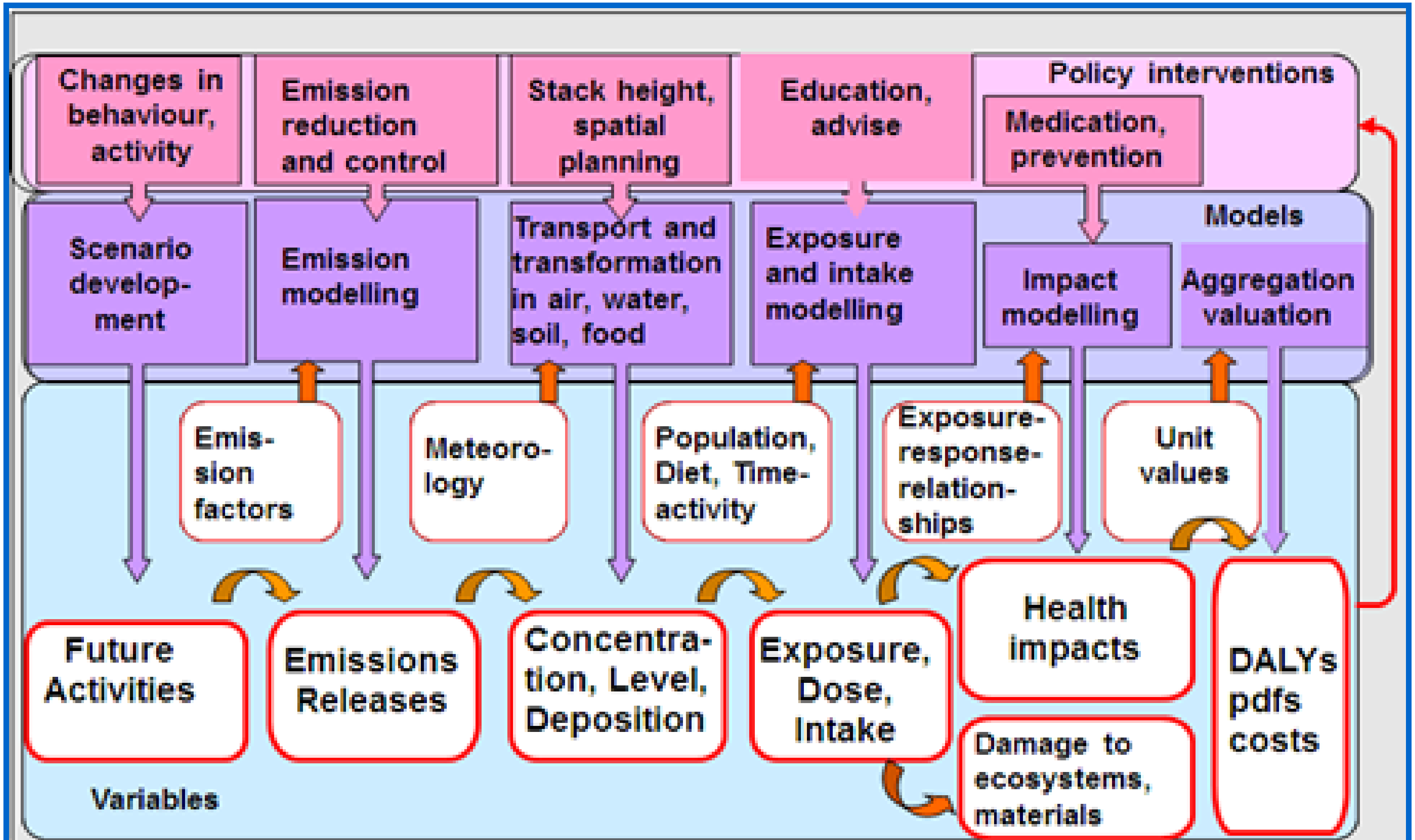


Baklanov & Kaas, 2011, CEEH sci rep #1: ceeh.dk

Which policy options are available to influence the emissions of air pollutants and greenhouse gases in megacities and how can these options be assessed?

Methodology The Full Chain Approach

MEGAPOLI applied a complex scenario approach with an energy model and emission inventory to perform an integrated assessment for European megacities.

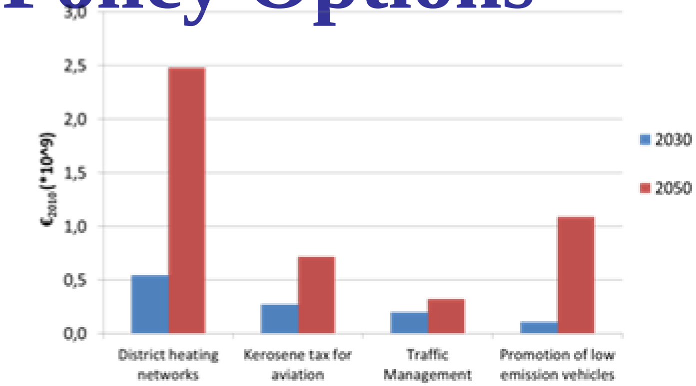


MEGAPOLI D8.2 report by UStutt

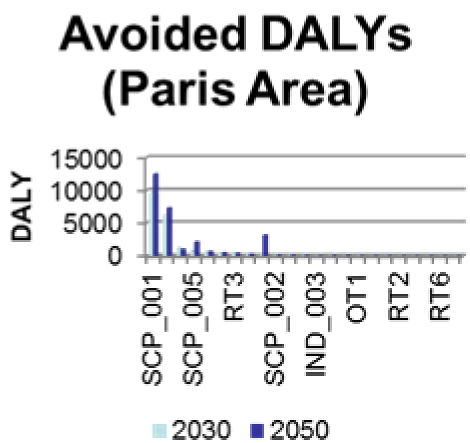
Considered Measures and Policy Options

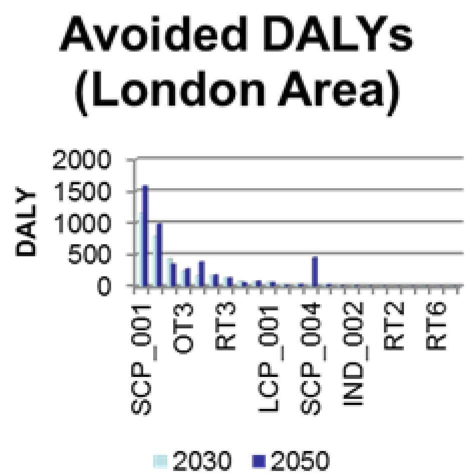
- Energy sector (LCP) => 2 measures
- Energy sector (Small combustion) =>5 measures
- Industry =>4 measures
- On-road => 9 measures
- Off-road => 4 measures

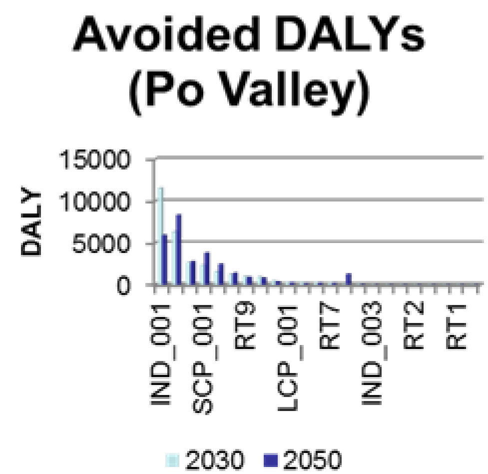
Pollutants: GHG, NO_x, SO_2, NMVOC, NH_3, PM10, PM2.5



Ranking of the measures with the most avoided DALYs (disability adjusted life years)







The measures with the most avoided DALYs for the whole European domain for 2030 are:

- Replacement of solid fuels fired small combustion plants with efficient combustion techniques (SCP1)
- Combined climate protection measures in cement industry (IND1)
- Energy-efficient modernisation of old buildings (SCP3)

For 2050 the energy efficient modernization of old building becomes more effective than others.

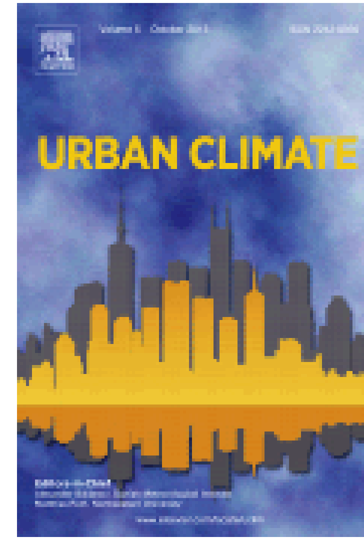
D8.3 report by J. Theloke et al., UStutt

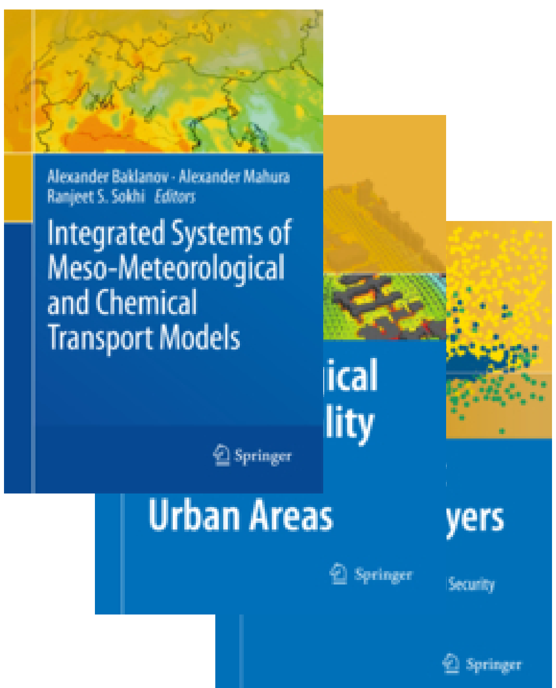
Conclusions

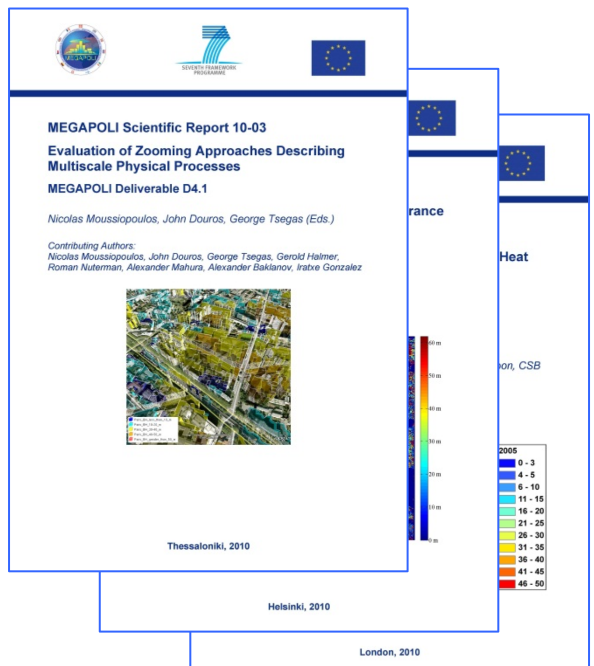
- Focus on urban climate and environment issues is timely (the XXI century is a century of urbanization).
- Cities will need improved climate, weather and environmental services to be resilient in withstanding environmental and climate hazards. Focus: hight impact weather events, UAQ, urban climate and comfort conditions.
- Urban effects and effects of urban emissions / air pollution are non-linearly interacting with each other.
- Depending on temporal and spatial scales, the key-processes and types of their interaction are different
- Integrated urban observation and model intercomparisons are needed: test beds
- Highly detailed local inventories are needed (emissions, AHF, urban morphology)
- Switching to a renewable heat supply in residential sector and promotion of low emission vehicles
- Prediction of PM remains a challenge and is an important area for continued research. SOA are very important
- Sensitivity of air quality to feedbacks from climate change interactions needs to be quantified; this will require online coupled multi-scale models.
- Interdisciplinary integrated assessment tools to optimize measures to reduce impact on health and climate are needed
- Successful experience need to be analyzed, adjusted and promoted from megacities in developing countries. Regional aspects are important.

MEGAPOLI Dissemination

- MEGAPOLI public web-site: http://megapoli.info
- MEGAPOLI Newsletter (12 issues and Volume)
- MEGAPOLI Sci. Reports (>50)
- Several Books published by Springer, etc.
- 3 Science Journal Special Issues
- A number of scientific papers (>70 and rising)
- New Elsevier 'Urban Climate' Journal







Thank You !

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