Integrated systems: on-line and off-line coupling of meteorological and air quality models, advantages and disadvantages

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COST728 WG2: Integrated systems of MetM and CTM/ADM: strategy, interfaces and module unification

COST-728 / NetFAM workshop on
"Integrated systems of meso-meteorological and chemical transport models"
Copenhagen, Denmark
21-23 May 2007

Meteorology and Air Pollution:
as a joint problem

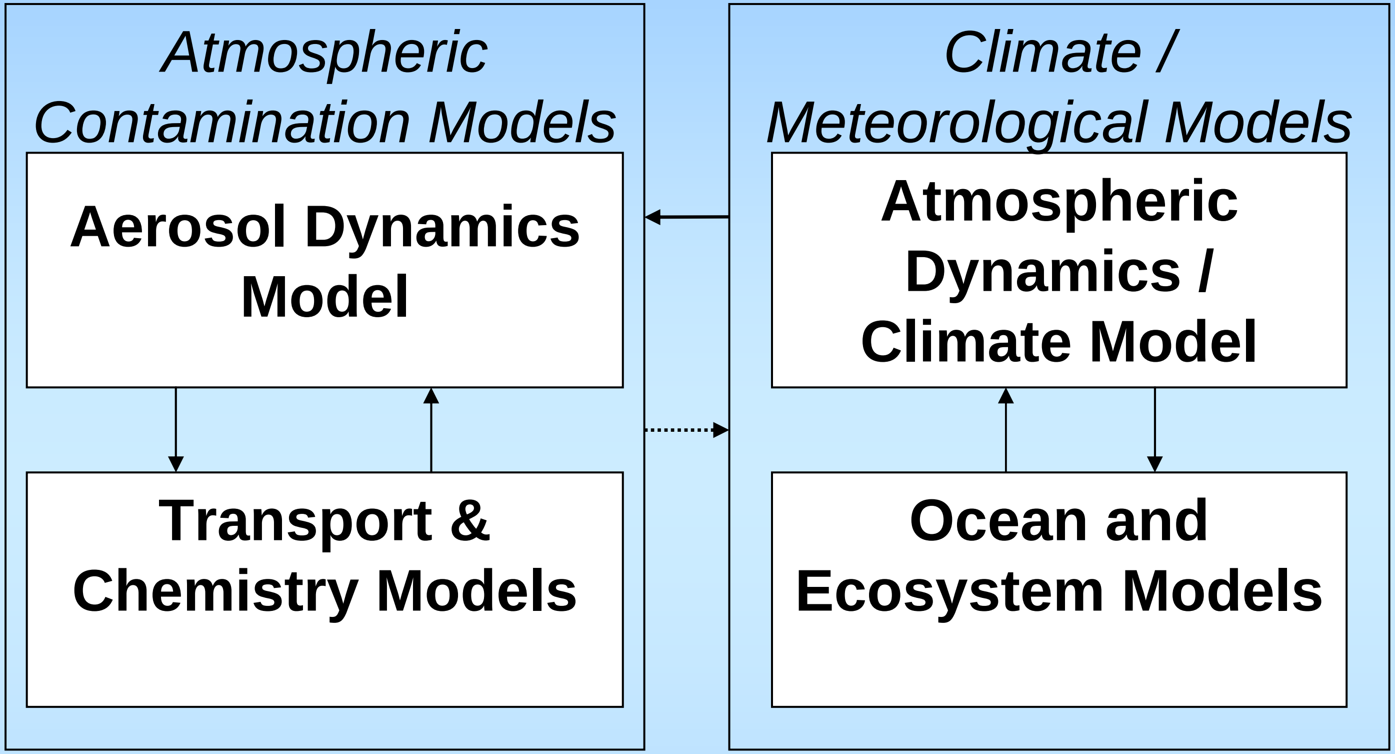
- Meteorology is a main source of uncertainty in ACTMs => needs for meso-scale MetM / NWP model improvements
- Complex & combined effects of meteo- and pollution components (e.g., Paris, Summer 2003)
- Effects of pollutants/aerosols on meteo-processes (precipitation, thunderstorms, etc) and climate change

Four main stones for Atmospheric Environment modelling:

1. Meteorology / ABL structure,
2. Chemistry,
3. Aerosol/pollutant dynamics
4. Effects and Feedbacks

=> *Integrated MetM & ACTM Approach (“Chemical Weather Forecasting”)*

Integrated Atmospheric System Model Structure



One-way: 1. Meteofields as a driver for ACTM; 2. Chemical composition fields as a driver for R/GCM (or for NWP)

Two-way: 1. Driver + partly feedback (data exchange); 2. Full feedbacks included on each time step (on-line coupling)

Applications of integrated models for:

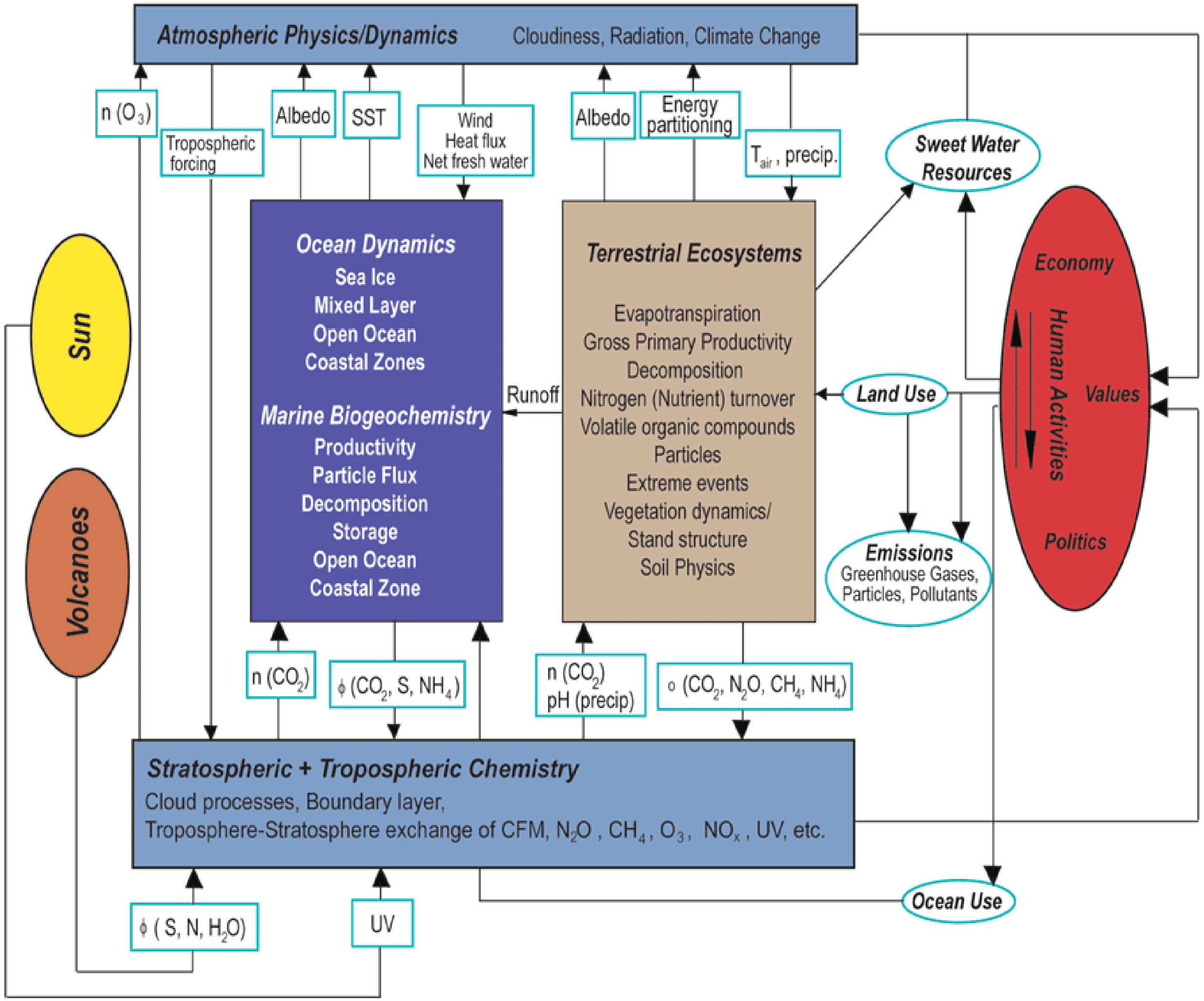
(i) climate change modelling,

(ii) weather forecast (e.g., in urban areas, severe weather events, etc.),

(iii) air quality and chemical composition longer-term assessment and

(iv) chemical weather forecasting

COSMOS: Community Earth System Models



Differences from COST728:

- ***Climate time-scale processes,***
- ***General (global and regional) atmospheric circulation models,***
- ***Atmosphere, ocean, cryosphere and biosphere integration***

The European PRISM project

<u>The PRISM project develops:</u>

- **infrastructure for Earth System Modelling including**
- **the coupler OASIS, as well as**
- **tools for configuration, monitoring and post-processing.**

PRISM also provides <u>guidelines for good coding practices</u>.

Detailed information can be found in the PRISM System Specifications Handbook.

[PRISM website: <u>http://prism.enes.org/</u>]

EC 5FP FUMAPEX
Project objectives:

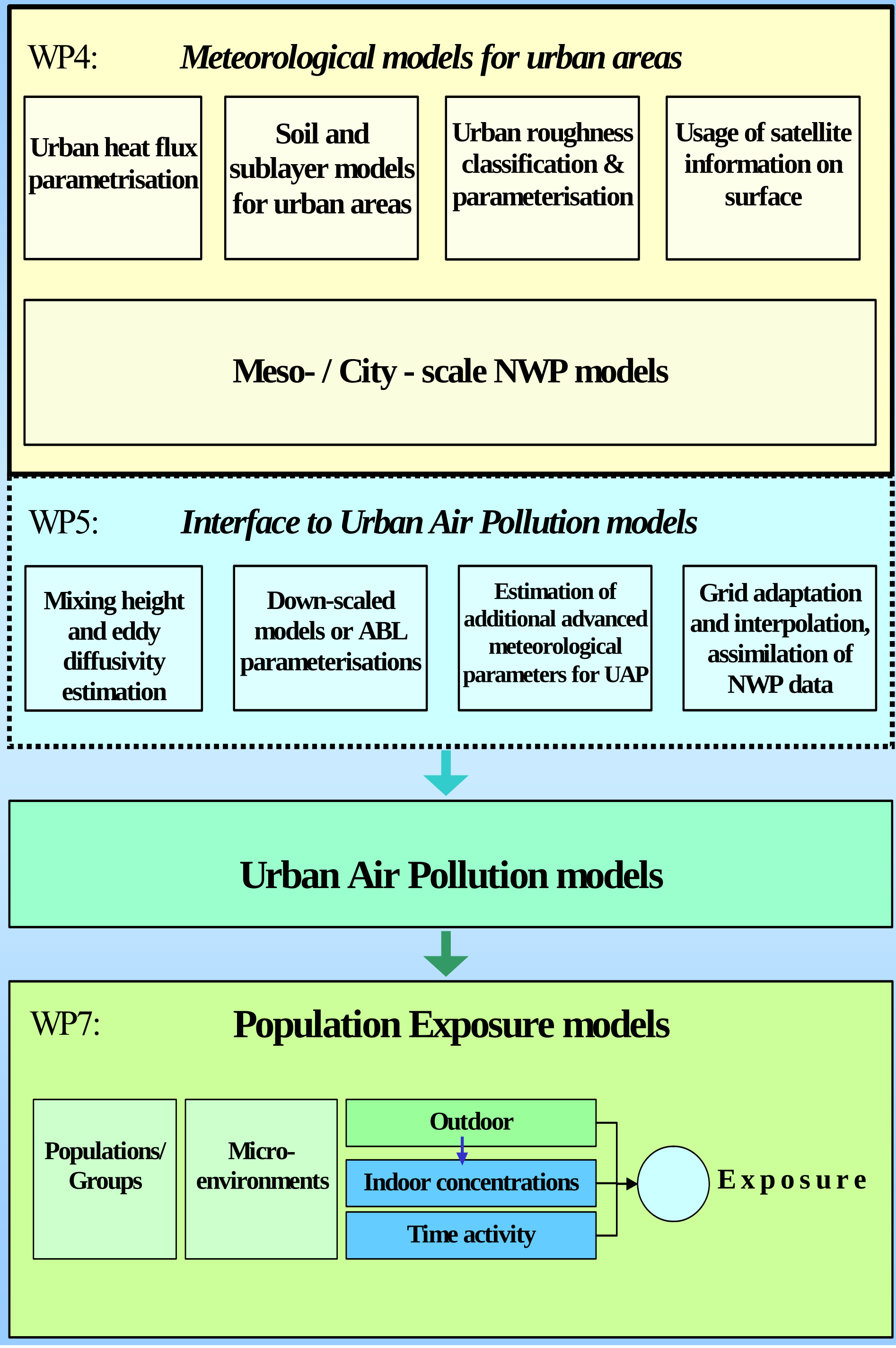
(i) the improvement of meteorological forecasts for urban areas,

(ii) the connection of NWP models to urban air pollution (UAP) and population exposure (PE) models,

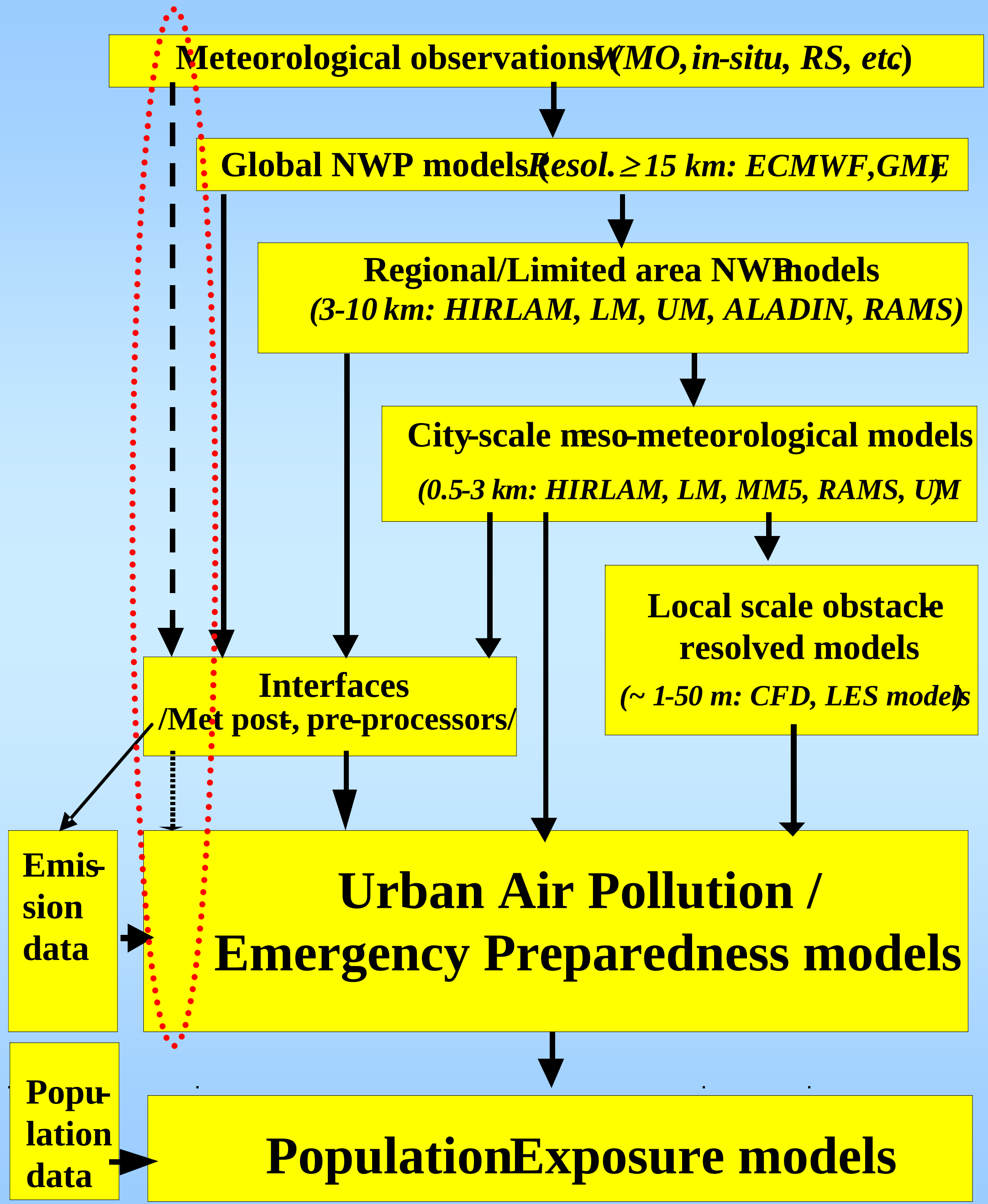
(iii) the building of improved *Urban Air Quality Information and Forecasting Systems* (UAQIFS), and

(iv) their application in cities in various European climates.

http://fumapex.dmi.dk



Current regulatory (dash line) and suggested (solid and dash lines) ways for multi-scale systems of forecasting of urban meteorology for UAQIFS



Off-line coupling: Development of meteo-processor and interface between urban scale NWP and UAP models

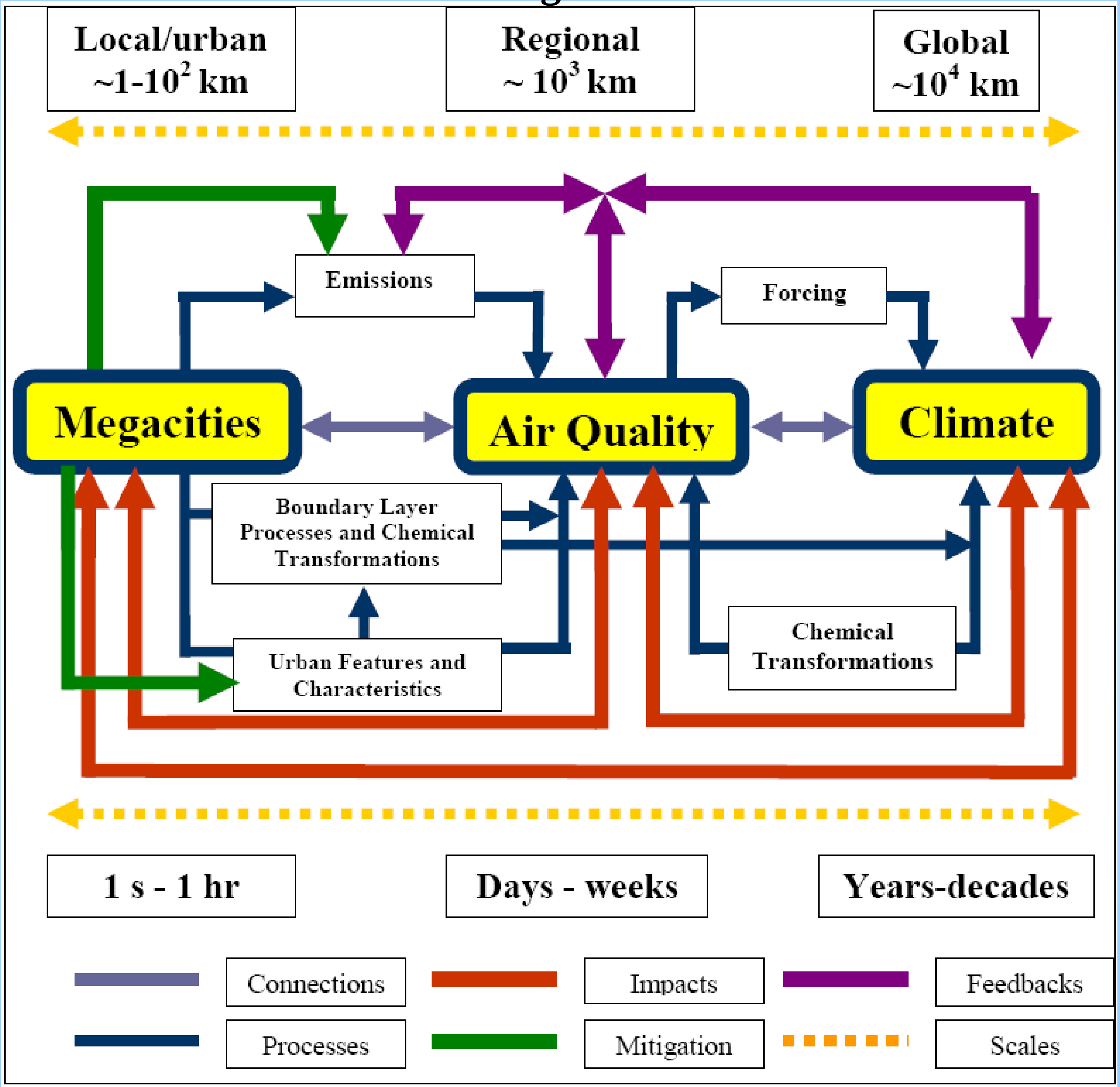
WP5: *Interface to Urban Air Pollution models*

Mixing height and eddy diffusivity estimation	Down-scaled models or ABL parameterisations	Estimation of additional advanced meteorological parameters for UAP	Grid adaptation and interpolation, assimilation of NWP data

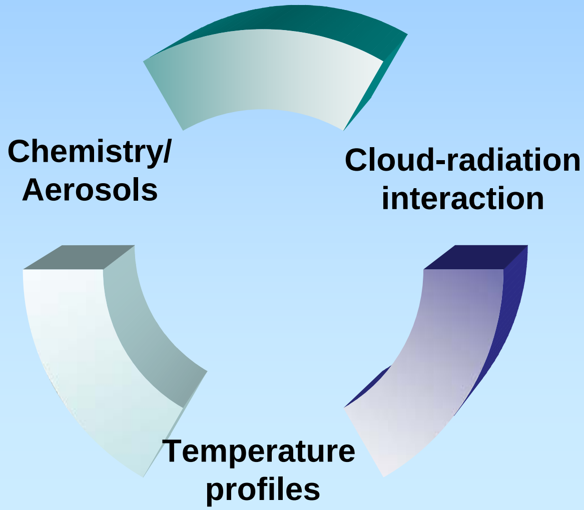
- **Guidelines for and improvements of interfaces (Finardi et al., 2004)**
- **Interface vs. pre-processors for modern UAQ models**
- **BEP urbanization module as a post-processor (Clapier et al., 2004)**
- **DMI new urban meteo-preprocessor (Baklanov and Zilitinkevich, 2004)**
- **MH methods for urban areas (WG2 COST715)**

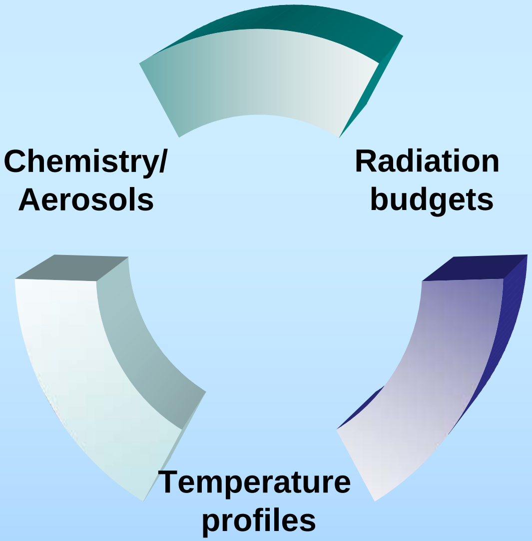
Connections between megacities, air quality and climate:

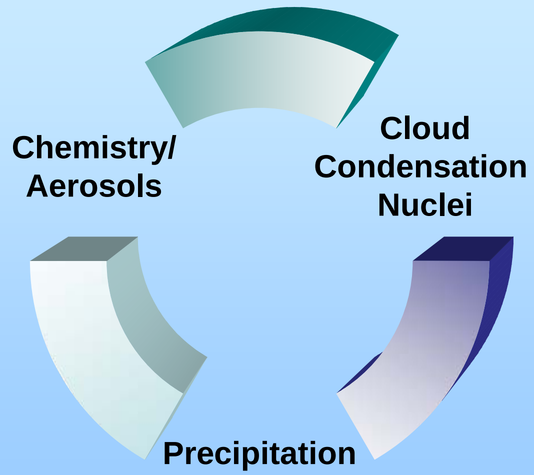
main feedbacks, ecosystem, health and weather impact pathways, and mitigation routes



Examples of feedbacks



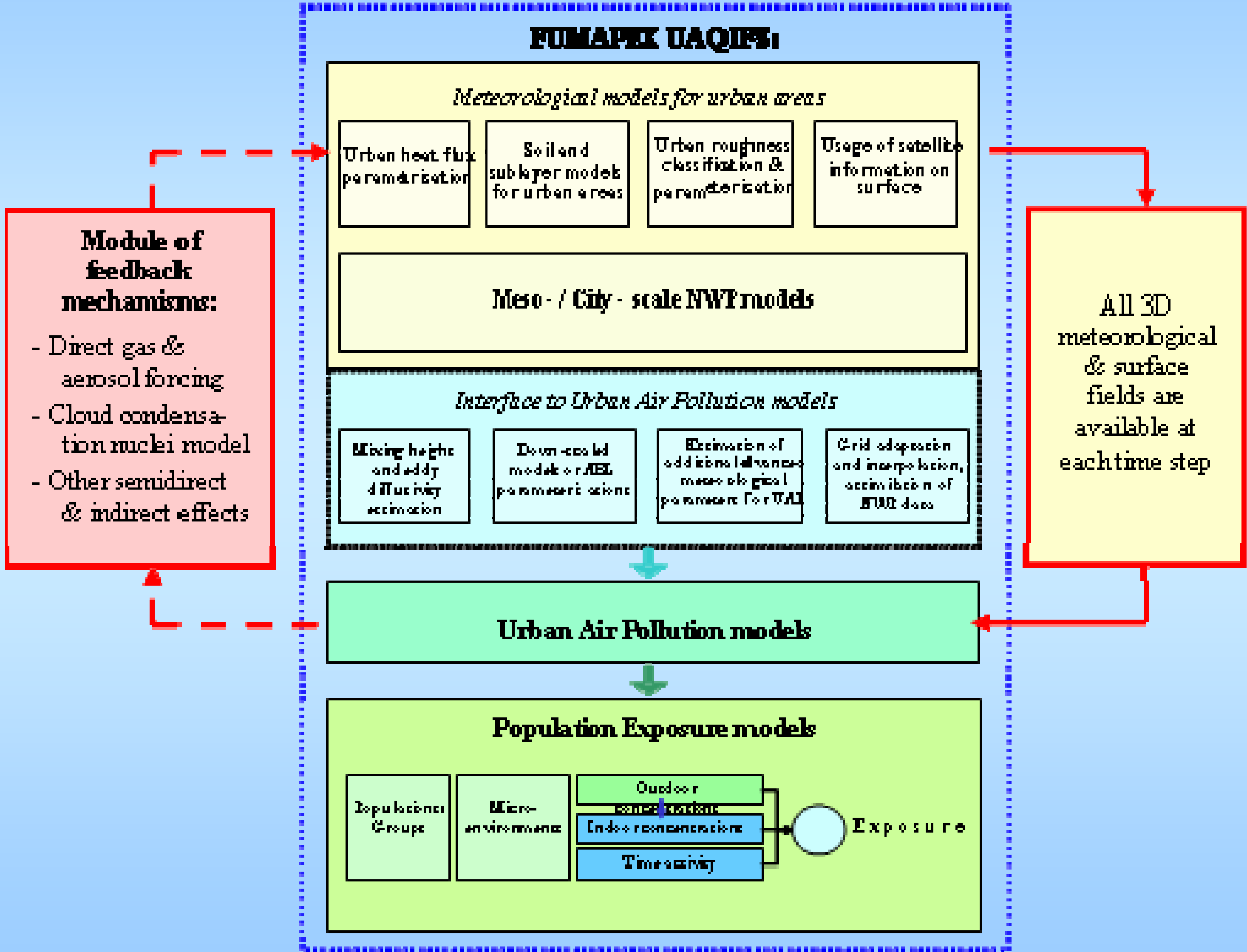




Effects of aerosol particles on climate:
(following Jacobson, 2002)

- Self-Feedback Effect
- Photochemistry Effect
- Smudge-Pot Effect
- Daytime Stability Effect
- Particle Effect Through Surface Albedo
- Particle Effect Through Large-Scale Meteorology
- Indirect Effect
- Semidirect Effect
- BC-Low-Cloud-Positive Feedback Loop

On-line integrated system structure



Extended FUMAPEX scheme of the improvements of meteorological forecasts (NWP) in urban areas, interfaces and on-line integration with UAP and population exposure models for urban air quality information forecasting and information systems (UAQIFS).

Definitions of integrated/coupled models

Definitions of off-line models:

• **separate CTMs driven by meteorological input data from meteo-preprocessors, measurements or diagnostic models,**

• **separate CTMs driven by analysed or forecasted meteodata from NWP archives or datasets,**

• **separate CTMs reading output-files from operational NWP models or specific MetMs with a limited periods of time (e.g. 1, 3, 6 hours).**

Definitions of on-line models:

• **on-line access models, when meteodata are available at each time-step (it could be via a model interface as well),**

• **on-line integration of CTM into MetM, when feedbacks are possible to consider. We will use this definition as on-line coupled modelling.**

Advantages of On-line & Off-line modeling

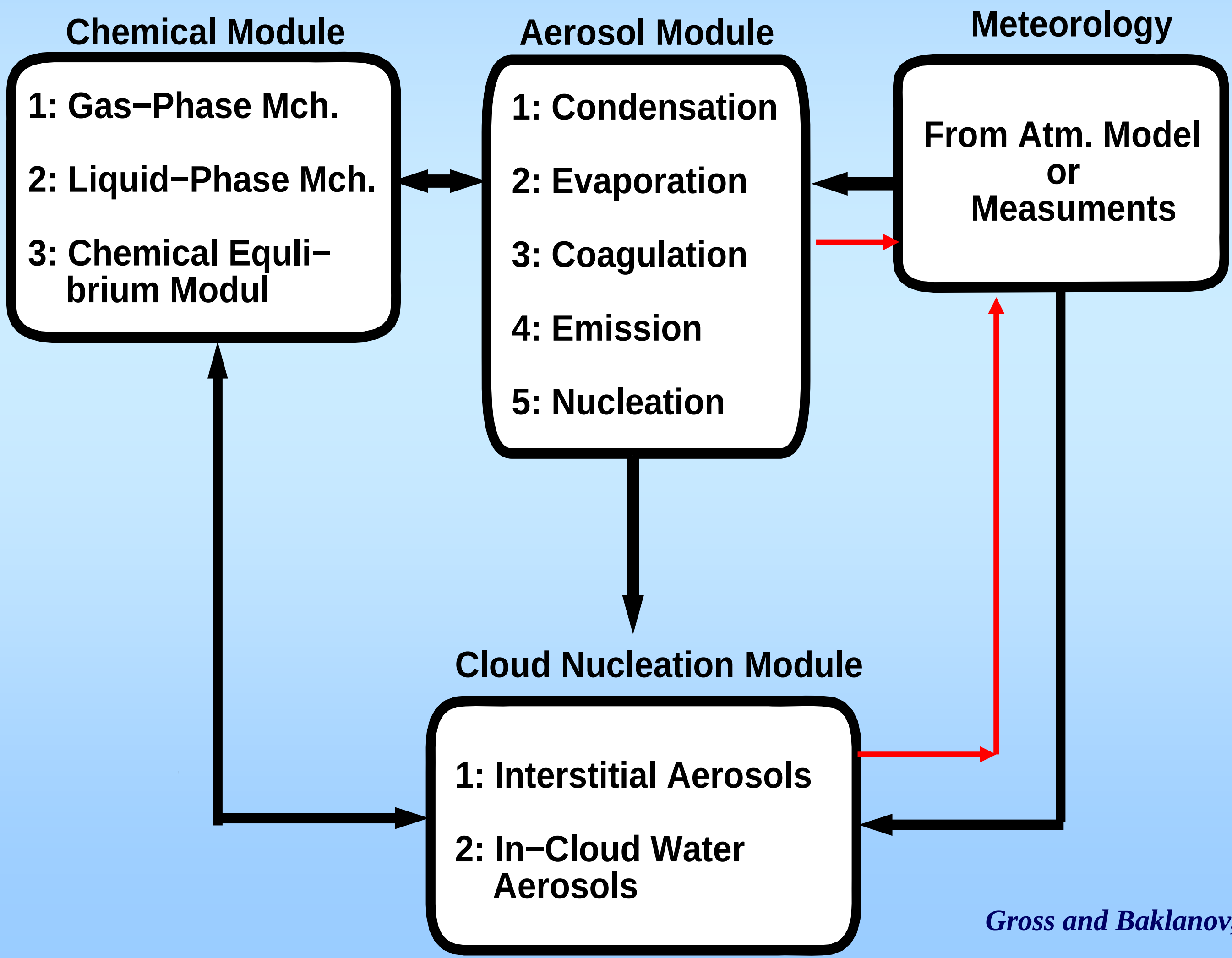
On-line coupling

- Only one grid;
- No interpolation in space
- No time interpolation
- Physical parameterizations are the same; No inconsistencies
- Possibility to consider aerosol forcing mechanisms
- All 3D met. variables are available at the right time (each time step); No restriction in variability of met. fields
- Possibility of feedbacks from meteorology to emission and chemical composition
- Does not need meteo- pre/post-processors

Off-line

- Possibility of independent parameterizations;
- Low computational cost (if NWP data are already available and no need to run meteorological model);
- More suitable for ensembles and operational activities;
- Easier to use for the inverse modelling and adjoint problem;
- Independence of atmospheric pollution model runs on meteorological model computations;
- More flexible grid construction and generation for ACT models,
- Suitable for emission scenarios analysis and air quality management.

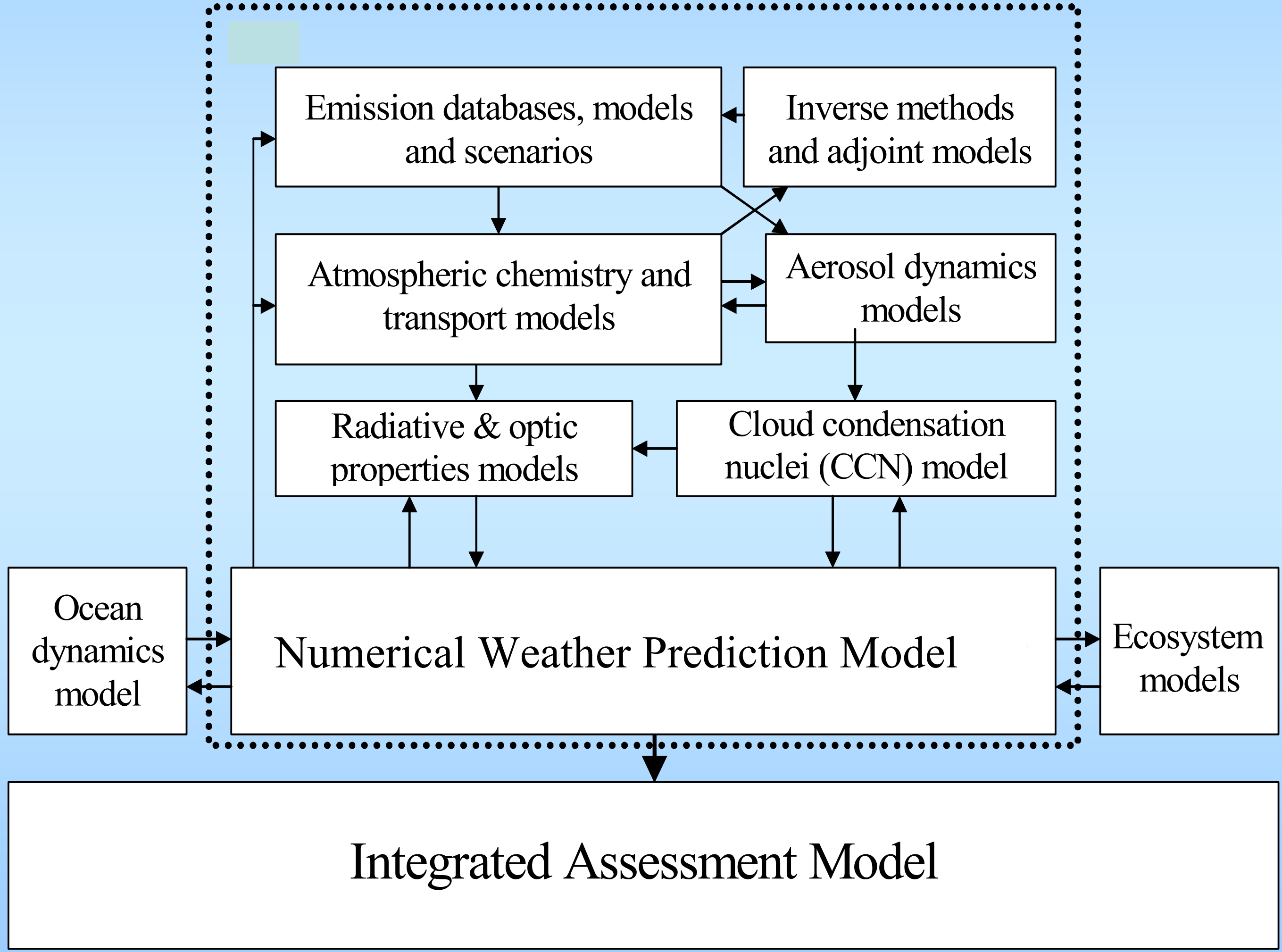
Schematic Illustration of the DMI Chemistry-Aerosol-Cloud (CAC) System implementing into Enviro-HIRLAM



Gross and Baklanov, IJEP, 2004, 22, 51

DMI-Enviro-HIRLAM

New integrated (on-line coupled) modeling system structure for predicting the atmospheric composition



On-line coupled MetM and CTM model systems already being used in Europe (and America):

- BOLCHEM (CNR/ISAC, Bologna, Italy),
- ENVIRO-HIRLAM (DMI, Denmark),
- LM-ART (Inst. for Meteorology and Climatology, FZ Karlsruhe, Germany),
- LM-MUSCAT (IfT Leipzig, Germany),
- MCCM (Inst. of Environmental Atmospheric Research at FZ Karlsruhe, Germany),
- MESSy: ECHAM5 (MPI-C Mainz, Germany),
- MC2-AQ (York Univ, Toronto, University of British Columbia, Canada, and Warsaw University of Technology, Poland),
- GEM/LAM-AQ (York Univ, Toronto, University of British Columbia, Canada, and Warsaw University of Technology, Poland),
- WRF-CHem: Weather Research and Forecast and Chemistry Community modelling system (NCAR and many other organisations),
- MESSy: ECHAM5-Lokalmodell LM planned at MPI-C Mainz, Univ. of Bonn, Germany.

cost

On-line coupled MetM - CTMs

Model name	*Coupled chemistry*	*Time step for coupling*	*Feedback*
BOLCHEM	Ozone as prognostic chemically active tracer	?	None
ENVIRO-HIRLAM	Gas phase, aerosol and heterogeneous chemistry	Each HIRLAM time step	Yes
GME ECMWF model (IFS)	Ozone as prognostic passive tracer	Each time step	Yes
LM_ART	Gas phase chem (58 variables), aerosol physics (102 variables), pollen grains	each LM time step	Yes
LM-MUSCAT	Several gas phase mechanisms, aerosol physics	Each time step or time step multiple	Yes
MCCM	RADM and RACM mechanisms, Photolysis model of Madronich	?	?
MESSy: ECHAM5 (development)	Gases and aerosols	?	?
MESSy: ECHAM5-LM (planned)	Gases and aerosols	?	?
MC2-AQ	Gas phase: 47 species, 98 chemical reactions and 16 photolysis reactions	Every time step	None
WRF-CHem	Gases and aerosols	Every time step	Yes
GEM/LAM-AQ	Gas phase, aerosol and heterogeneous chemistry	Set up by user – in most cases every time step	None

DMI

Non-European Union countries experience

- from America: the US EPA and other US and Canadian institutions (see WRF-Chem; Grell et al., 2005; Jacobson, 2005, 2006; Byun and Schere, 2006; Kaminski et al., 2005; etc.);
- from Russia, e.g. one of the first experience in on-line coupling atmospheric pollution models and meteorological models in the Novosibirsk scientific school (Marchuk, 1982; Penenko and Aloyan, 1985; Baklanov, 1988), for example for modelling of active artificial/anthropogenic impacts on atmospheric processes;
- from Japan: integrated chemical weather forecasting systems, based on the Earth Simulator (Uno et al., 2003, 2004).

Why we need to build the European integration strategy?

• NWP models are not primarily developed for CTM/ADMs and there is no tradition for strong co-operation between the groups for meso/local-scale

• the conventional concepts of meso- and urban-scale AQ forecasting need revision along the lines of integration of MetM and CTM

• US example (The models 3, WRF-Chem)

• A number of European models …

• A universal modelling system (like ECMWF in EU or WRF-Chem in US) ???

• an open integrated system with fixed architecture (module interface structure)

European mesoscale MetM/NWP communities:

• ECMWF
• HIRLAM
• COSMO
• ALADIN/AROME
• UM

• WRF
• MM5
• RAMS

European CTM/ADMs:

• a big number
• problem oriented
• not harmonised (??)
• …..

Shortcomings of existing NWP models for using in Chemical Weather Forecasting:

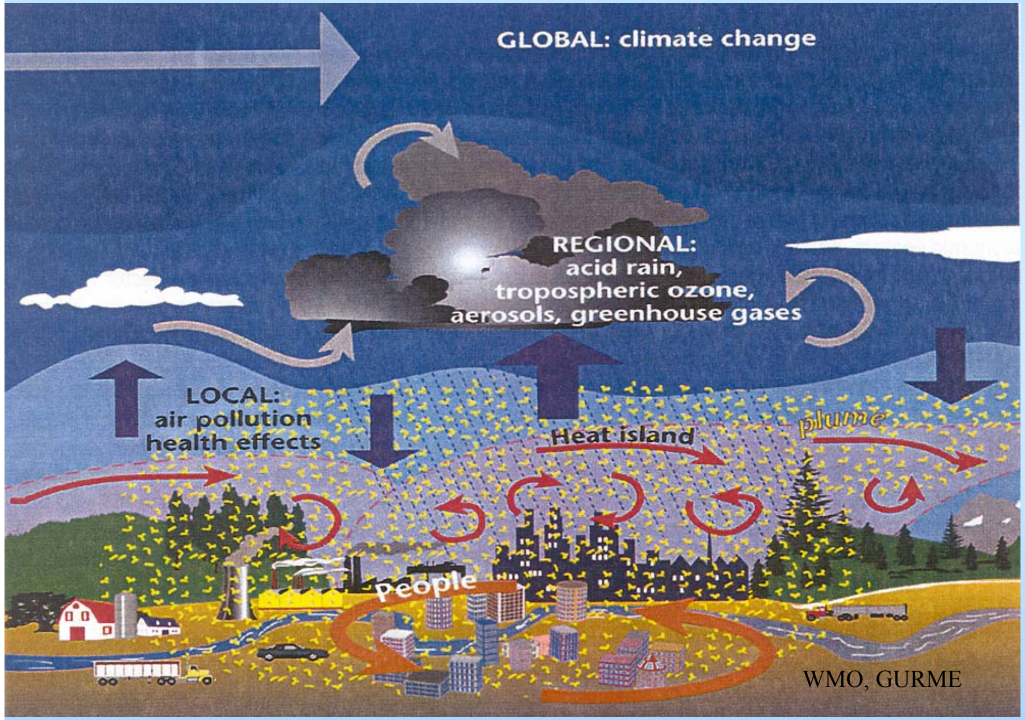
- ❑ Atmospheric environment modelling requires to resolve more accurately the PBL and SLs structure in NWP models (in comparison with weather forecast tasks)

- ❑ Despite the increased resolution of existing operational NWP models, urban and non-urban areas mostly contain similar sub-surface, surface, and boundary layer formulation.

- ❑ These do not account for specifically urban dynamics and energetics and their impact on the ABL characteristics (e.g. internal boundary layers, urban heat island, precipitation patterns).

- ❑ NWP models are not primarily developed for air pollution modelling and their results need to be designed as input to or be integrated into urban and meso-scale air quality models.

Megacities:
Urban features in focus:



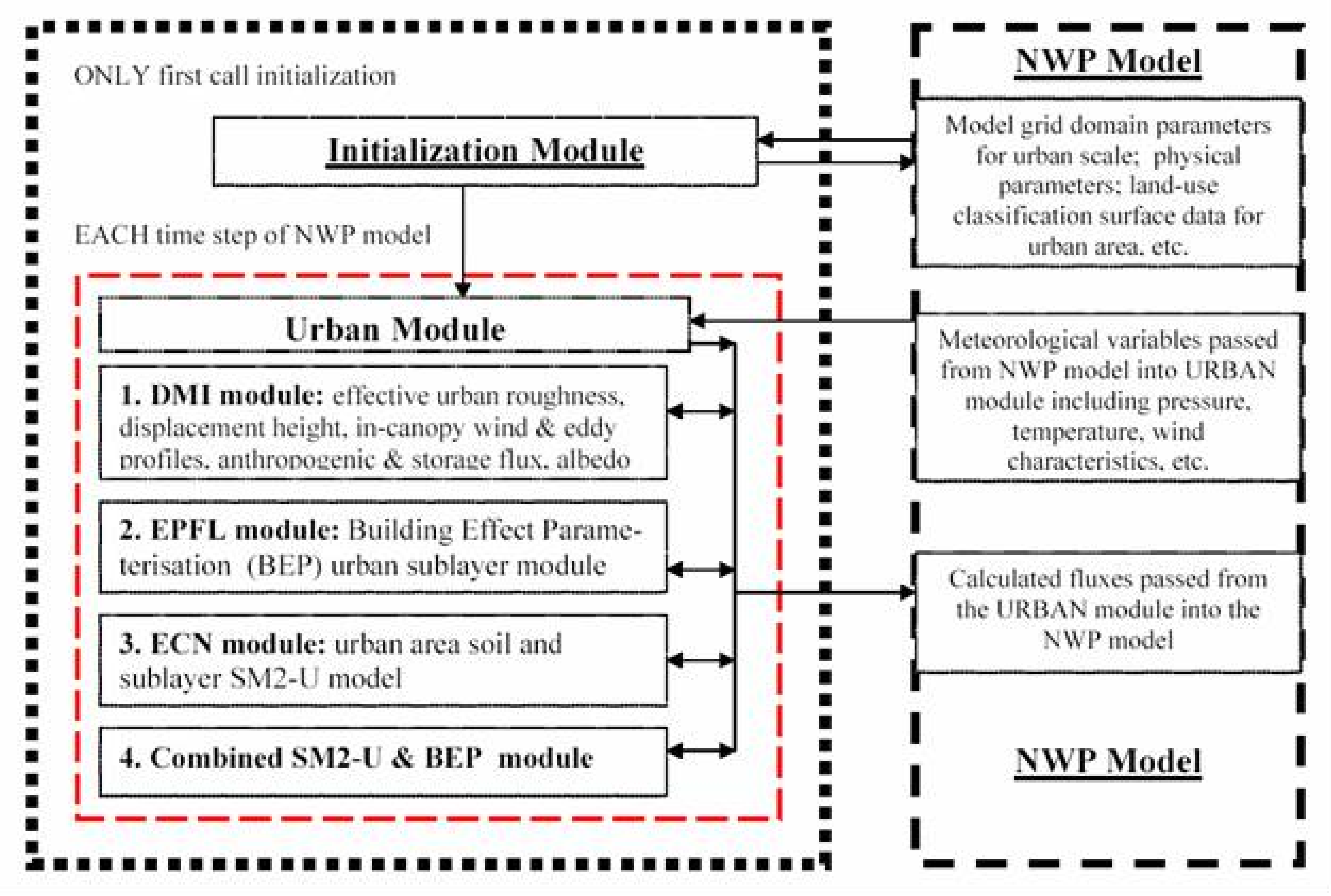
- **Urban pollutants emission, transformation and transport,**
- **Land-use drastic change due to urbanisation,**
- **Anthropogenic heat fluxes, urban heat island,**
- **Local-scale inhomogeneties, sharp changes of roughness and heat fluxes,**
- **Wind velocity reduce effect due to buildings,**
- **Redistribution 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.**

Urbanisation of NWP models:

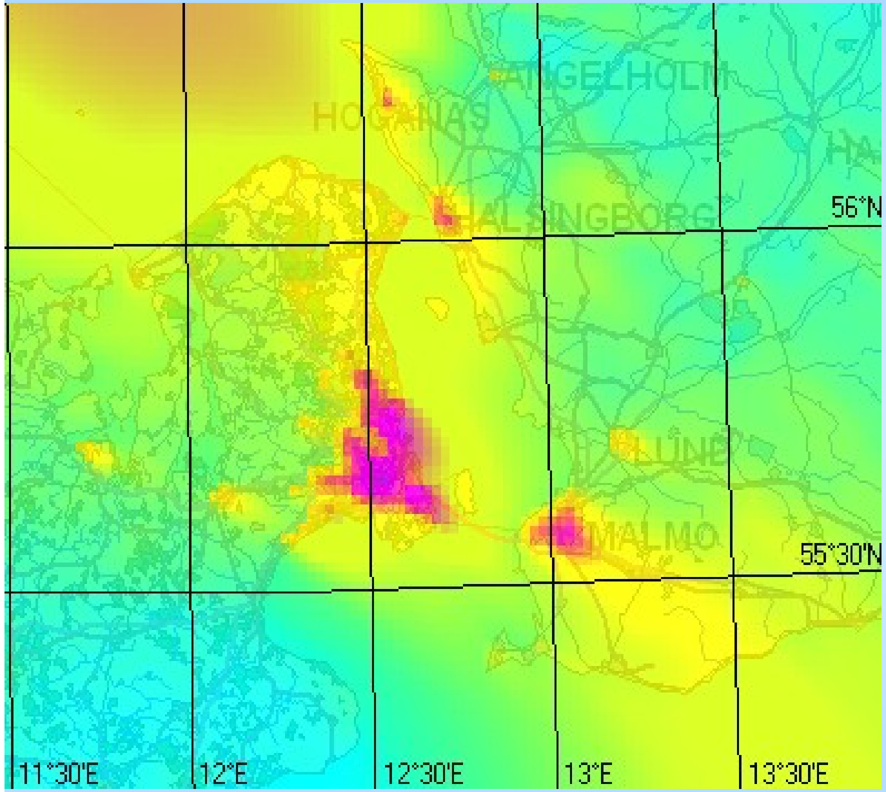
1. Model down-scaling, including increasing vertical and horizontal resolution and nesting techniques (one- and two-way nesting);
2. Modified high-resolution urban land-use classifications, parameterizations and algorithms for roughness parameters in urban areas based on the morphologic method;
3. Specific parameterization of the urban fluxes in meso-scale models;
4. Modelling/parameterization of meteorological fields in the urban sublayer;
5. Calculation of the urban mixing height based on prognostic approaches;
6. Assimilation surface characteristics based on satellite data into Urban Scale NWP models.

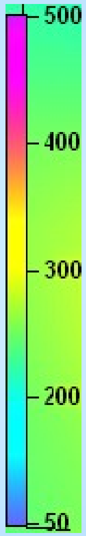
Integrated Fumapex urban module for NWP models

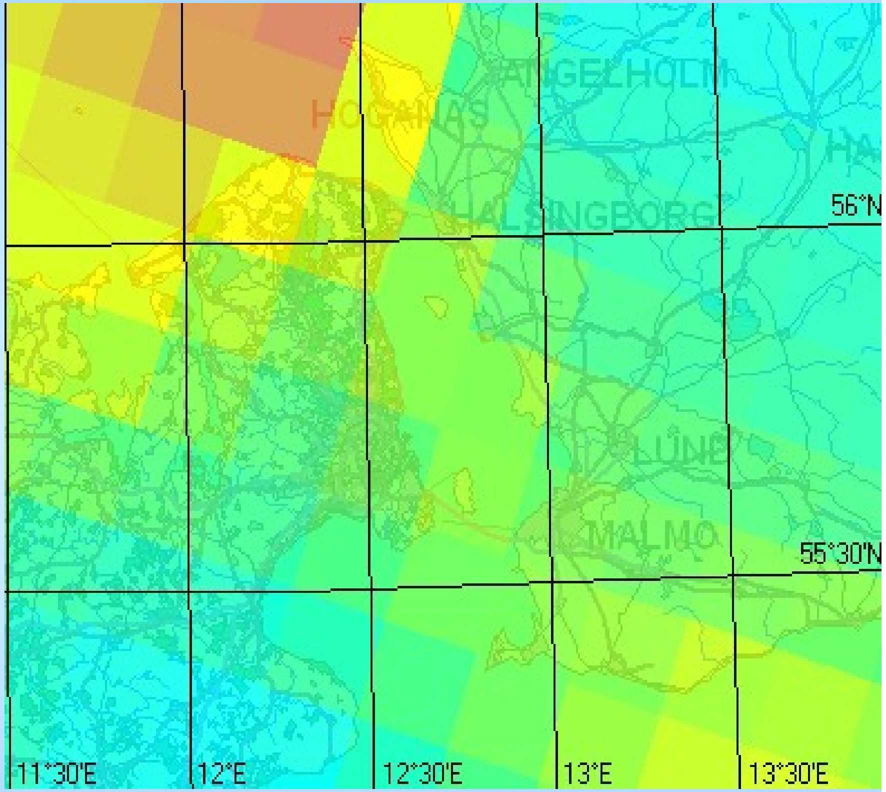
including 4 levels of complexity of the NWP 'urbanization' (see *fumapex.dmi.dk*)



Mixing height in ARGOS as calculated from different versions of DMI-HIRLAM



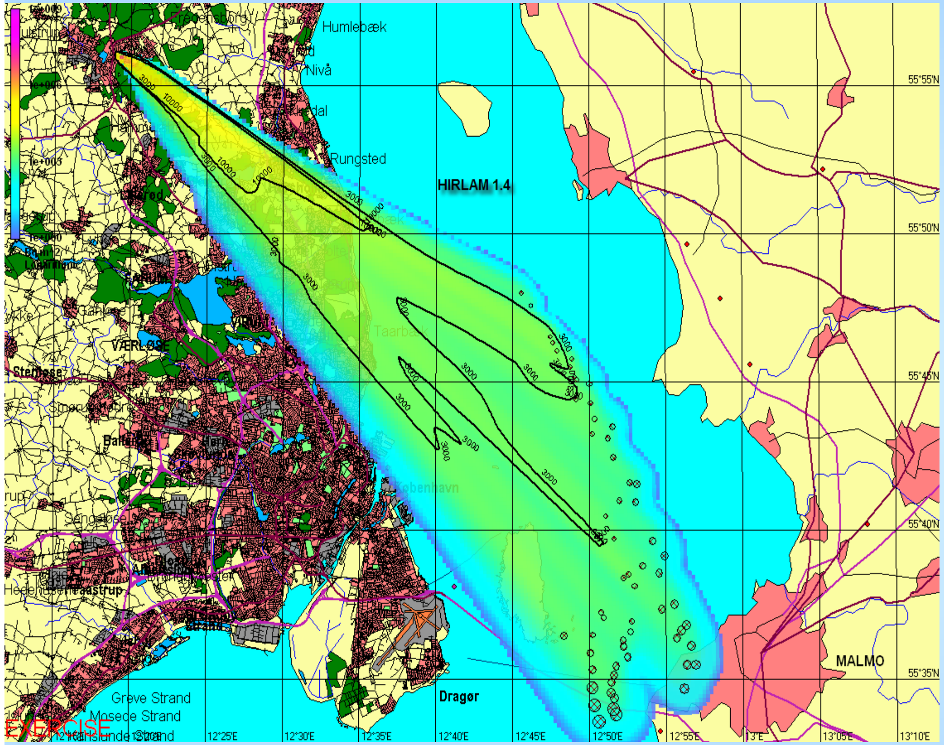




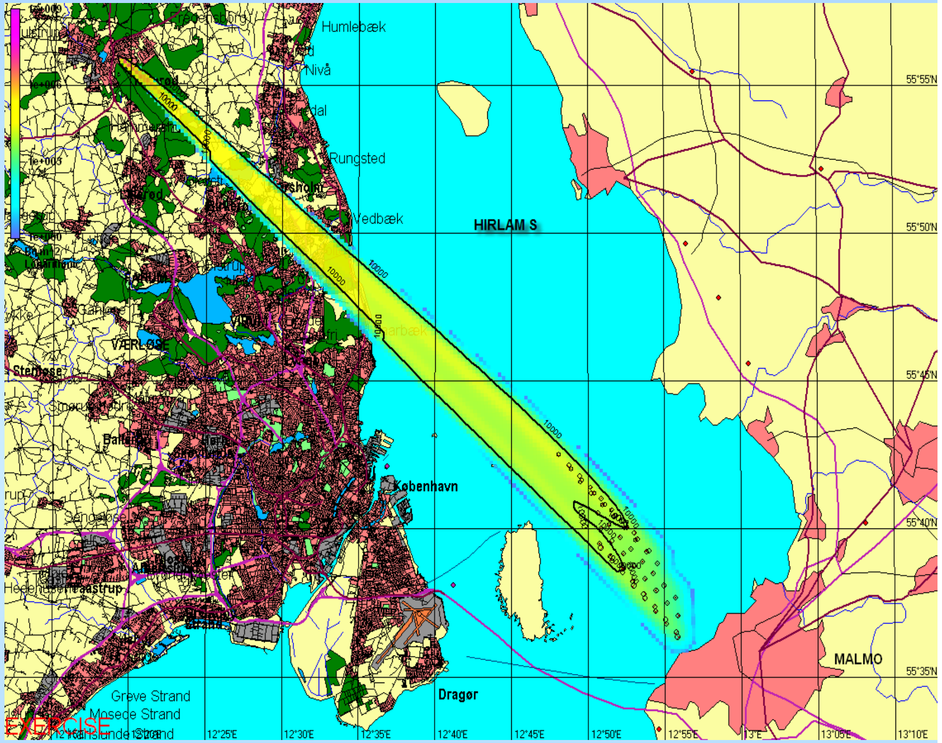
urbanised 1.4 km

operational 15 km

Sensitivity of ARGOS dispersion simulations to urbanized DMI-HIRLAM NWP data



urbanised U01, 1.4 km resolution



operational S05, 5 km resolution

Cs-137 air concentration for different DMI-HIRLAM data
A local-scale plume from the ^{137}Cs hypothetical atmospheric release in Hillerød at 00 UTC, 19 June 2005 as calculated with RIMPUFF using DMI-HIRLAM and visualised in ARGOS for the Copenhagen Metropolitan Area.

Approaches applicability

- The first module is the cheapest way of "urbanising" the model and can be easily implemented into operational NWP models as well as in Regional Climate Models.
- The second module is a relatively more expensive (≈ 5-10 % computational time increase), but it gives a possibility to consider the energy budget components and fluxes inside the urban canopy. However, this approach is sensitive to the vertical resolution of NWP models and is not very effective if the first model level is higher than 30 meters. Therefore, the increasing of the vertical resolution of current NWP models is required.
- The third module is considerably more expensive computationally than the first two modules (up to 10 times!). However, it provides the possibility to accurately study the urban soil and canopy energy exchange including the water budget. Therefore, the second and third modules are recommended for use in advanced urban-scale NWP and meso-meteorological research models.

COST-728: MESOSCALE METEOROLOGICAL MODELLING CAPABILITIES FOR AIR POLLUTION AND DISPERSION APPLICATIONS

Working Group 2: Integrated systems of MetM and CTM/ADM: strategy, interfaces and module unification (http://cost728.dmi.dk/)

The overall aim of WG2 is to identify the requirements for the unification of MetM and CTM/ADM modules and to propose recommendations for a European strategy for integrated mesoscale modelling capability.

NWP Communities Involved:

- ***HIRLAM, COSMO, ALADIN/AROME, UM communities***
- MM5/WRF/RAMS users/developers

HIRLAM presented by DMI (A.Baklanov), ***FMI*** (M.Sofiev), ***SMHI*** (V.Foltescu), ***UT*** (A.Mannik), KNMI (U.

Tasks/Sub-groups:

1. Off-line models and interfaces
2. Model down-scaling/ nesting
3. On-line coupled modelling systems
4. Data assimilation
5. Models unification and harmonization

COST728 WG2 activities:

1. Overview of **existing integrated (off-line and on-line) systems** in Europe and outside Europe.
2. Identification of the **advantages and disadvantages of strategies for integrating of MetMs and CTM/ADMs**.
3. Development of **guidance and strategy for on-line coupling** of MetMs and CTM/ADMs and **for their off-line interfacing**.
4. Overview of **existing module structures** of MetMs and CTM/ADMs, along with **recommendations and requirements for module unification**.
5. Formulation of **requirements of mesoscale MetMs** suitable **as input to air pollution models** and **improved meteorological pre-processors and model interfaces**, including deposition processes, capable of connecting mesoscale MetM results to CTM/ADMs.
6. Recommended methods for the **model down-scaling and nesting**, as well as **assimilation techniques**.
7. Identifying **requirements** (including observation data needs) for an **integrated mesoscale modelling capability/strategy for Europe**.

Important to involve:

- ***EU NWP communities:***
  - ***HIRLAM*** (A. Baklanov, V. Foltescu, A. Mannik, M. Sofiev),
  - ***COSMO*** (B. Fay, A. Clappier, MeteoSwiss),
  - ***ALADIN/AROME*** (V.H. Peuch)
  - ***UM*** (P. Clark, M. Athanassiadou)
- ECMWF
- MM5/WRF/RAMS (integrated with CTMs) users/developers (US: G. Grell, EU: R. Sokhi, M. Millan, S. Finardi)
- GEM Environment Canada (J. Kaminski)
- To link with existing EC and other projects (GEMS, ACCENT, COSMOS, PRISM2, ENSEMBLES, EUCAARI, …)
- EnviroGroup of EUMetNet, EEA, Chemical Weather Forecast COST Action (Jaakko Kukkonen) – to link
- Experience from 5FP projects: FUMAPEX, PHOENICS, …

Workshop Aim, Emphasis and Topics

The aim of the workshop is to join numerical weather prediction (NWP) and air quality (AQ) modelers to discuss and make recommendations on the best practice and strategy for further developments and applications of integrated/coupled modelling systems "NWP & MesoMeteorology (MM) - Atmospheric Chemical Transport (ACT)".

Main emphasis is on the fine-resolution models applied for local chemical weather forecast and considering feedback mechanisms between meteorological and atmospheric pollution (e.g. aerosols) processes.

Main topics in focus are:
- Online and offline coupling of meteorological and air quality models;
- Implementation of feedback mechanisms, direct and indirect effects of aerosols;
- Advanced interfaces between NWP and ACT models;
- Model validation studies, including air quality-related episode cases.