Introduction to Integrated Modelling of Meteorological and Chemical Transport Processes

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Introductory lecture for

the NetFAM summer school "Integrated Modelling of Meteorological and Chemical Transport Processes / Impact of Chemical Weather on Numerical Weather Prediction and Climate Modelling"

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Lecture Contents

- Meteorological modelling,
- integration of gases and aerosols,
- on-line versus off-line,
- feedbacks, etc.

Objective:

- what will be the basic subjects of the school, short overview of all these subjects.

School’s Aim, Emphasis and Topics

The aim of this event is to join young scientists and researches of the HIRLAM community in order to elaborate, outline, discuss and make recommendations on the best strategy and practice for further developments and applications of the integrated modelling of both meteorological and chemical transport processes into the HIRLAM/HARMONIE modelling system.

The main emphasis is on fine-resolution models applied for chemical weather forecasting and feedback mechanisms between meteorological and atmospheric pollution (e.g. aerosols) processes.

The main topics will include:

• general introduction to meteorological modelling (numerical weather prediction, parameterizations and physics, numerics, advection, land-use, radiation, clouds, aerosols, urbanization) for MM-ACTM integration;

• off-line vs. on-line atmospheric-chemical-aerosol (ACA) modelling;

• possible feedbacks and their impact from ACA on short and long time-range atmospheric circulation models; etc.

Table 3.4. Some Gases and Aerosol Particle Components Important for Specified Air Pollution Topics

Indoor Air Pollution	Outdoor Urban Air Pollution	Acid Deposition	Stratospheric Ozone Reduction	Global Climate Change
		Gases		
Nitrogen dioxide Carbon monoxide Formaldehyde Sulfur dioxide Organic gases Radon	Ozone Nitric oxide Nitrogen dioxide Carbon monoxide Ethene Toluene Xylene PAN	Sulfur dioxide Sulfuric acid Nitrogen dioxide Nitric acid Hydrochloric acid Carbon dioxide	Ozone Nitric oxide Nitric acid Hydrochloric acid Chlorine nitrate CFC-11 CFC-12	Water vapor Carbon dioxide Methane Nitrous oxide Ozone CFC-11 CFC-12
		Aerosol Particle Components		
Black carbon Organic matter Sulfate Nitrate Ammonium Allergens Asbestos Fungal spores Pollens Tobacco smoke	Black carbon Organic matter Sulfate Nitrate Ammonium Soil dust Sea spray Tire particles Lead	Sulfate Nitrate Chloride	Chloride Sulfate Nitrate	Black carbon Organic matter Sulfate Nitrate Ammonium Soil dust Sea spray

(after Jacobson, 2002)

Meteorology and Air Pollution:
as a joint problem

- Meteorology is a main source of uncertainty in ACTMs => needs for urban- and 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:**

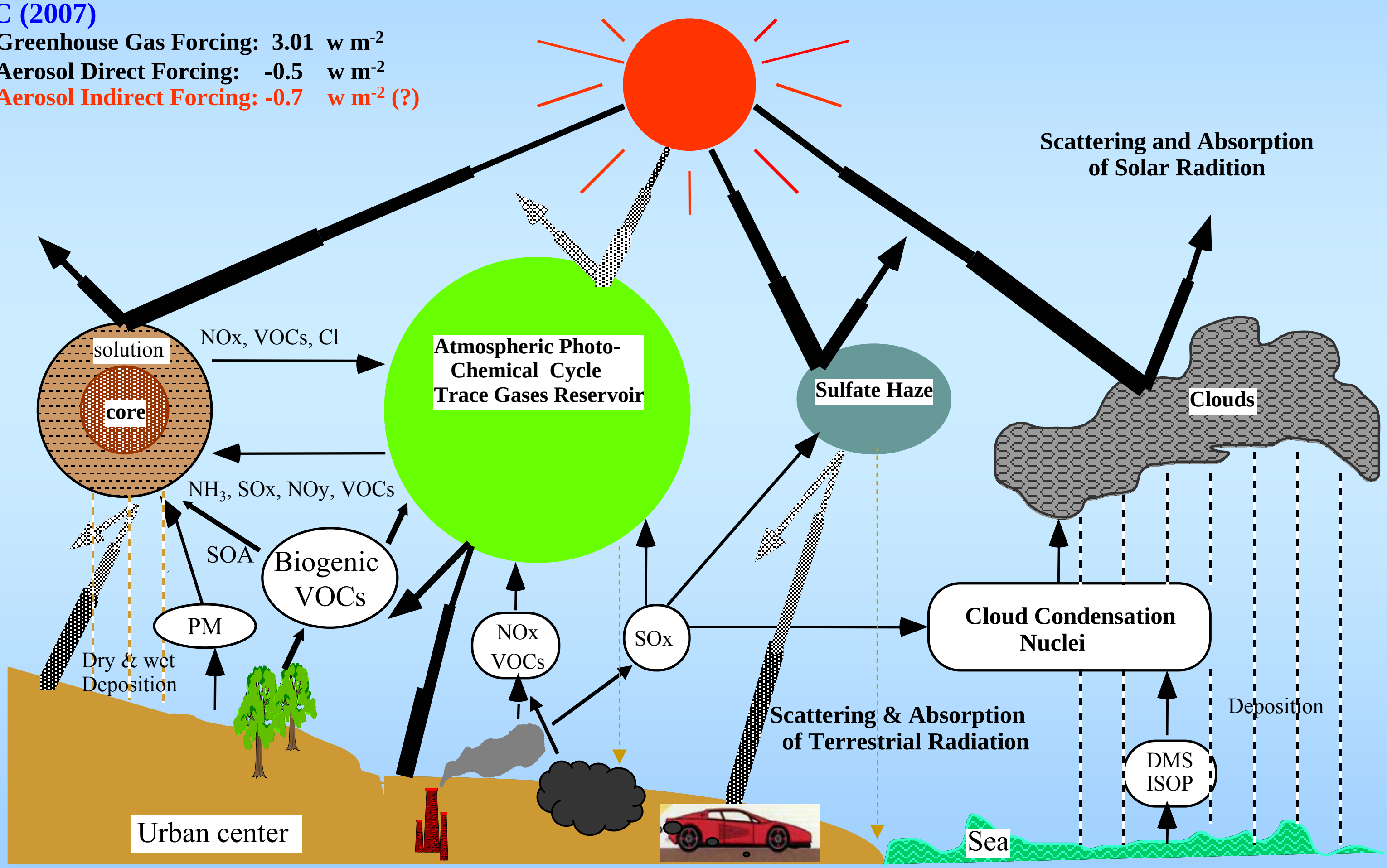
In perspective, integrated Meso-Meteorological (MetM) and Atmospheric Chemical Transport (ACT) modelling may be a promising way for future atmospheric simulation systems leading to a new generation of models for improved meteorological, environmental and "chemical weather" forecasting.

Atmosphere Interactions:

Gases, Aerosols, Chemistry, Transport, Radiation, Climate

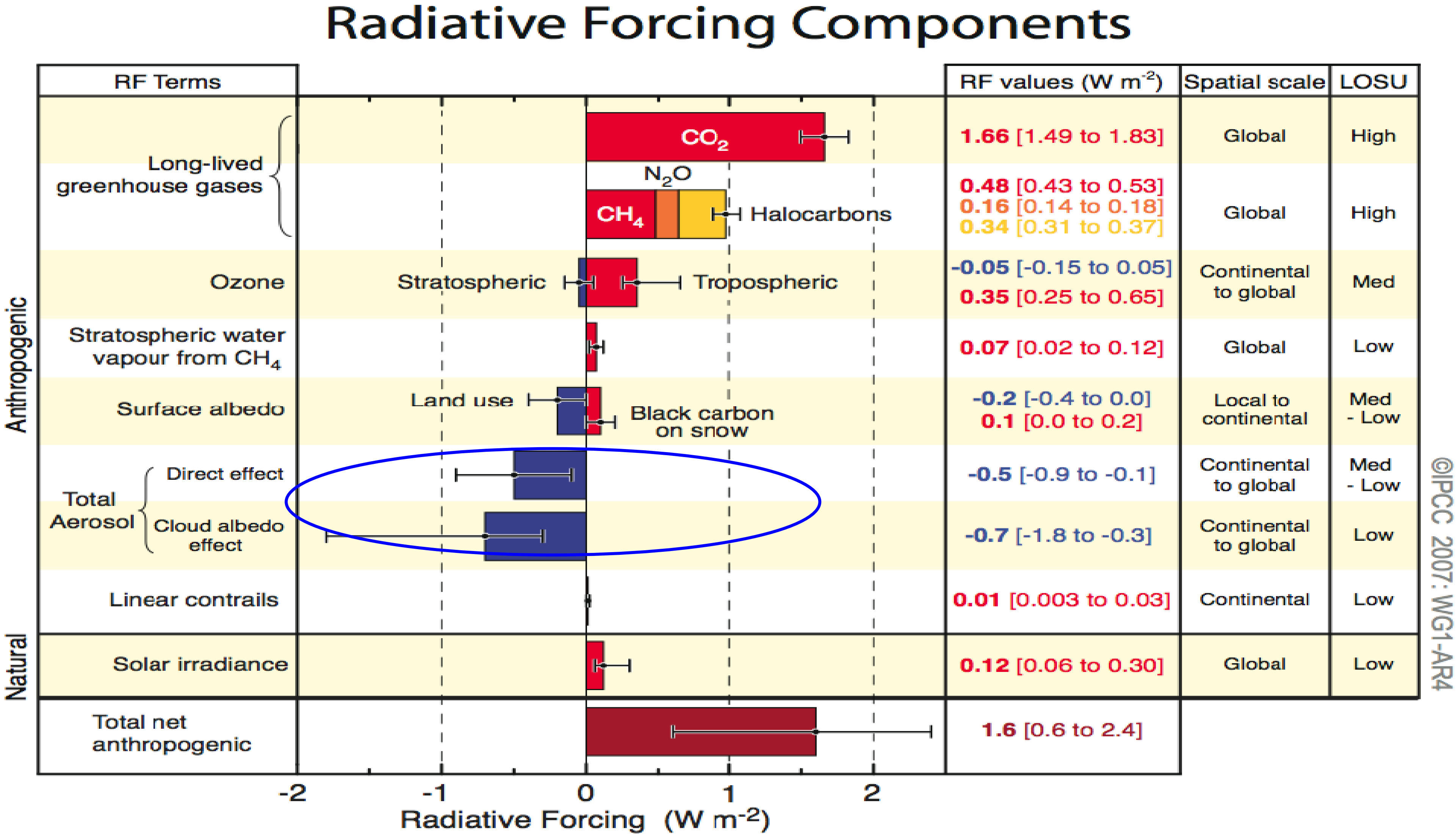
IPCC (2007)

Greenhouse Gas Forcing: 3.01 w m^{-2}
Aerosol Direct Forcing: -0.5 w m^{-2}
Aerosol Indirect Forcing: -0.7 w m^{-2} (?)



After Y. Zhang, DMI, Copenhagen, 2007

2007 IPCC Estimate of Gas and Aerosol Radiative Effects



Examples of Important Feedbacks

- **Effects of Meteorology and Climate on Gases and Aerosols**
  - **Meteorology is responsible for atmospheric transport and diffusion of pollutants**
  - **Changes in temperature, humidity, and precipitation directly affect species conc.**
  - **The cooling of the stratosphere due to the accumulation of GHGs affects lifetimes**
  - **Changes in tropospheric vertical temperature structure affect transport of species**
  - **Changes in vegetation alter dry deposition and emission rates of biogenic species**
  - **Climate changes alter biological sources and sinks of radiatively active species**
- **Effects of Gases and Aerosols on Meteorology and Climate**
  - **Decrease net downward solar/thermal-IR radiation and photolysis (direct effect)**
  - **Affect PBL meteorology (decrease near-surface air temperature, wind speed, and cloud cover and increase RH and atmospheric stability) (semi-indirect effect)**
  - **Aerosols serve as CCN, reduce drop size and increase drop number, reflectivity, and optical depth of low level clouds (LLC) (the Twomey or first indirect effect)**
  - **Aerosols increase liquid water content, fractional cloudiness, and lifetime of LLC but suppress precipitation (the second indirect effect)**

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).

- ❑ Numerical advection schemes in the meteorological part are not meeting all the requirements for ACTMs, so they should be improved and harmonized in NWP and ACT models.

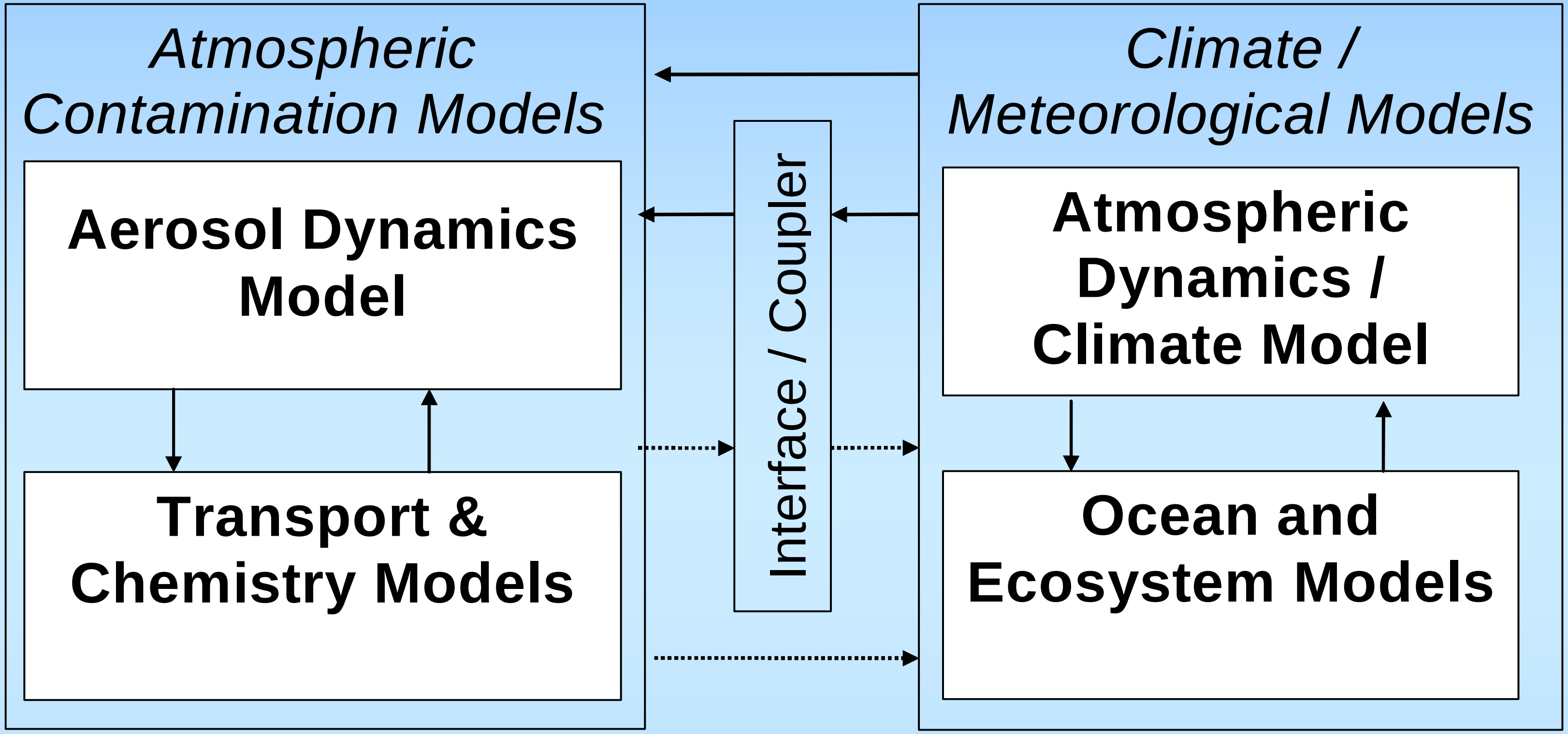
- ❑ NWP models are not primarily developed for air pollution modelling and their results need to be designed as input to or be integrated into urban and meso-scale air quality models.

2 different tasks in HIRLAM-ACTM:

(i) improvement of HIRLAM outputs for ACT modelling applications and correspondingly improvement of ACT models (for different off-line ACT models, like MATCH, SILAM, EMEP, CAC, DERMA; DACFOS),

(ii) improvement of NWP itself by implementation of ACTMs and aerosol/gases forcing/feedback mechanisms into HIRLAM (mostly by on-line integration, like in EnviroHIRLAM).

Integrated Atmospheric System Model Structure



One-way: 1. Meteo-fields 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

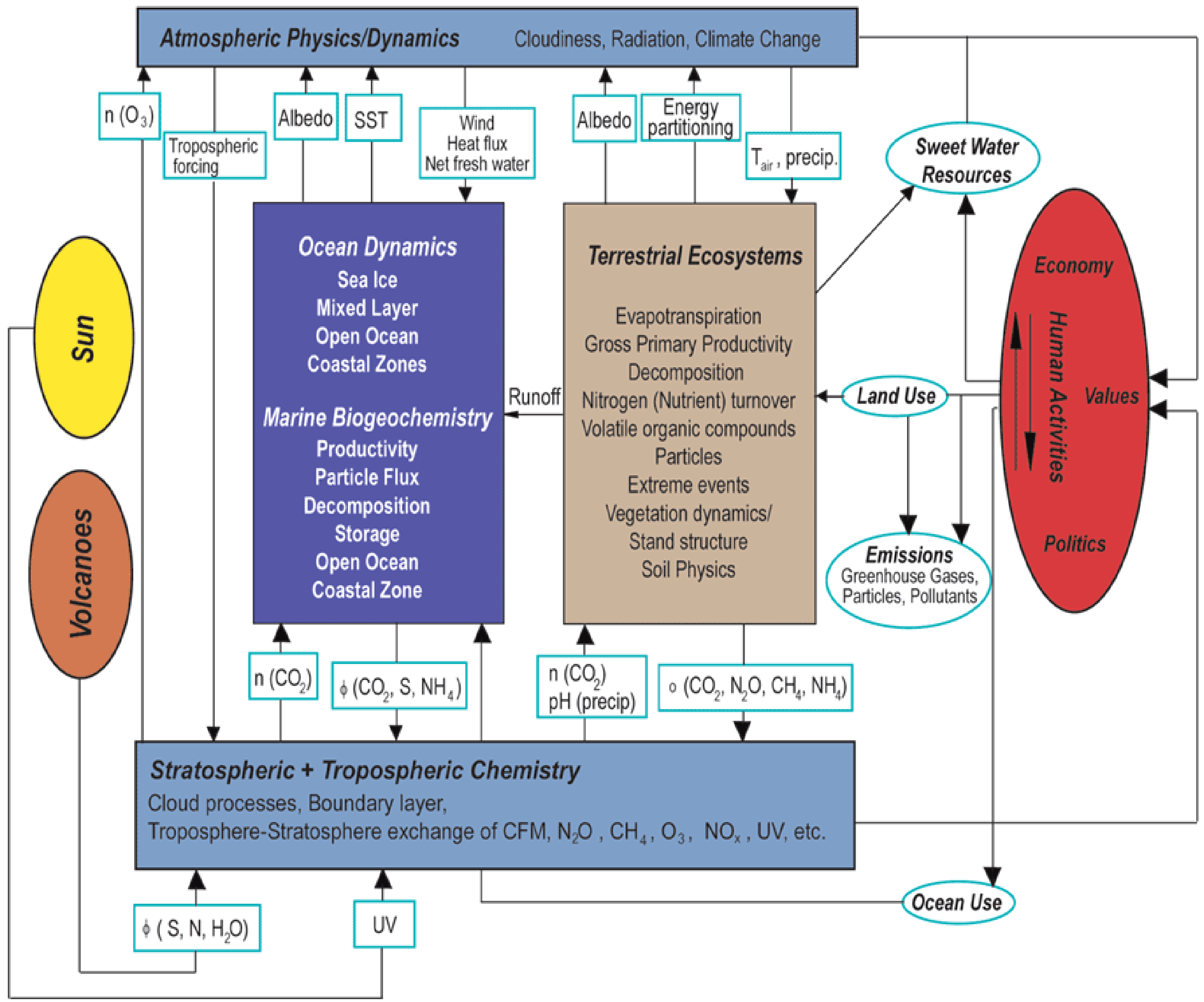
(v) Nuclear war or explosion consequences

(vi) Emergency preparedness

(vii) Stratospheric dynamics and cloud models

(viii) Indoor microclimate and air quality

COSMOS: Community Earth System Models



New initiative:
EU-EARTH program & System modelling center

Differences from COST728:

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

Specification of module structure for interfacing and module couplers

The European PRISM project (Valcke at el., 2006) develops:

- infrastructure for Earth System Modelling including
- the coupler OASIS4 (eg for Ocean-Atmosphere, GCM-CTM),
- tools for configuration, monitoring and post-processing.

PRISM also provides guidelines for good coding practices.

More information are on PRISM website: http://prism.enes.org/

There is also a similar USA system ESMF (Earth System Modelling Framework (Dickenson et al. 2002) for integrated Earth System Models.

EC 5FP FUMAPEX
Project objectives:

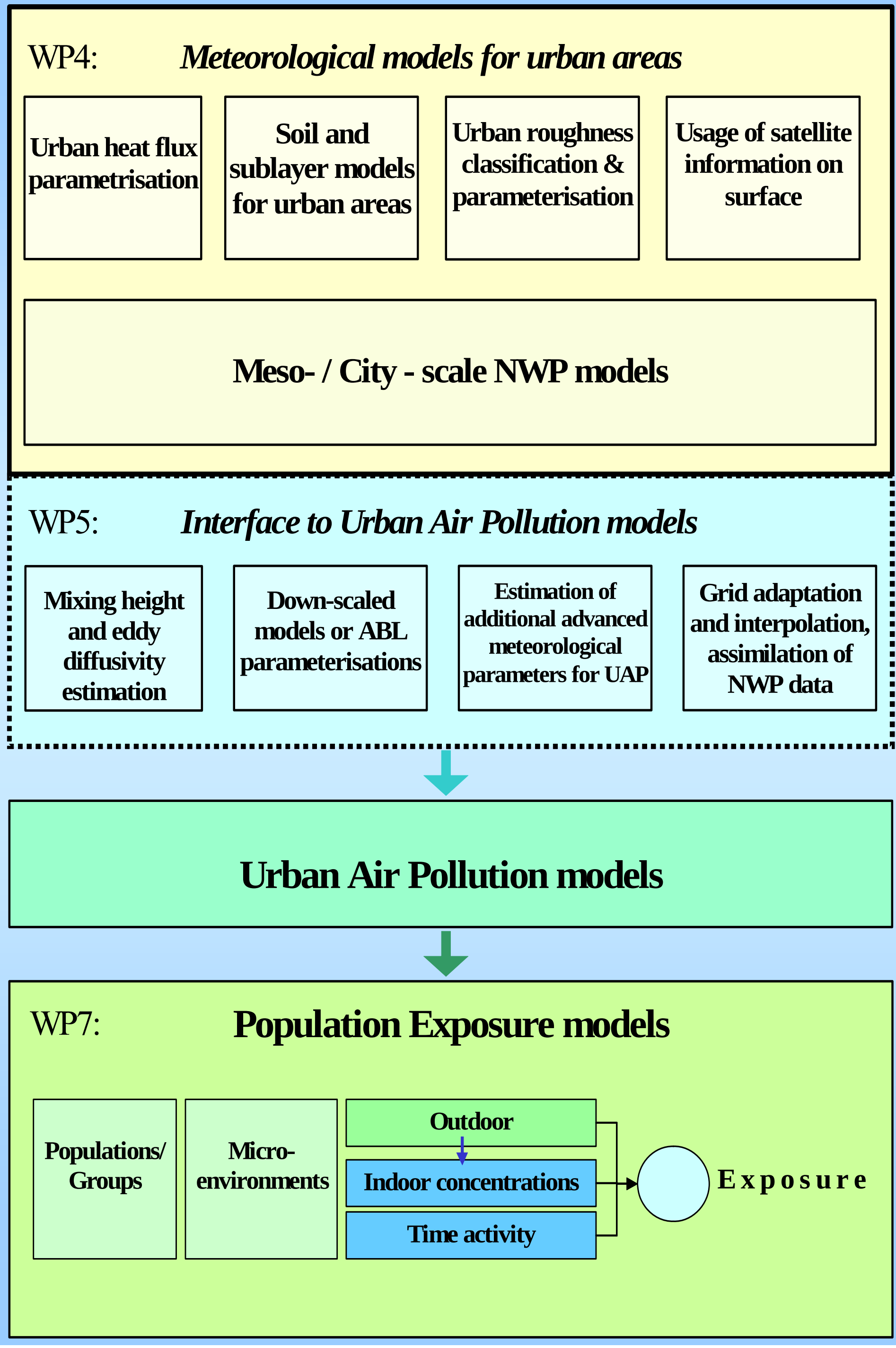
(i) the improvement of meteorological forecasts for urban areas,

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

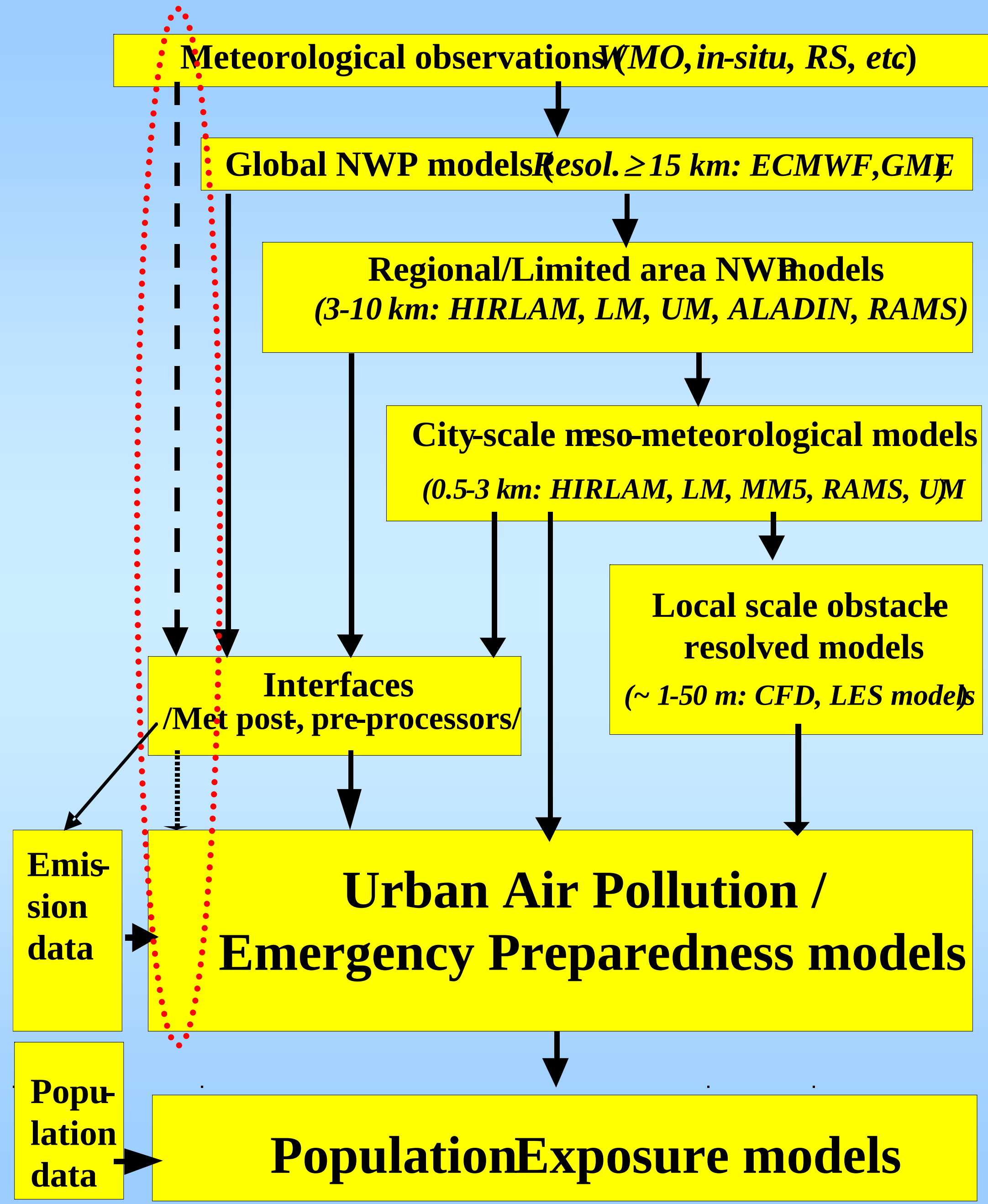
(iii) the building of improved *Urban Air Quality Information and Forecasting Systems* (UAQIFS), and

(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



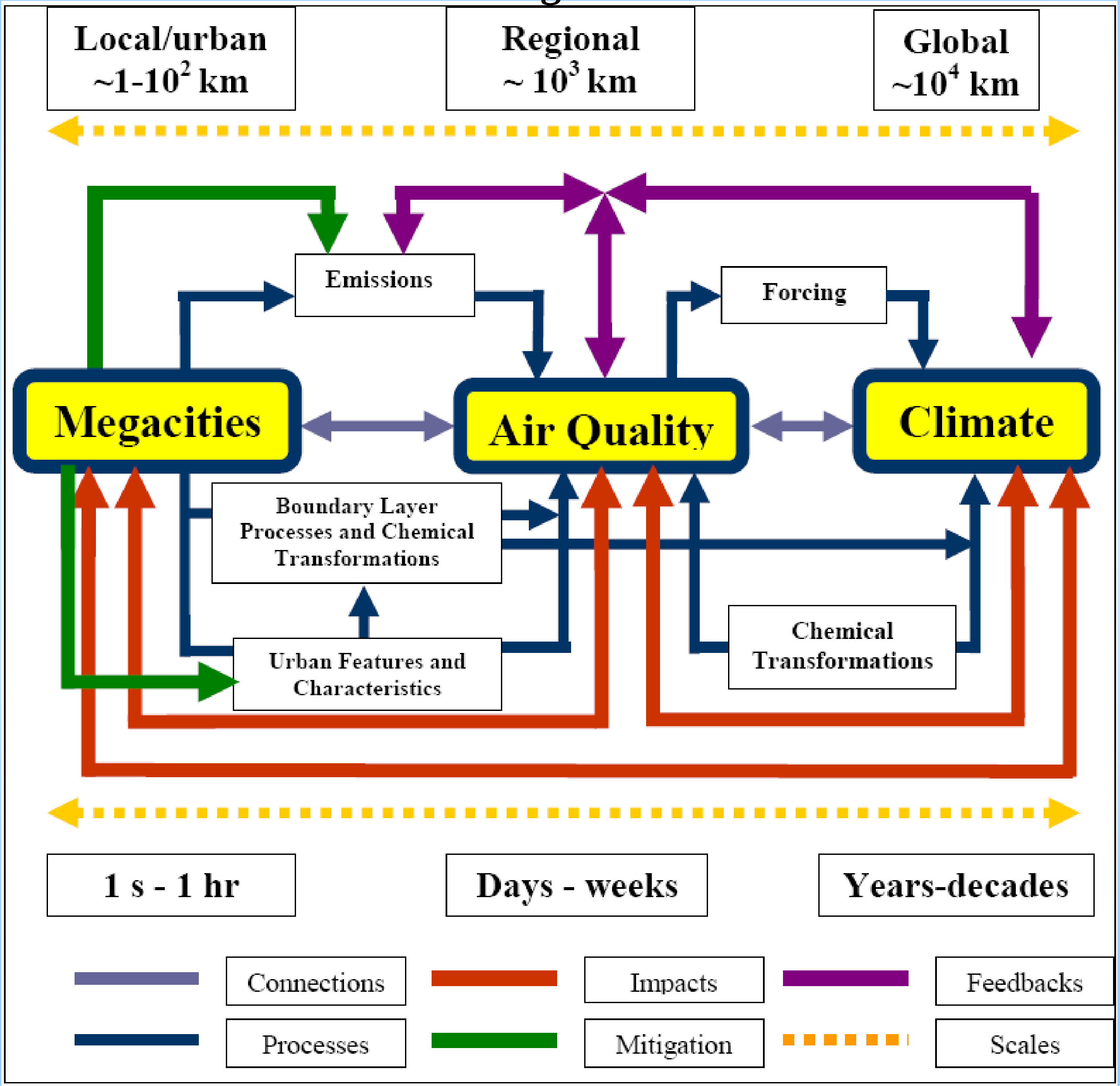
Off-line coupling: Development of meteo-processor and interface between urban scale NWP and UAP models

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, 2005)**
- **MH methods for urban areas (WG2 COST715 Report, 2005)**

Connections between megacities, air quality and climate:
main feedbacks, ecosystem, health and weather impact pathways, and mitigation routes



Main feedback mechanisms of aerosol forcing

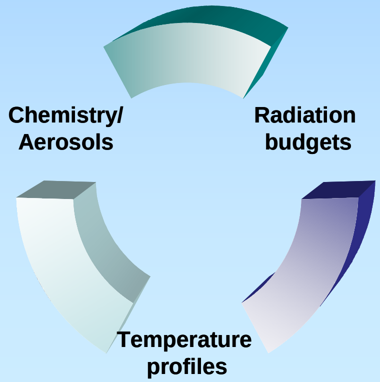
- **Direct effect via radiation**: (i) warm the air by absorbing solar and thermal-IR radiation (black carbon, iron, aluminium, polycyclic and nitrated aromatic compounds), (ii) cool the air by backscattering incident short wave radiation to space (water, sulphate, nitrate, most of organic compounds)
- **Semi-direct effect**: via PBL meteorology, photochemistry, photolysis and aerosol emission/blowing changes
- **First indirect effect**: via reflectivity, optical depth, cloud albedo and other radiation characteristics due to growing CCN
- **Second indirect effect**: via microphysics of clouds, interacting with aerosols, CCN growing, washout and rainout

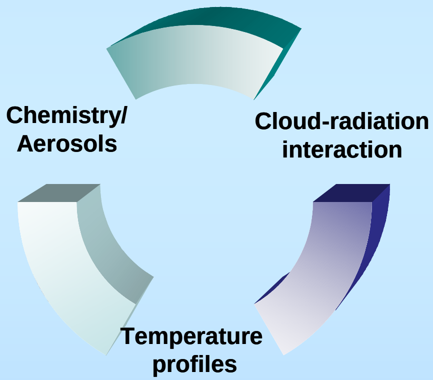
They have to be prioritised and considered in on-line coupled modelling systems. Sensitivity studies are needed to understand the relative importance of different feedback effects.

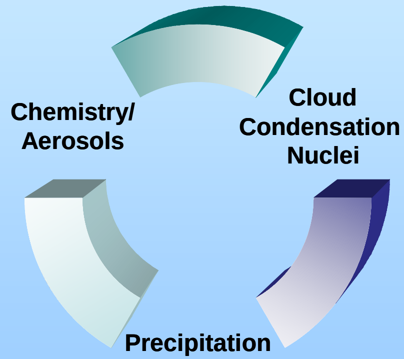
Effects of aerosol particles on climate:

Jacobson (2002) classification and Some examples

- 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







EnviroHIRLAM

Implementation of the feedback mechanisms into integrated models:

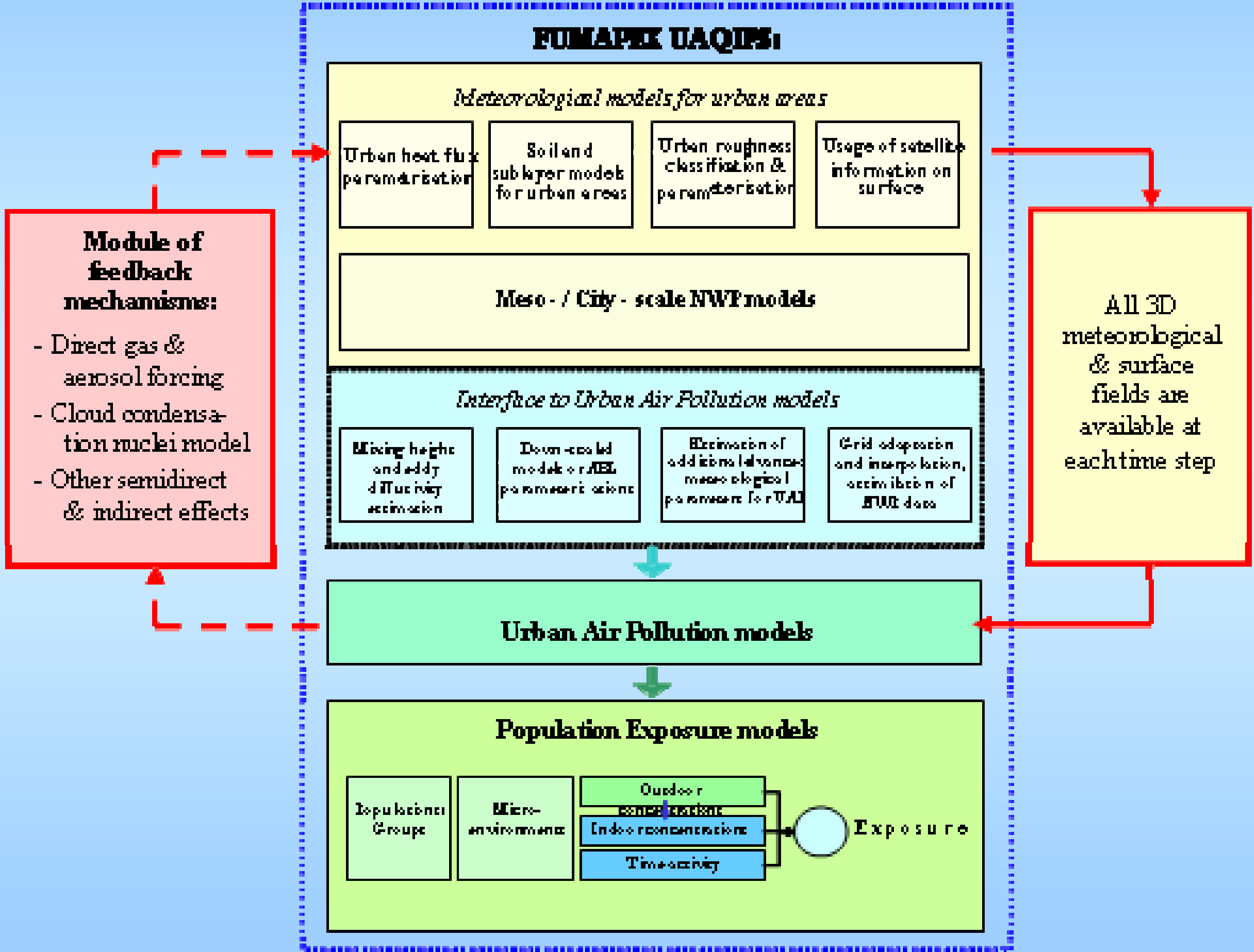
One-way integration (off-line):

- 1. Simplest way (no aerosol forcing): NWP meteo-fields as a driver for CTM (this classical way is used already by most of air pollution modellers);
- 2. CTM chemical composition fields as a driver for Regional/Global Climate Models (including the aerosol forcing on meteo-processes, it could also be realized for NWP or MetMs).

Two-way integration:

- 1. Driver + partly aerosol feedbacks, for CTP or for NWP (data exchange with a limited time period coupling: off-line or on-line access coupling, with or without second iteration with corrected fields);
- 2. Full feedbacks included on each time step (on-line coupling/integration).

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
- Harmonised advection schemes for all variables (meteo and chemical)
- 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.

Non-European Union countries experience

- from America: the US EPA and other US and Canadian institutions (see WRF-Chem; Grell et al., 2005; (GATOR-MMTD: Jacobson, 2005, 2006; Byun and Schere, 2006; GEM-AQ: 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, using the Earth Simulator CFORS (Uno et al., 2003, 2004), CHASER (Takigawa et al., 2007), etc.

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

- 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.

Characteristics of On-line coupled MetM - CTMs

Model name	On-line 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
WRF-Chem	RADM+Carbon Bond, Madronich+Fast-J photolysis, modal+sectional aerosol	Each model time step	Yes
COSMO LM-ART	Gas phase chem (58 variables), aerosol physics (102 variables), pollen grains	each LM time step	Yes (*
COSMO LM-MUSCAT (**	Several gas phase mechanisms, aerosol physics	Each time step or time step multiple	None
MCCM	RADM and RACM, photolysis (Madronich), modal aerosol	Each model time step	(Yes) (***
MESSy: ECHAM5	Gases and aerosols		Yes
MESSy: ECHAM5-COSMO LM (planned)	Gases and aerosols		Yes
MC2-AQ	Gas phase: 47 species, 98 chemical reactions and 16 photolysis reactions	each model time step	None
GEM/LAM-AQ	Gas phase, aerosol and heterogeneous chemistry	Set up by user – in most cases every time step	None
Operational ECMWF model (IFS) ECMWF GEMS modelling	Prog. stratos passive O3 tracer GEMS chemistry	Each model time ste Each model time step	 Yes
GME	Progn. stratos passive O3 tracer	Each model time step	
OPANA=MEMO+CBMIV		Each model time step	

*) Direct effects only; **) On-line access model; ***) Only via photolysis

On-line integrated meso-scale models

(COST728 D2.1 overview report, 2007)

http://netfam.fmi.fi/Integ07/COST728_WG2_report.pdf

- At the current stage most of the online coupled models do not consider feedback mechanisms or include only direct effects of aerosols on meteorological processes (like COSMO LM-ART and MCCM).
- Only two meso-scale on-line integrated modelling systems (WRF-Chem and ENVIRO-HIRLAM) consider feedbacks with indirect effects of aerosols.

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

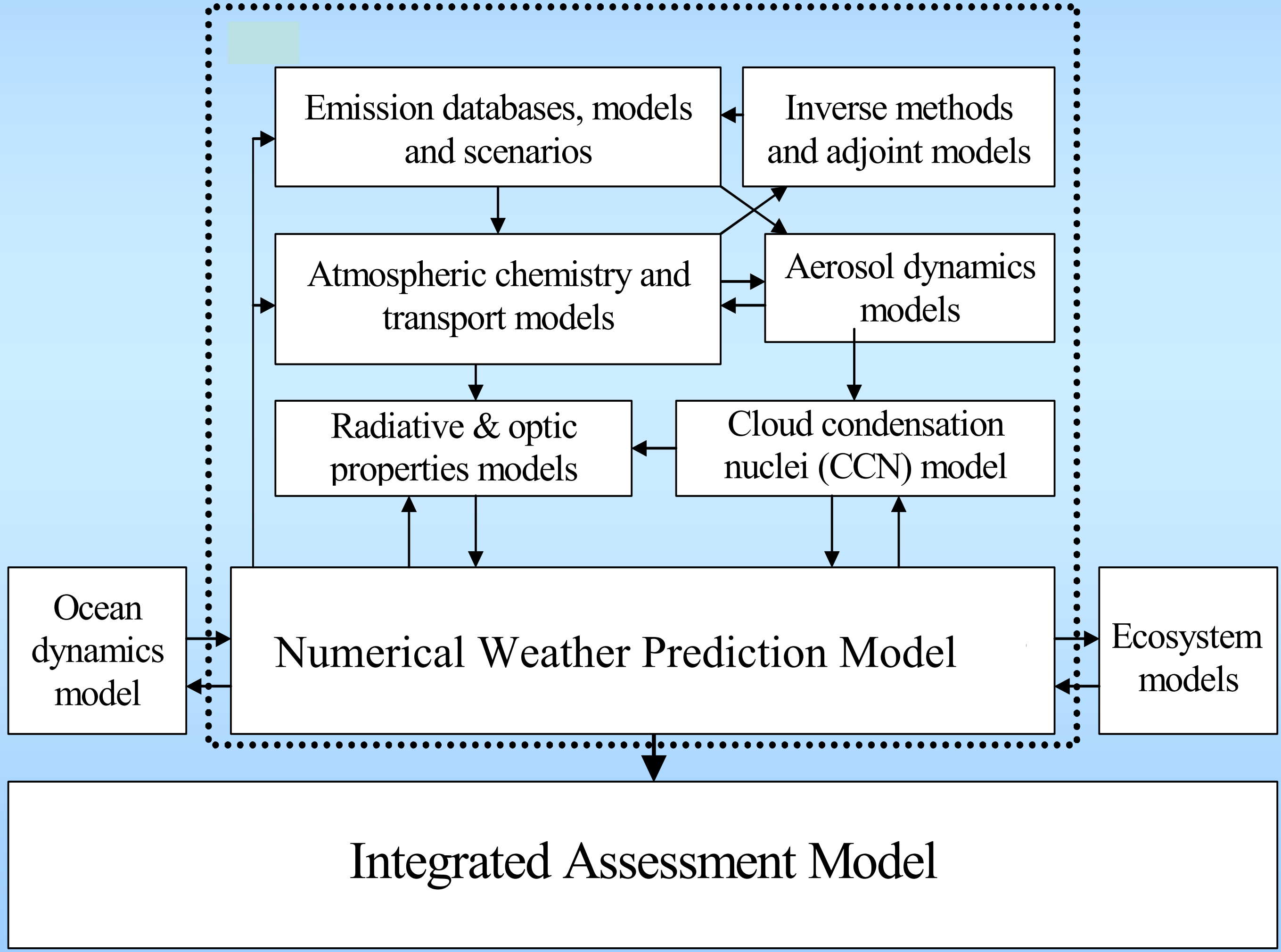
• WRF
• MM5
• RAMS

European CTM/ADMs:

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

DMI-Enviro-HIRLAM

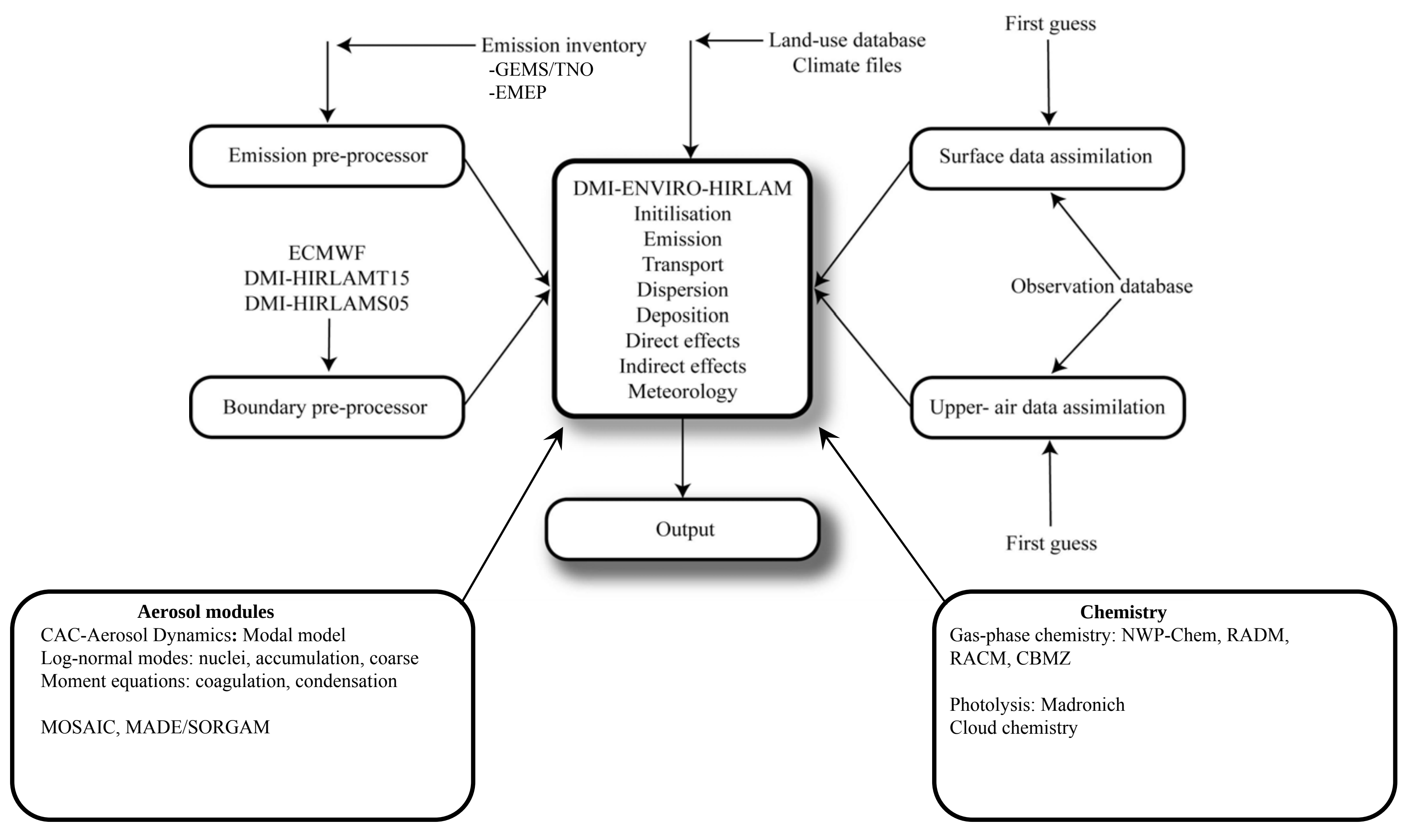
New integrated (on-line coupled) modeling system structure for predicting the atmospheric composition



DMI-ENVIRO-HIRLAM on-line system realisation steps:

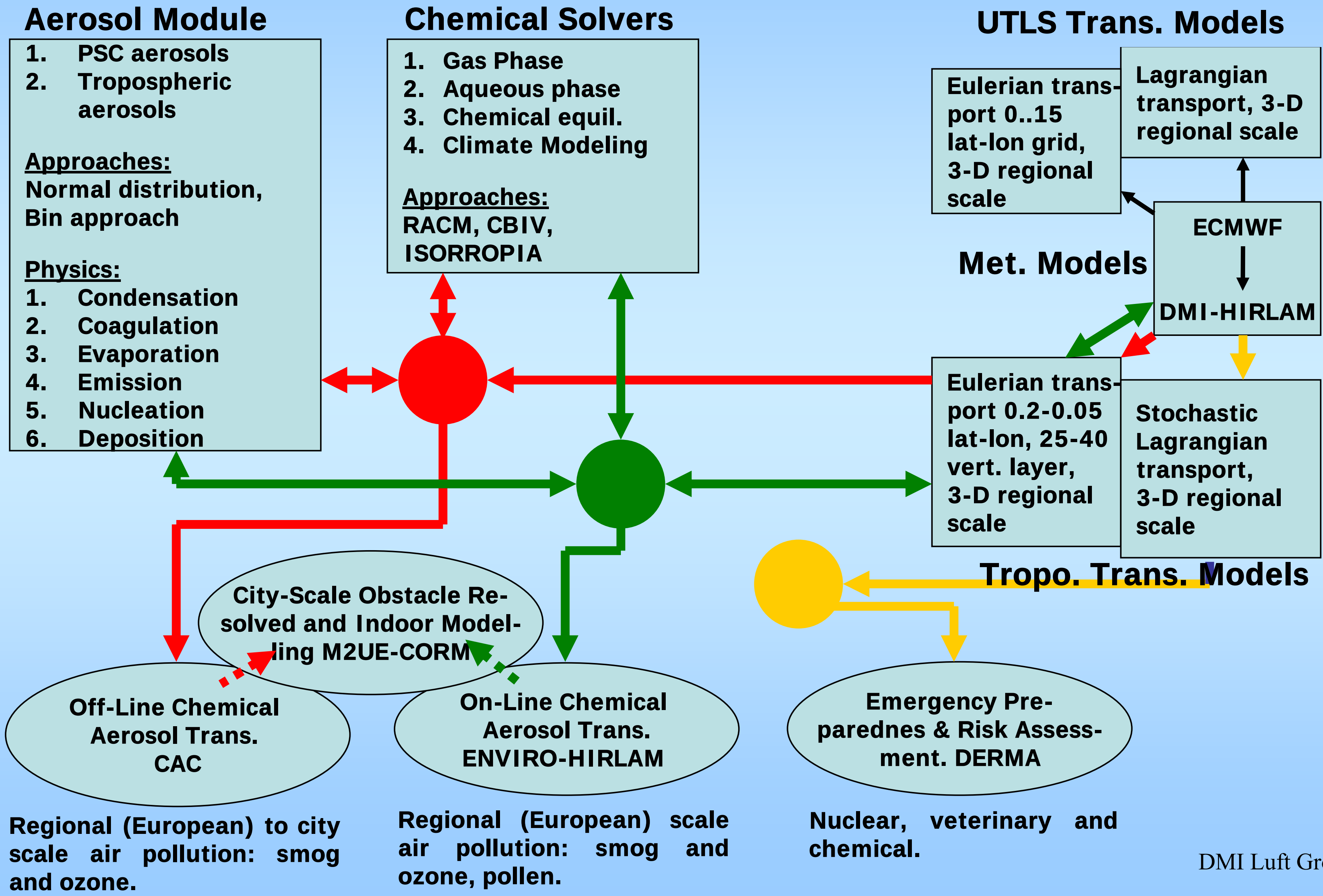
- (i) nesting of models for high resolutions,
- (ii) improved resolution of boundary and surface layer characteristics and structures,
- (ii) ‘urbanisation’ of the model,
- (iii) improvement of advection schemes,
- (iv) implementation of chemical mechanisms,
- (v) implementation of aerosol dynamics,
- (vi) realisation of feedback mechanisms,
- (vii) assimilation of monitoring data.

First version of DMI-ENVIRO-HIRLAM modelling systems, showing the components of a forecast

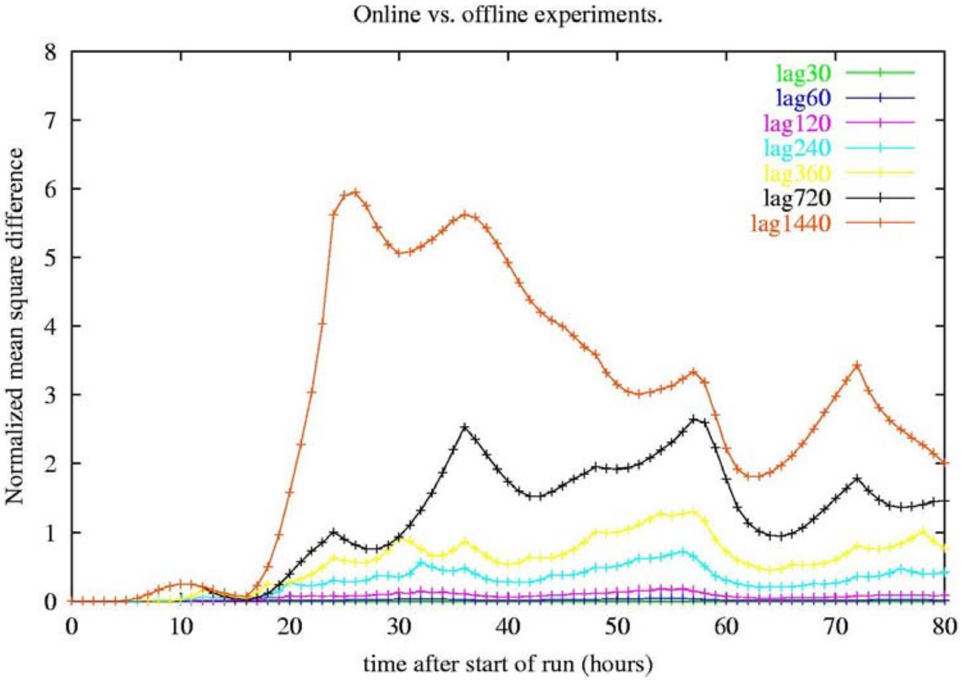


Korsholm, Baklanov, Gross, Mahura (2007)

Scheme of Chemistry-Aerosol-Cloud (CAC) System implementing into Enviro-HIRLAM



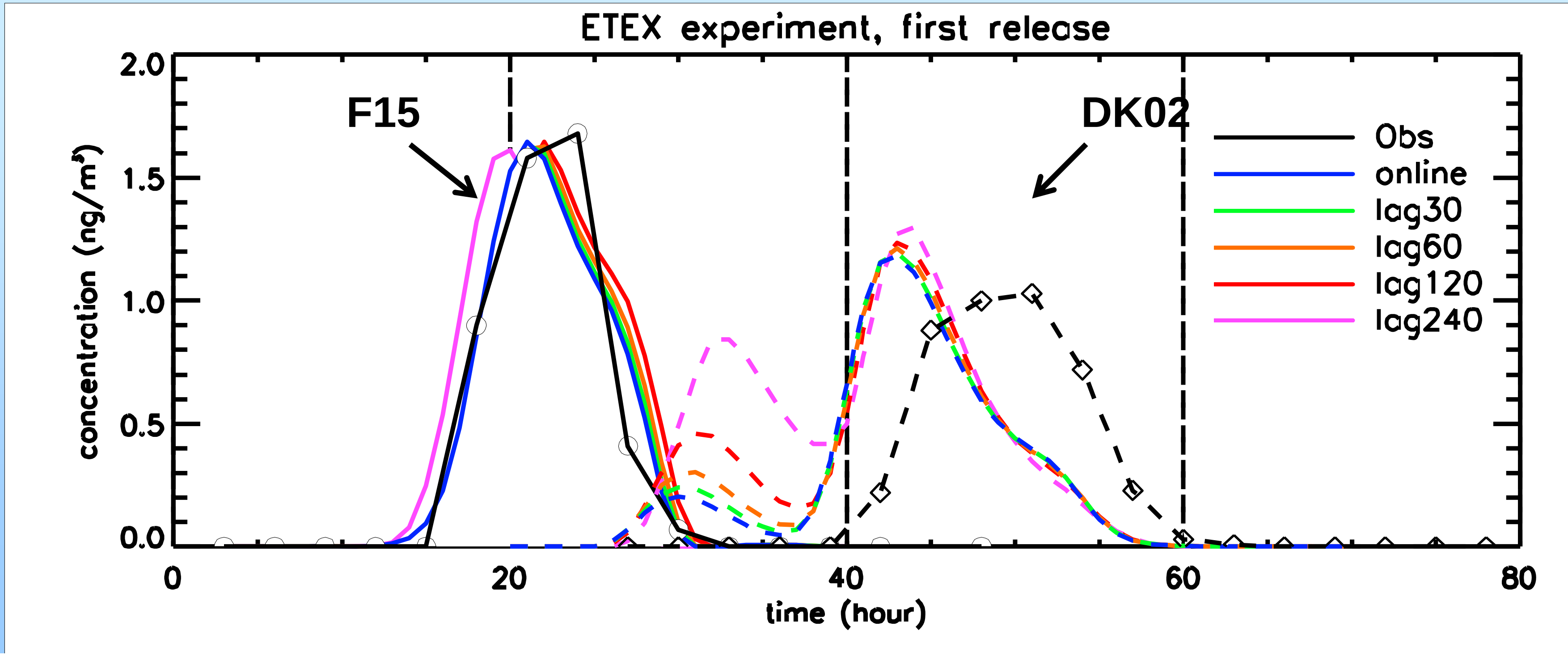
DMI Luft Group



DMI-ENVIRO-HIRLAM: On-line versus off-line for ETEX-1 experiment

<= Normalized mean square difference

Measured and modelled time development of concentration (ngm-3) at ETEX stations F15 (left) and DK02 (right) for coupling intervals 10 (online), 30, 60, 120, 240 and 360 minutes



DMI-ENVIRO-HIRLAM: Feedbacks of urban aerosols

For water clouds:

$r^3_{eff} = kr^3_v$

$r^3_{eff} = 3L/(4\pi\rho_l kN)$

(*Wyser et al. 1999*)

L : Cloud condensate content

N: Number concentration of cloud droplets

$\Delta N_{cont} = 10^{8.06}\ conc^{0.48}$

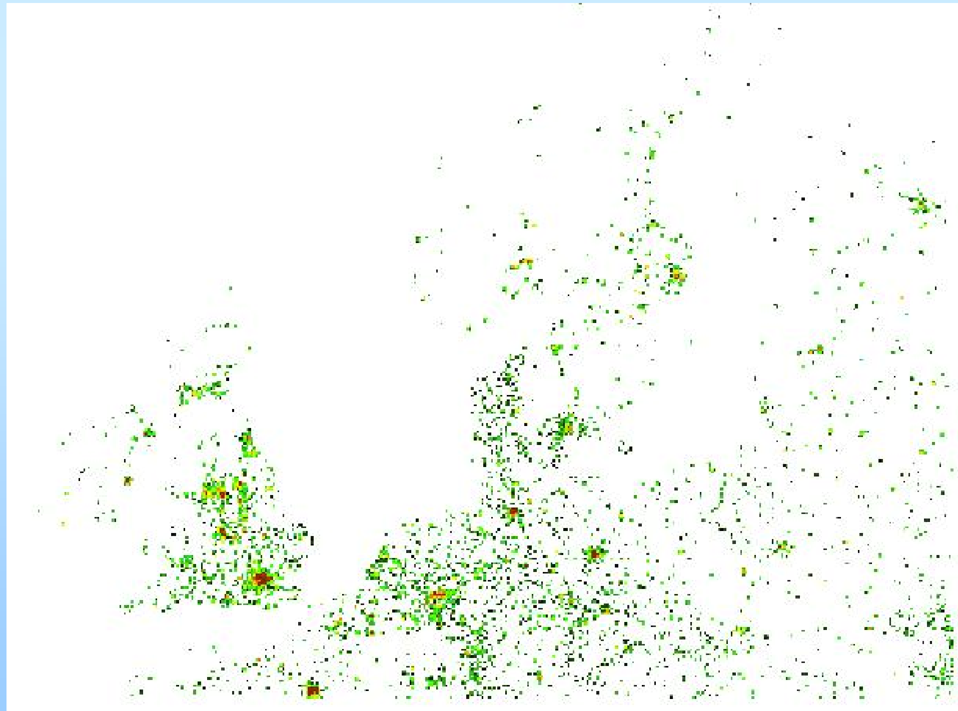
$\Delta N_{marine} = 10^{2.24}\ conc^{0.26}$

(*Boucher & Lohmann, 1995*)

Emission rate: 7.95 gs^{-1}; ETEX

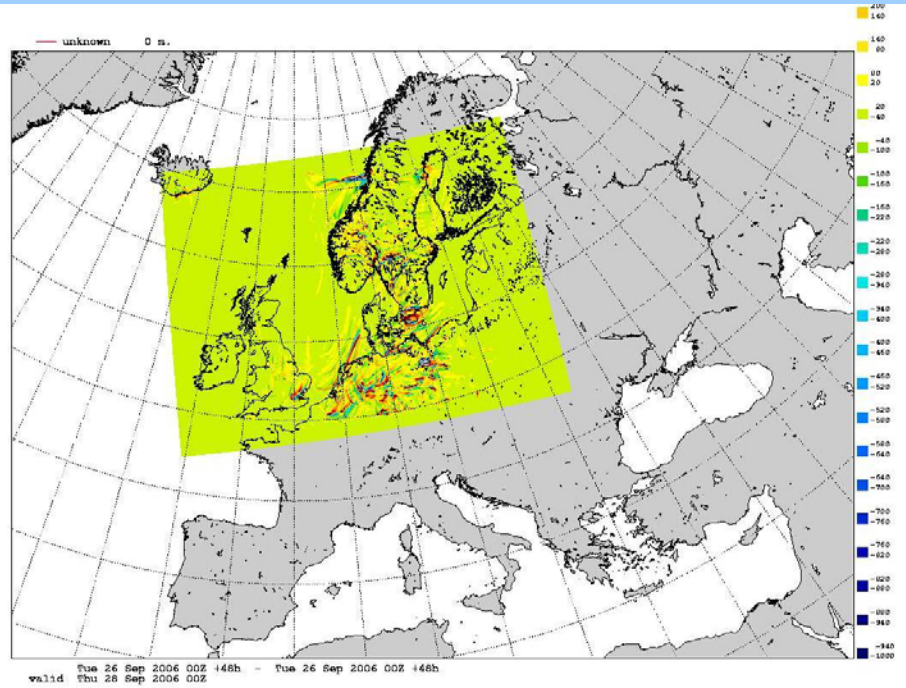
Diameter: 1 µm

	k	N [m^{-3}]
Marine	0.81	10^8
Cont	0.69	$4x10^8$

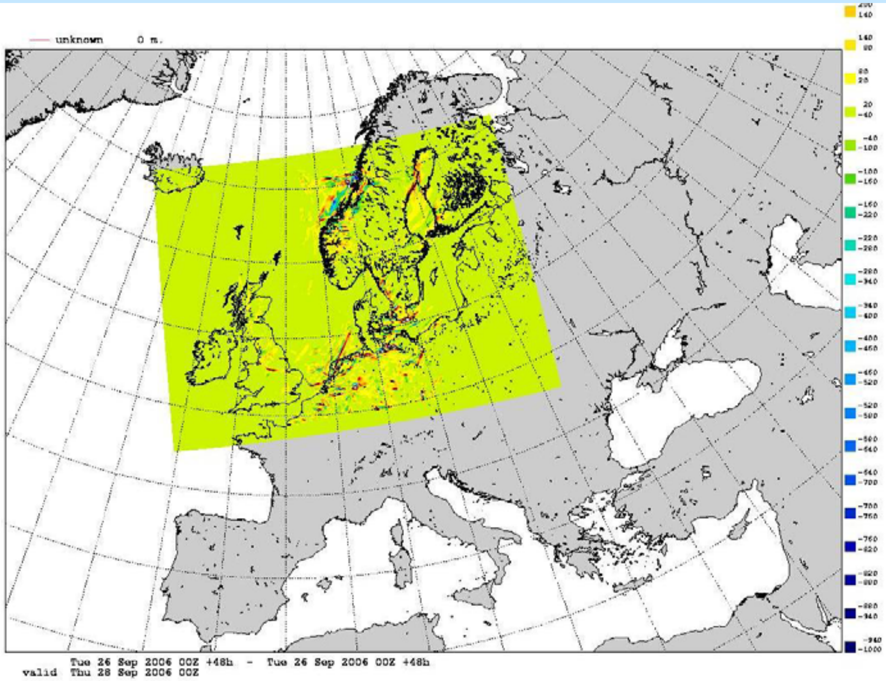


Urban fractions [%; dark green – dark red]

DMI-ENVIRO-HIRLAM: Feedbacks of urban aerosols



Difference (ref - perturbation)
in accumulated dry deposition [ng/m^2]



Difference (ref - perturbation)
in accumulated wet deposition [ng/m^2]

Feedbacks through the first indirect effect lead to modifications of the order 7 % in dry and wet deposition patterns over major polluted areas in Europe.

Korsholm & Baklanov, 2007

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

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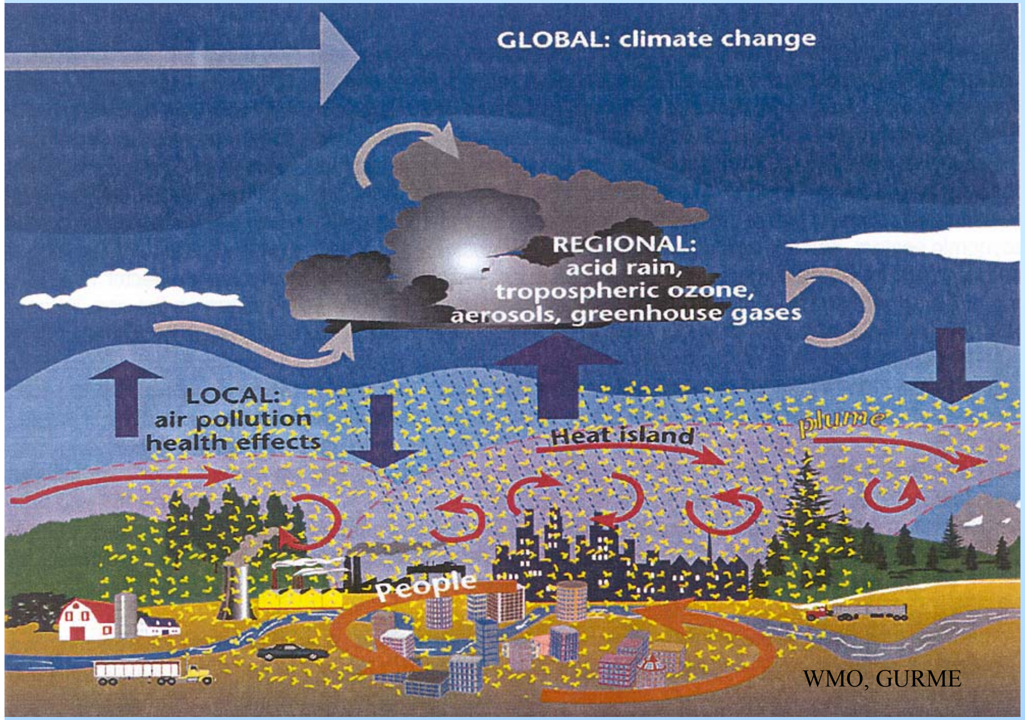
Megacities:
Urban features in focus:



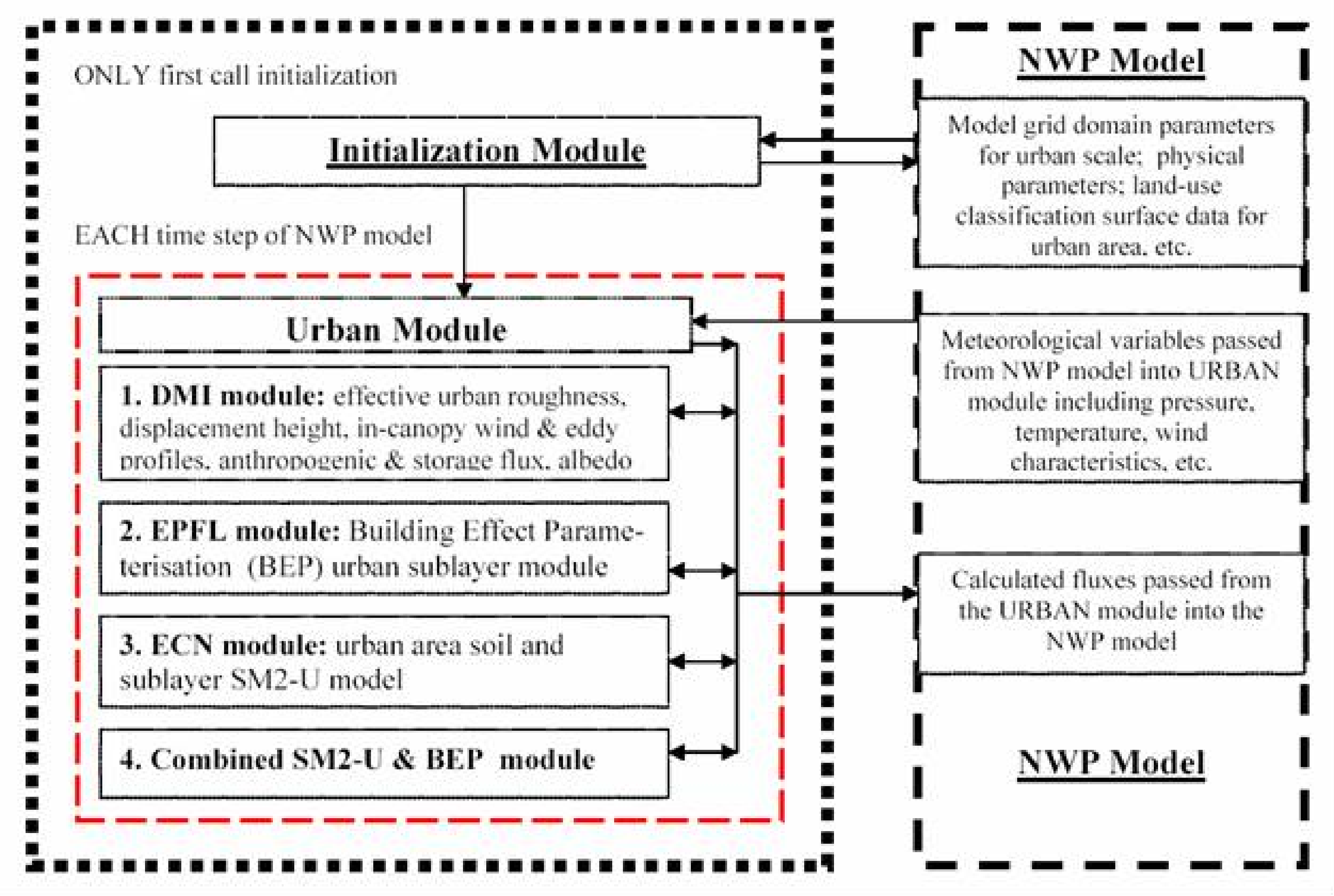
- Urban pollutants emission, transformation and transport,
- Land-use drastic change due to urbanisation,
- Anthropogenic heat fluxes, urban heat island,
- Local-scale inhomogeneties, sharp changes of roughness and heat fluxes,
- Wind velocity reduce effect due to buildings,
- Redistribution of eddies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

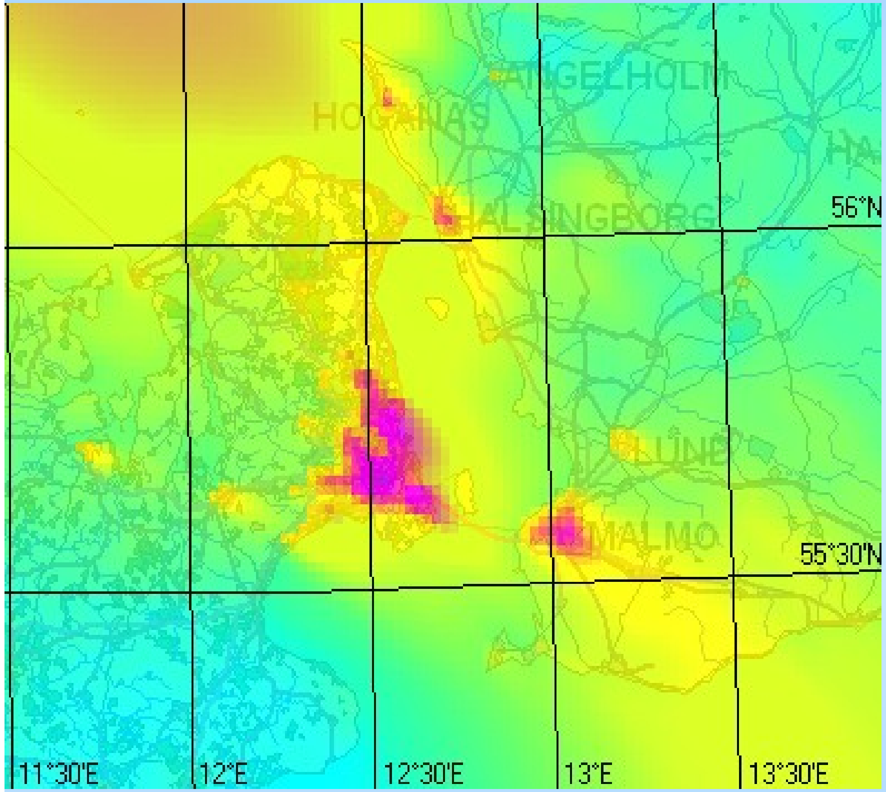
1. Model down-scaling, including increasing vertical and horizontal resolution and nesting techniques (one- and two-way nesting);
2. Modified high-resolution urban land-use classifications, parameterizations and algorithms for roughness parameters in urban areas based on the morphologic method;
3. Specific 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.

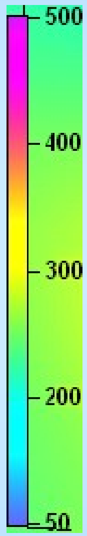
Integrated Fumapex urban module for NWP models

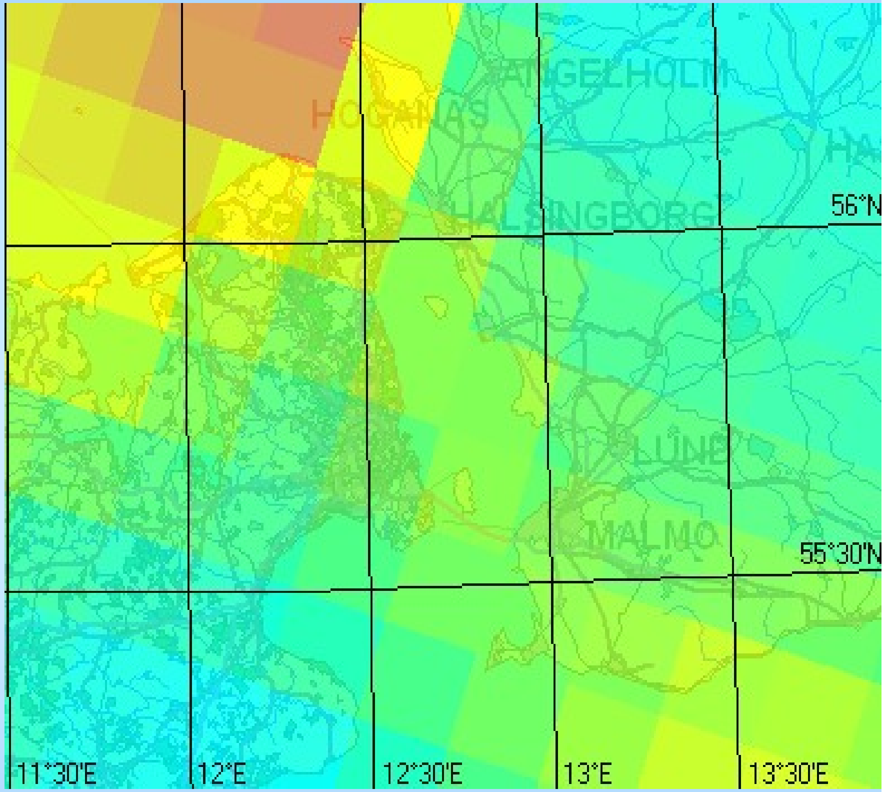
including 4 levels of complexity of the NWP 'urbanization' (see *fumapex.dmi.dk*)



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



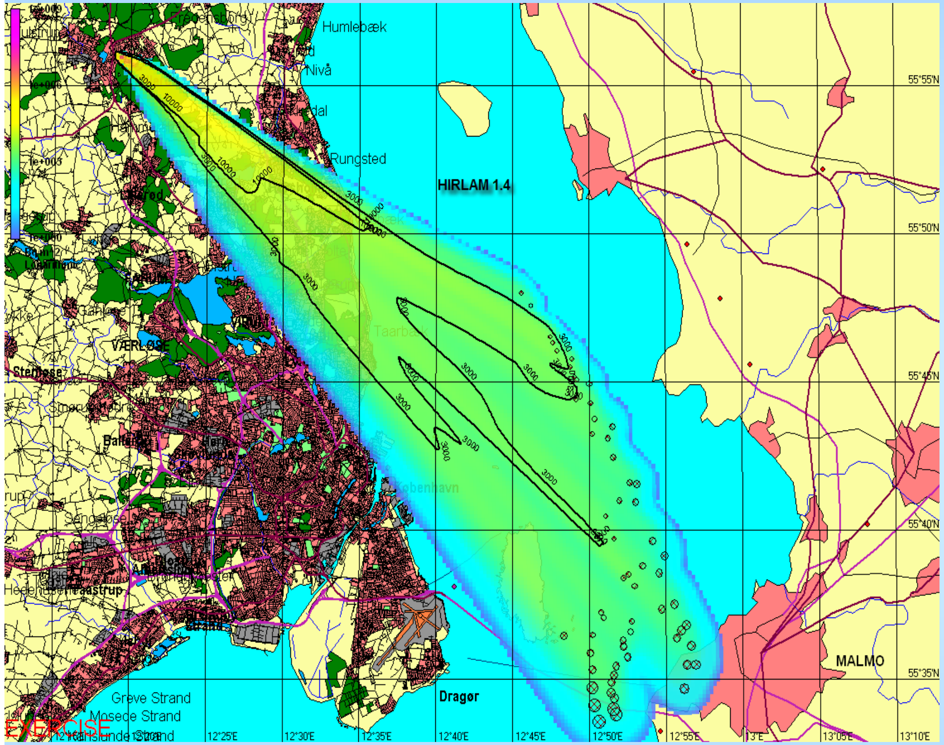




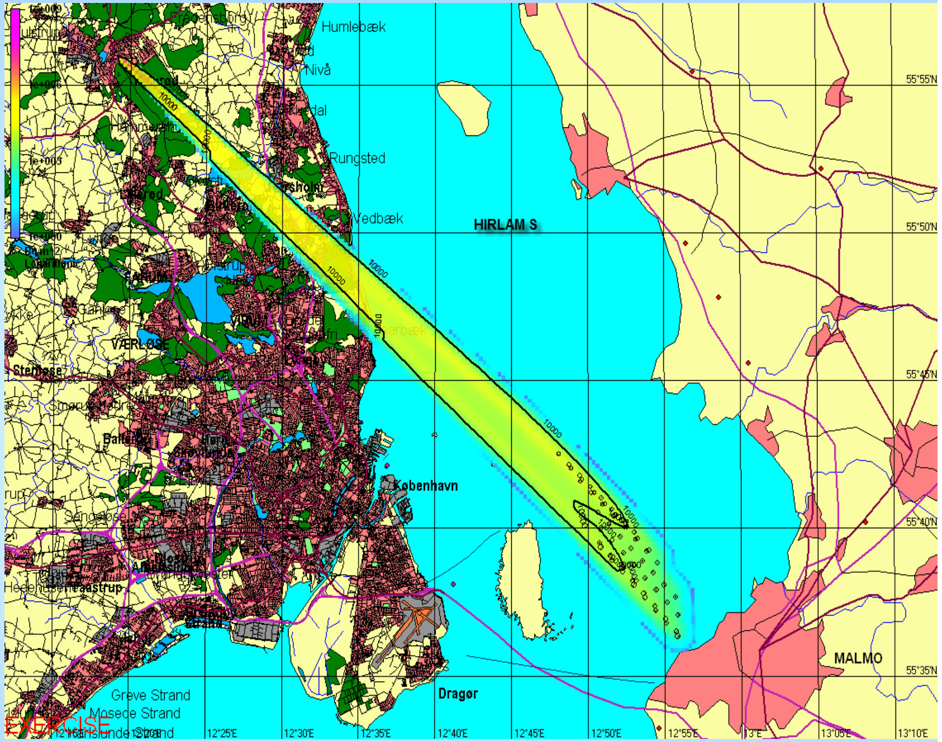
urbanised 1.4 km **operational 15 km**

DEMA

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.

Urbanisation 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

Tasks/Sub-groups:

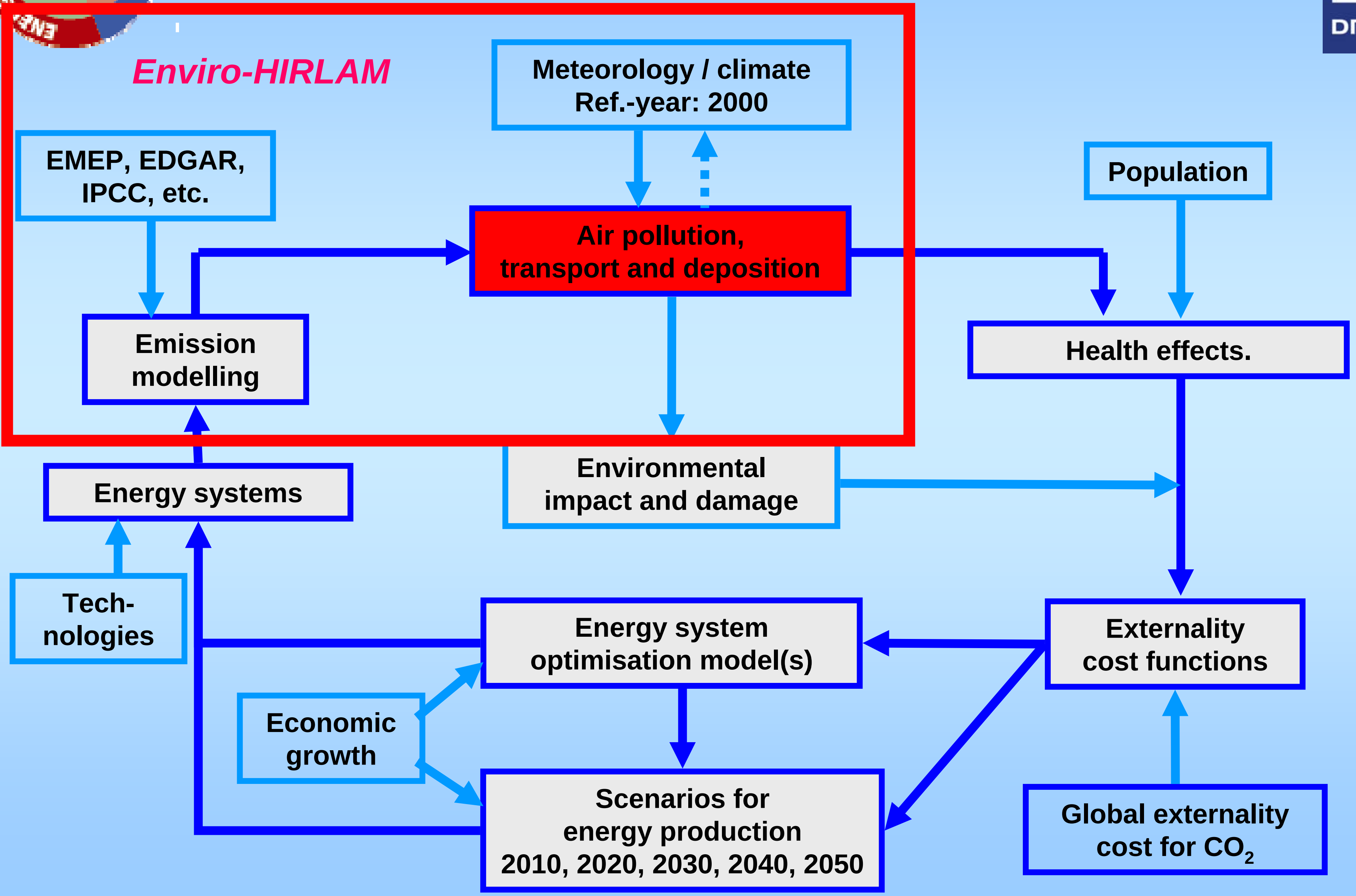
1. Off-line models and interfaces
2. On-line coupled modelling systems and feedbacks
3. Model down-scaling/ nesting and data assimilation
4. Models unification and harmonization

1. COST-728 / WMO, 2007: **"Overview of existing integrated (off-line and on-line) mesoscale systems in Europe" published by WMO, Geneva, 122p.**
2. COST-728 / NetFAM workshop **on "Integrated systems of meso-meteorological and chemical transport models", Copenhagen, Denmark 21-23 May 2007. In press. Web-site: http://netfam.fmi.fi/Integ07/**

New European COST Action 602: Chemical Weather Forecasting (2008-2012) *chaired by J. Kukkonen*

New Application: CEEH modelling framework

see: http://ceeh.dk



Conclusions

- One Atmosphere: Meteorology and Air Pollution as a joint problem considering climate-aerosol-chemistry-cloud-radiation feedbacks; Feedback mechanisms are important in accurate modeling of NWP/MM-ACT and quantifying direct and indirect effects of aerosols.
- The on-line integration of meso-scale meteorological models and atmospheric aerosol and chemical transport models enables the utilisation of all meteorological 3D fields in CTMs at each time step and the consideration of the feedbacks of air pollution (e.g. urban aerosols) on meteorological processes and climate forcing.
- These on-line coupled model developments will lead to a new generation of integrated models for climate change modelling, weather forecasting (e.g., in urban areas, severe weather events, etc.), air quality, long-term assessment chemical composition and chemical weather forecasting.

Recommended literature:

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- Baklanov A., U. Korsholm, A. Mahura, C. Petersen, A. Gross, 2008: ENVIRO-HIRLAM: on-line coupled modelling of urban meteorology and air pollution. Advances in Science and Research, 2, 41-46
- Grell GA, Peckham SE, Schmitz R, McKeen SA, Frost G, Skamarock WC, Eder B (2005) Fully coupled “online“ chemistry within the WRF model, Atmos. Environ., 39(37), 6957–6975.
- Zhang, Y., 2008: Online-coupled meteorology and chemistry models: history, current status, and outlook. Atmos. Chem. Phys., 8, 2895–2932
- Baklanov, A. and U. Korsholm: 2007: On-line integrated meteorological and chemical transport modelling: advantages and prospective. In: ITM 2007: 29th NATO/SPS International Technical Meeting on Air Pollution Modelling and its Application, 24 – 28.09.2007, University of Aveiro, Portugal, pp. 21-34.
- Baklanov, A., B. Fay, J. Kaminski, R. Sokhi. Overview of Existing Integrated (off-line and on-line) Mesoscale Meteorological and Chemical Transport Modelling Systems in Europe, WMO GAW Report No. 177, Joint Report of COST Action 728 and GURME, 107 pp. Available from: http://www.cost728.org