SEAMLESS PREDICTION: FROM EARTH SYSTEM TO INTEGRATED URBAN HYDROMETEOROLOGY, CLIMATE AND ENVIRONMENT SYSTEMS

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"Plus hundred more" (see on slides & in reference list)

WEATHER CLIMATE WATER
TEMPS CLIMAT EAU

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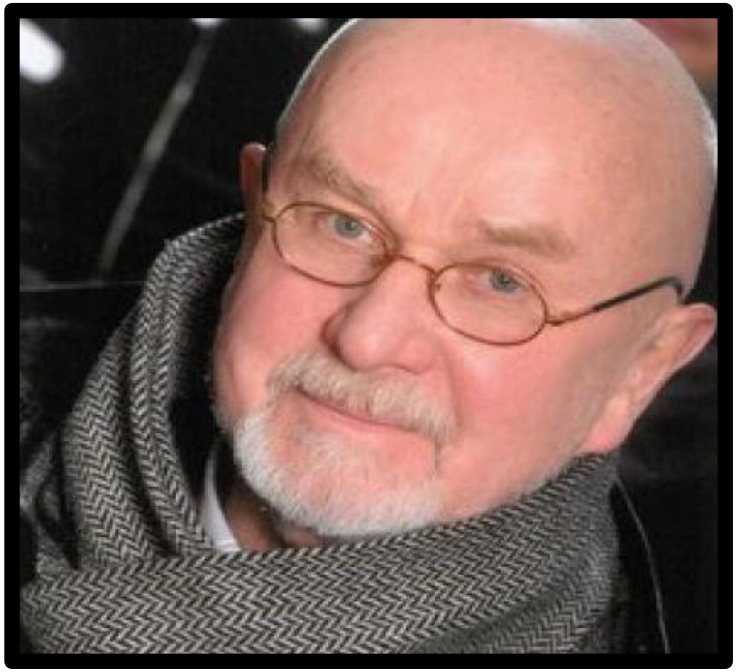
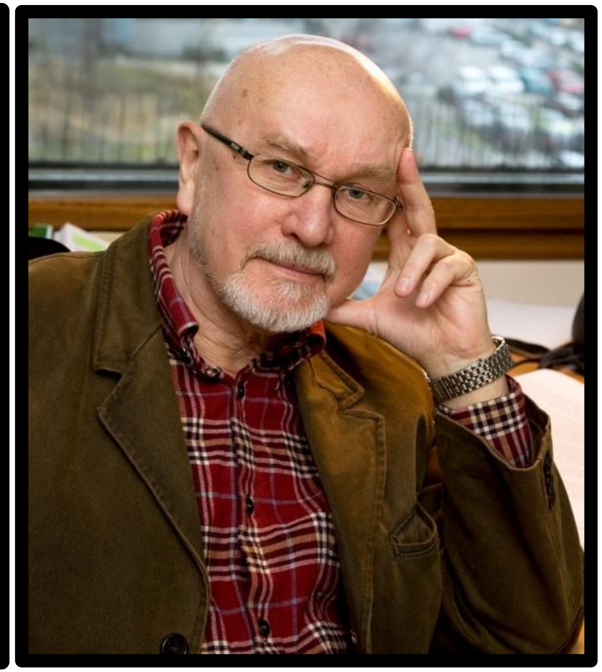
World Meteorological Organization
Organisation météorologique mondiale

Based on my lecture on the seminar "Supercomputer modeling of the climate system" led by Prof. V.N. Lykossov on 17.02.2021

Tributes and Memories
Professor Sergej Zilitinkevich
Дань памяти профессора Сергея Сергеевича Зилитинкевича





13.04.1936 – 15.02.2021

Dedicated to the memory of an outstanding scientist, teacher and closest friend

Памяти выдающегося ученого, учителя и близкого друга посвящается

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Tributes and Memories Professor Vasily Lykossov
Дань памяти члена-корреспондента РАН
Василия Николаевича Лыкосова (14.01.1945-10.09.2021)

Dedicated to the memory of an outstanding scientist, teacher and good friend

Памяти выдающегося ученого, учителя и друга посвящается

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Vasily Lykossov

FOLLOW

Institute for Numerical Mathematics, Russian Academy of Sciences
Verified email at inm.ras.ru

Physics of climate system

TITLE	CITED BY	YEAR
Diagnostic and prognostic equations for the depth of the stably stratified Ekman boundary layer S Zilitinkevich, A Baklanov, J Rost, AS Smedman, V Lykosov, C P. Quarterly Journal of the Royal Meteorological Society 128 (579), 25-46	125	2002
Third-Order Transport and Nonlocal Turbulence Closures for Convective Boundary Layers S Zilitinkevich, VM Gryanik, VN Lykossov, DV Mironov Journal of Atmospheric Sciences 56 (19), 3463-3477	118	1999
Моделирование климата и его изменений: современные проблемы ВП Дымников, ВН Лыкосов, ЕМ Володин Вестник РАН 82 (3), 227-236	111	2012
Simulation of the present-day climate with the climate model INMCM5 EM Volodin, EV Mortikov, SV Kostrykin, VY Galin, VN Lykossov, ... Climate dynamics 49 (11), 3715-3734	91	2017
Моделирование современного климата с помощью атмосферной модели ИВМ РАН. Описание модели A5421 версии 1997 года и результатов эксперимента по программе AMIP II ВА Алексеев, ЕМ Володин, ВЯ Галин, ВП Дымников, ВН Лыкосов	81	1998
Математическое моделирование общей циркуляции атмосферы и океана ГИ Марчук, ВП Дымников, ВБ Залесный, ВН Лыкосов, ВЯ Галин Л : Гидрометеоиздат	80	1984

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Outline

- **WMO Reform and Research Priorities**
- **Part 1: Seamless ESP and CCMM**

i. **Seamless prediction of the Earth system (ESP) approach;**
ii. **Online coupling of atmospheric dynamics and chemistry models (CCMM);**
iii. Multi-scale (time and space) prediction ;
iv. Multi-platform observations and data assimilation;
v. Data fusion, machine learning methods and bias correction techniques;
vi. Ensemble approach; Fit for purpose approach and Impact based forecast.

- **Part 2: Urban cross-cutting focus and IUS**

i. Why the urban focus?
ii. Urban meteorology and air pollution modelling and prediction;
iii. Urbanization of NWP, climate and AQ models;
iv. From urban NWP & UAQIFS to MHEWS;
v. Integrated Urban Hydrometeorology, Climate & Environment Systems;
vi. Integrated Urban Services (IUS) for sustainable cities.

- **From Research to Services**




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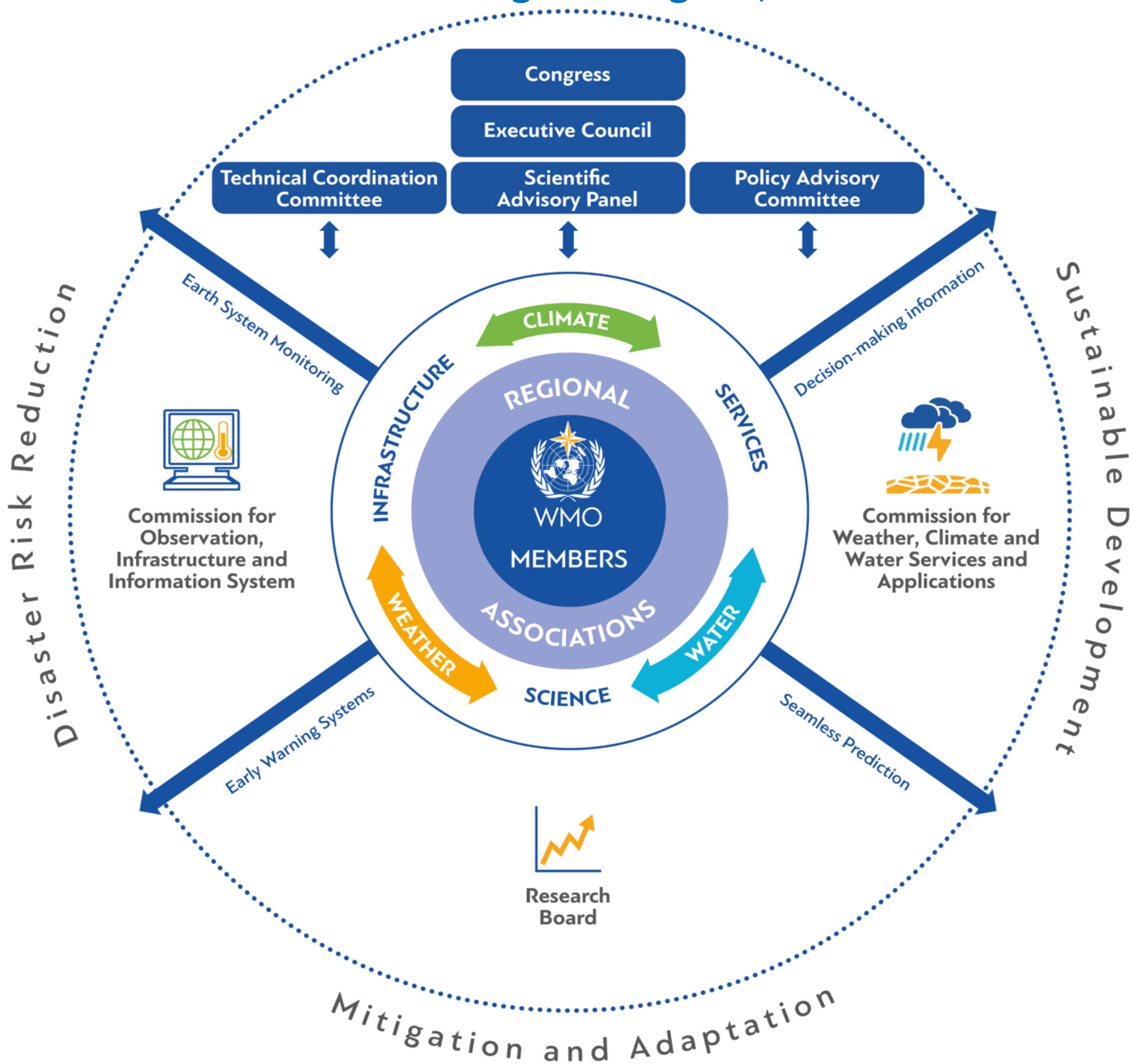
WMO for the 21st Century meeting the UN SDGs

WMO Reform and Proposed structure approved by
the **18th World Meteorological Congress**, on 3-14 June 2019



WMO

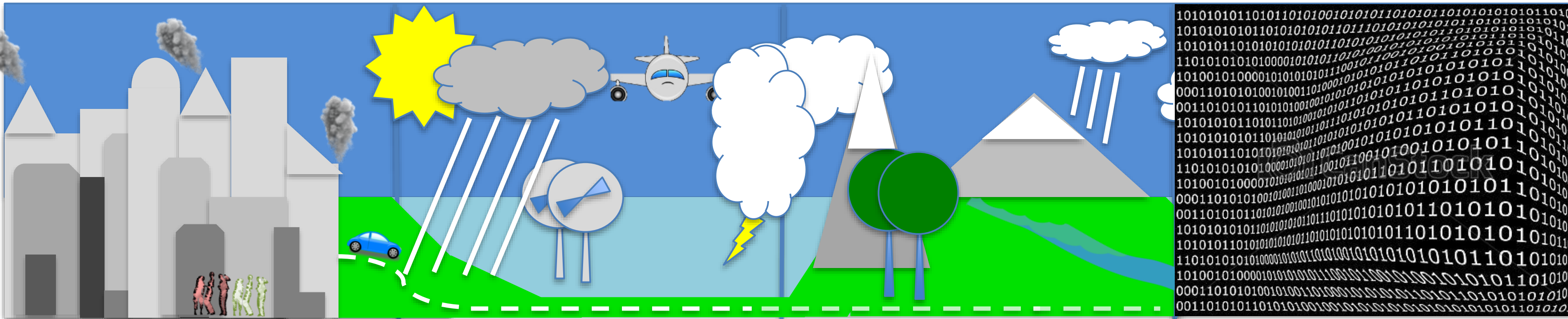
Science and Innovation Department at WMO

- **Frontier of Science**
  - Advances in fundamental science, in observing the earth system and in complex simulations, combined with the exploitation of cutting-edge technologies (satellites, supercomputers, innovative approaches)
- **Earth System science-oriented structure**
  - A seamless approach (across time and spatial scales, across topics and communities) to Earth system prediction, to address the interests and needs of users
  - Strengthening regional and national innovation capabilities
- **Science for Services**
  - Bridging the gap between research, operations and increasing demands of users/society for sophisticated, integrated services (including integrated health science and services)
  - Efficient exchange/interactions between research programmes, infrastructure and service providers → show important role of Science in seamless value chain
  - Fostering regional research capabilities; strong support for members at local and regional level for leveraging their RTD capacity

WMO chief scientist & SID director J. Luterbacher

WMO Commission for Atmospheric Science (CAS)

Societal Challenges



URBANIZATION	HIGH IMPACT WEATHER	WATER & AEROSOLS	NEW TECHNOLOGIES & GHG Information System

Seamless prediction in the CAS context considers all compartments of the **Earth system** as well as disciplines of the **weather enterprise value chain** (monitoring and observation, models, forecasting, dissemination and communication, perception and interpretation, decision- making, end-user products) to deliver tailor made **weather information from minutes to months and from global to local**.

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Øystein Hov, CAS President, 2018

Part 1: Seamless ESP and CCMM

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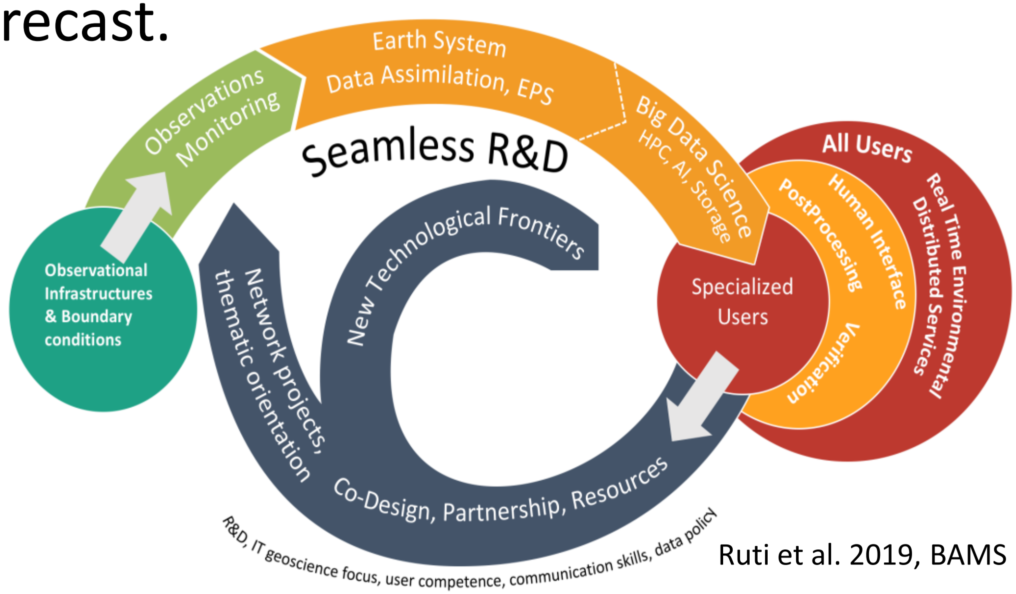

Ruti et al. 2019, BAMS

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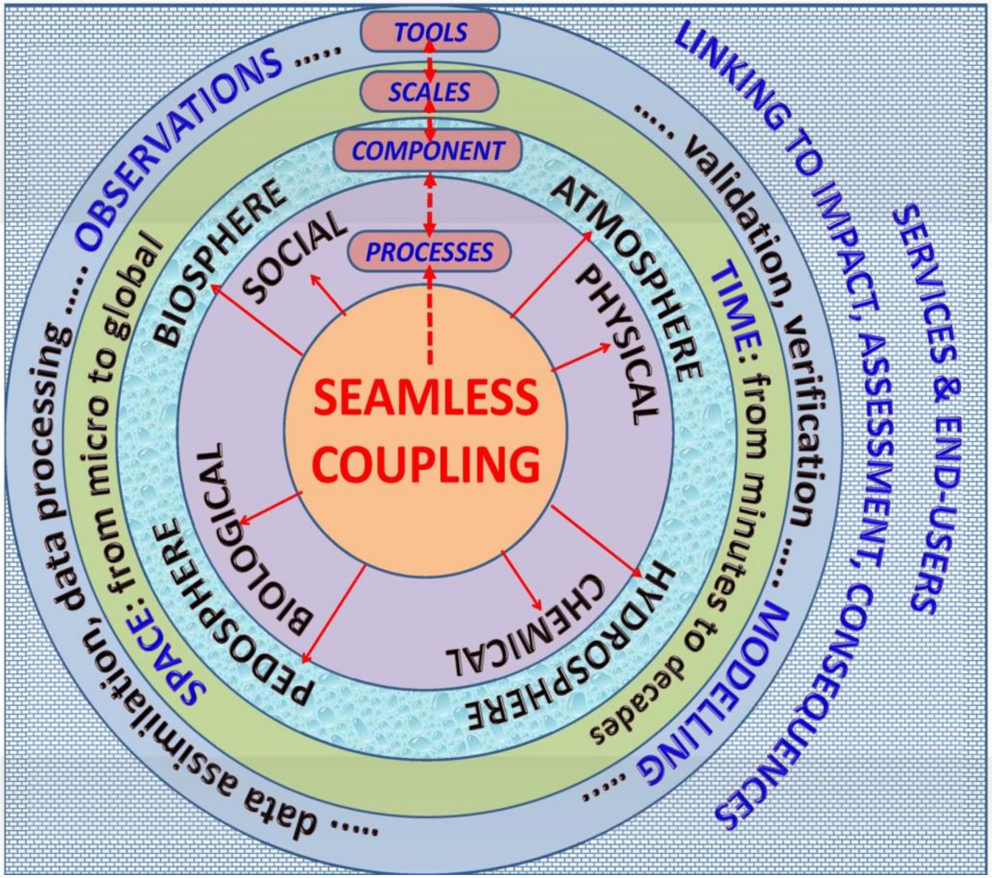
(i) Seamless prediction of the Earth system approach

Several dimensions of the seamless coupling/integration, including:

- Time scales: from seconds and nowcasting to decadal and centennial (climate) time-scale;
- Spatial scales: from street-level to global scale (downscaling and upscaling);
- Processes: physical, chemical, biological, social;
- Earth system components/environments: atmosphere, hydrosphere, lithosphere, pedosphere, ecosystems/biosphere;
- Different types of observations and modelling as tools: observations-model fusion, data processing and assimilation, validation and verification;
- Links with health and social consequences, impact, assessment, and services and end-users.



(Baklanov & Zhang (2020); WWOSC (2015); ***Baklanov, Mahura et al. (2017)***

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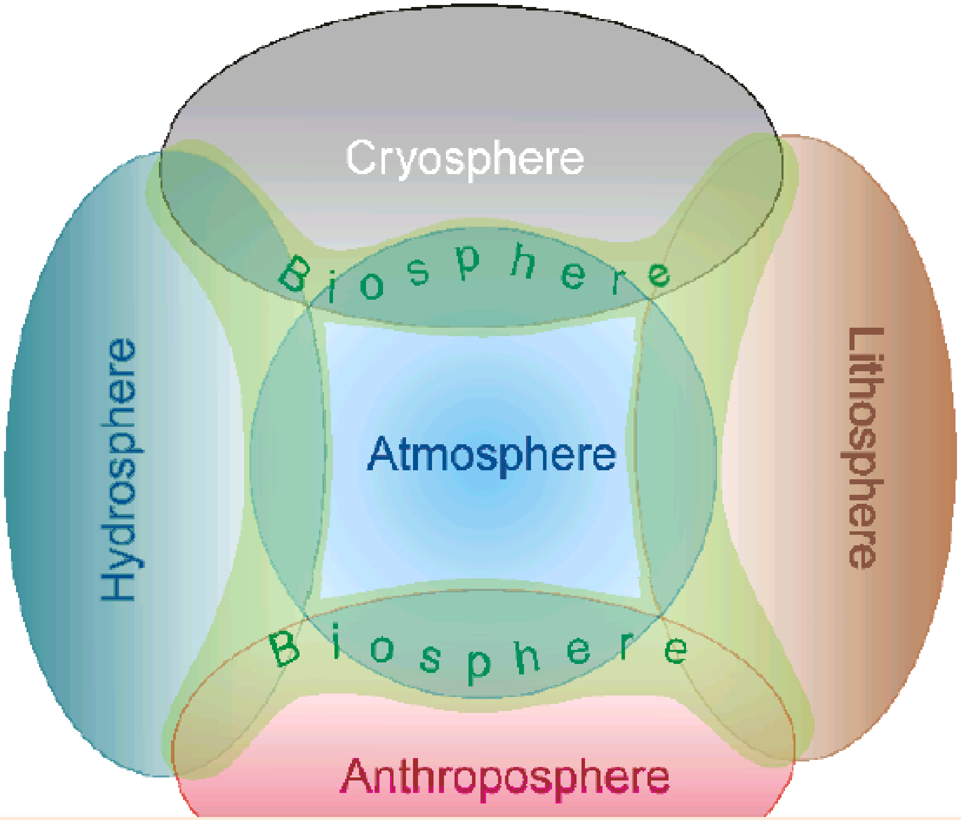
Geospheres in climate machine

From presentation of Prof. Zilitinkevich

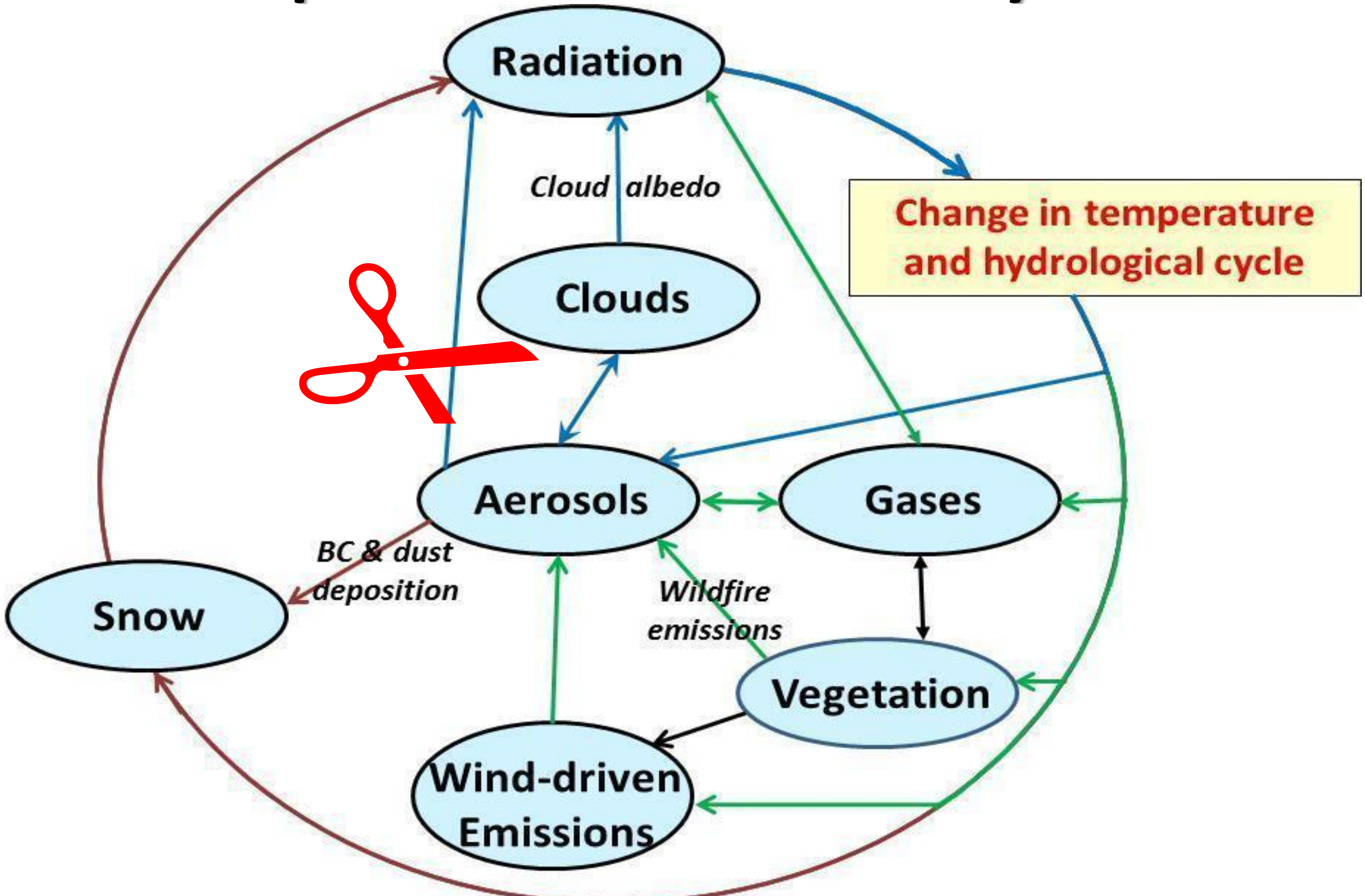
Atmosphere, **hydrosphere**, **lithosphere** and **cryosphere** are coupled through turbulent **planetary boundary layers PBLs** (dark green lenses)

PBLs include **90% biosphere** and entire **anthroposphere**



S.S. Zilitinkevich discovered the fully unorthodox nature of the stratified environmental turbulence, namely, of its control by the two coexisting arrows: well-known "chaos out of order" and yet missed in this type of turbulence "order out of chaos"; and launching long-awaited scientific revolution in this area of PBL research, which allows to effectively resisting to the global pollution and climate change.

Interactions between aerosols, gases and components of the Earth system



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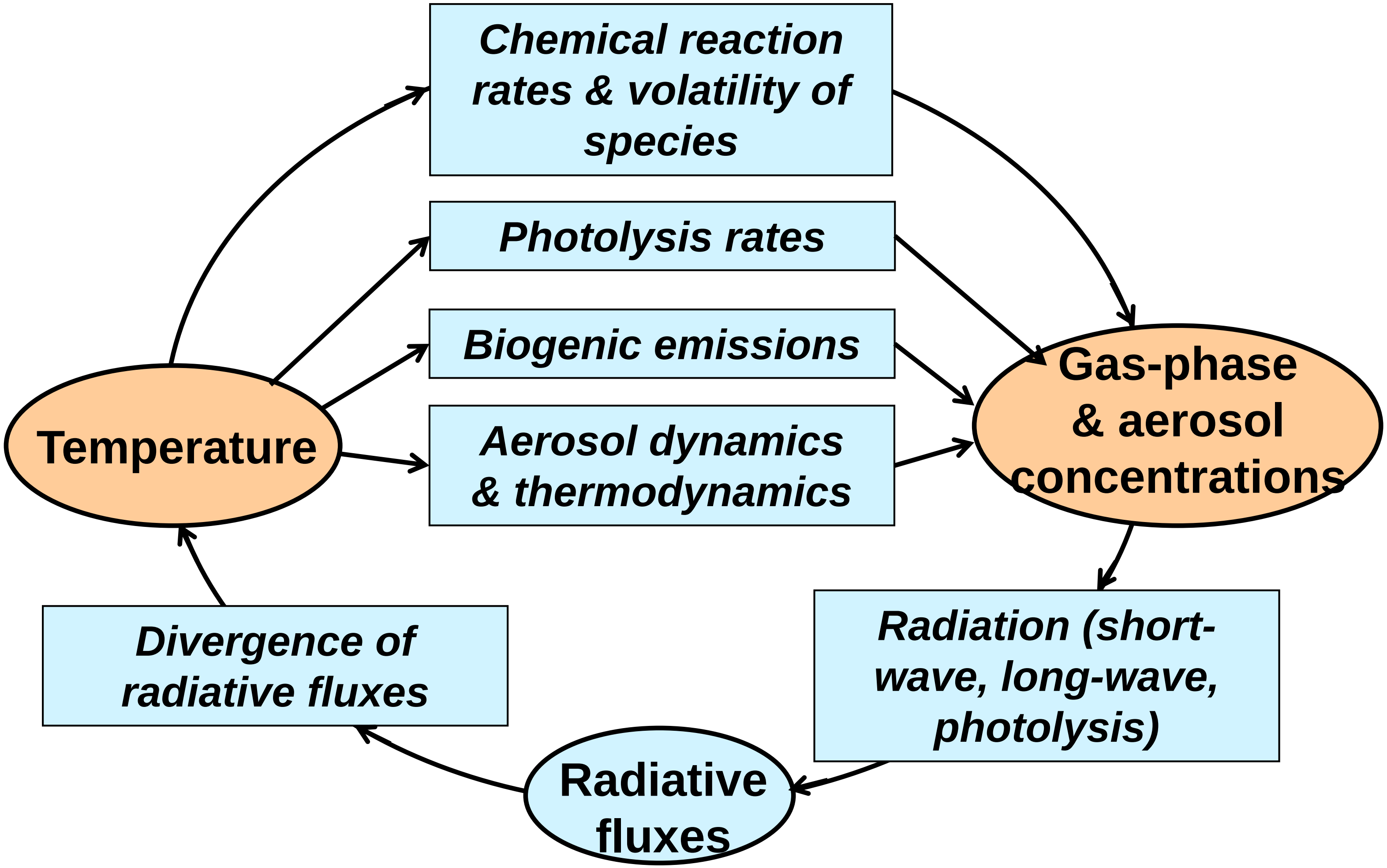
Baklanov et al., ACP, 2014

Example: Conceptual model of impacts from temperature on concentrations and vice versa

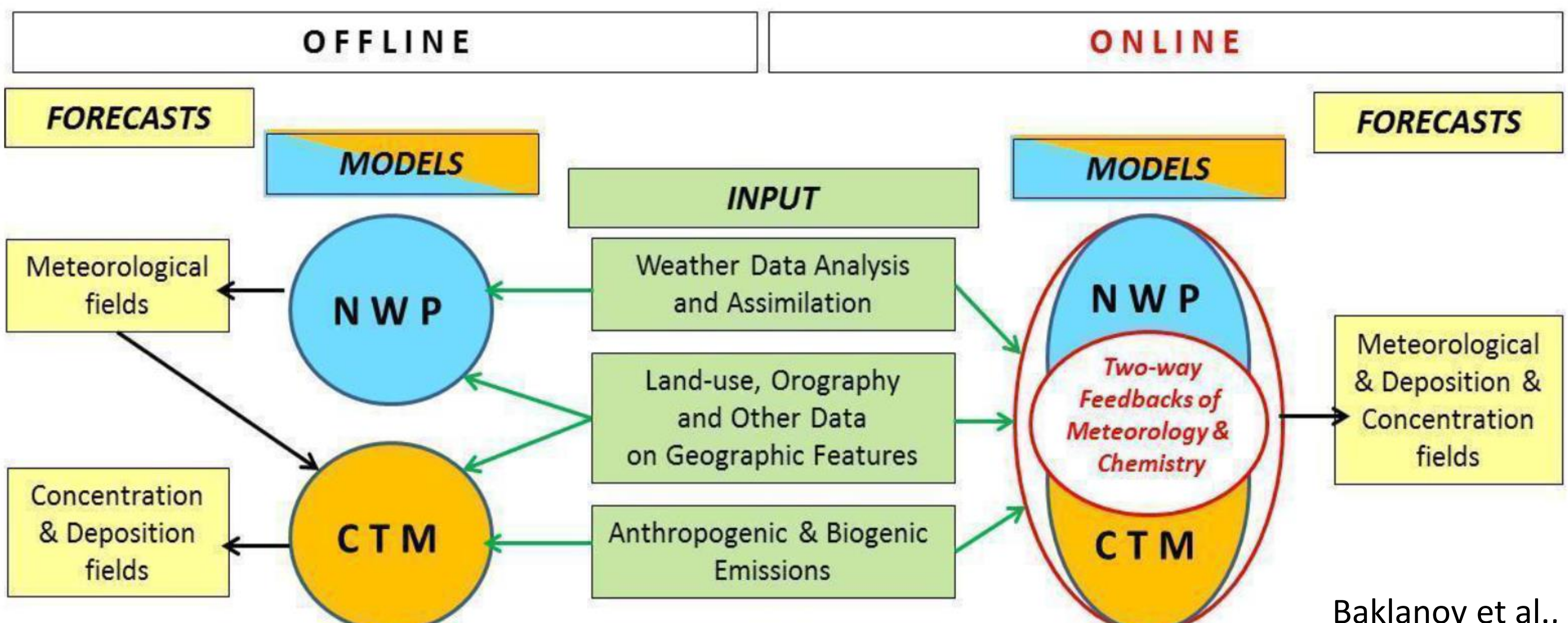


Based on Baklanov et al. ACP, 2014

(ii) Online coupling & integration of atmospheric dynamics and chemistry models

- Physical and Chemical Weather: dependence of meteorological processes (incl. precipitation, thunderstorms, radiation, clouds, fog, visibility and PBL structure) on atmospheric concentrations of chemical components (especially aerosols).
- Meteorological data assimilation (in particular assimilation of radiative properties) also depends on chemical composition.
- Air quality forecasts loose accuracy when CTMs are run offline.
- Climate modeling: large uncertainty of SLCFs, water vapor feedbacks, etc.

=> Need for a new generation of seamless integrated meteorology and chemistry modelling systems for predicting atmospheric composition, meteorology and climate evolution !



Baklanov et al., ACP, 2014

(ii) Online coupling of atmospheric dynamics and chemistry models

- The CTM and meteorological models are run at the same time, and exchange information at every time step; they consider chemistry feedbacks to meteorology to various degrees
- Types of Framework

– **Online access models:** couples a meteorology model with an air quality model in which the two systems operate separately but exchange information every time step through an interface

– **Online integrated models:** integrates an air quality model into a meteorology model as a unified model system in which meteorology and air quality variables are simulated together in one time step without an interface between the two models

- Representative online models

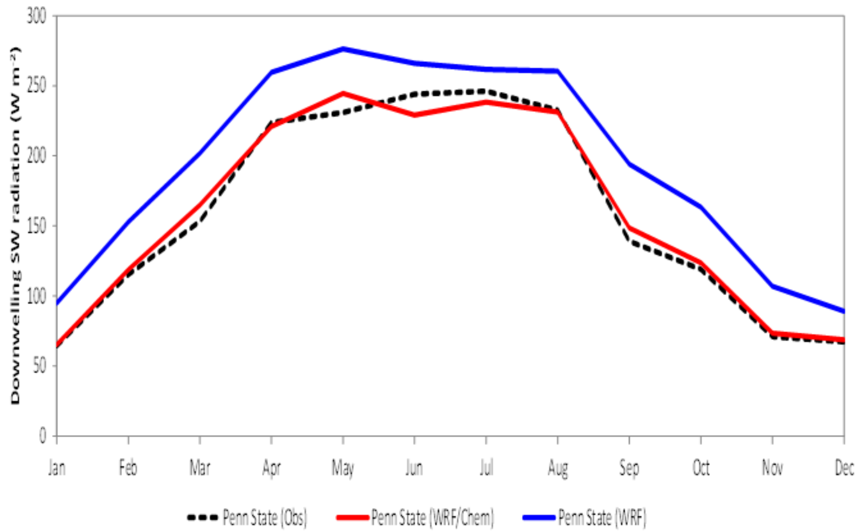
– In USSR: Novosibirsk school of G.I. Marchuk in 80th

– In USA: NCAR/NOAA WRF/Chem, US EPA Two-way coupled WRF-CMAQ, etc.

– In Europe: see overview in Baklanov et al. ACP, 2014

WRF vs. WRF/Chem

Downward SW Radiative Flux, 2006
(Yahya et al., 2016)



Compared to meteorological model WRF, online WRF/Chem model can improve meteorological forecast

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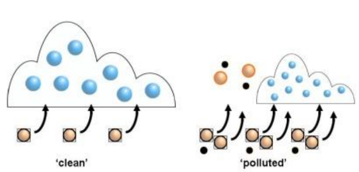
Online coupled meteo-chemistry modeling history

- Online modeling systems have been developed and used by the research community since the 1990's.
- Richardson was first (in 1922) who started online coupled approach: in his NWP model formulation one of the variables (equations) was 'atmospheric dust' (however, it was not realised…)
- The Novosibirsk school of atmospheric modeling (Marchuk, 1982) has been started using the online coupling approach for atmospheric environment modeling in 1980th (Penenko and Aloyan, 1985; Baklanov, 1988), e.g. for modeling of active artificial/anthropogenic impacts on atmospheric processes.
- The earliest online approach for the simulation of climate, air quality and chemical composition may have been a model developed by Jacobson (1994, 1996).
- The earliest recognition of the importance of online chemistry for NWP models was given by the European Center for Medium Range Weather Forecasting (ECMWF, Hollingsworth et al. 2008).
- Climate modeling centers have gone to an Earth system modeling system modeling approach that includes atmospheric chemistry and oceans (and bases on NWP models).
- Operational NWP centers, as well as CWF centers, are only now beginning to discuss whether an online approach is important enough (IFS, 2009; Grell and Baklanov, 2011).
- Great progress in Europe during last 15 years: > 20 online modelling systems; in 2007 – one model with aerosol indirect feedbacks (Enviro-HIRLAM!), now – about 15.
- Scientific perspective of CCMM would argue for an eventual migration from off-line to on-line modeling.

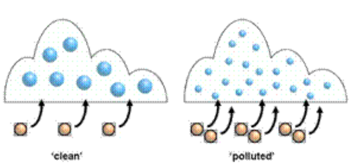
Examples of Important Met-AQ Feedbacks

- **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)

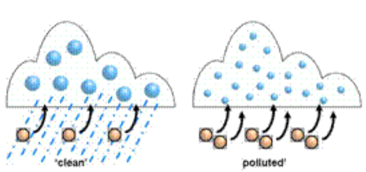
Semi-Direct Effect



First Indirect Effect



Second Indirect Effect



Effects of Meteorology on Chemistry

Baklanov et al., ACP, 2014

Meteorological parameter	Effect on ...	Model variables
temperature	chemical reaction rates	T, reaction rate coefficients
	biogenic emissions	BVOC emission rates, isoprene, terpenes, DMS, pollen
	aerosol dynamics (coagulation, evaporation, condensation)	aerosol number size distributions scattering and absorption coefficients PM mass and composition
temperature and humidity	aerosol formation, gas/aerosol partitioning	gas phase SO_2, HNO_3, NH_3 particulate NO_3^-, SO_4^{2-}, NH_4^+ VOCs, SOA
	aerosol water take-up, aerosol solid/liquid phase transition	PM size distributions, extinction coefficient, aerosol water content
SW radiation	photolysis rates	JNO_2, JO1D, etc.
photosynthetic active radiation	biogenic emissions	SW radiation BVOC emissions, isoprene & terpene conc.
cloud liquid water and precipitation	wet scavenging of gases and particles	wet deposition (HSO_{3-}, SO_{4-}, NO_{3-}, NH_{4-}, Hg), precipitation (rain and total precip) cloud liq. water path
	wet phase chemistry, e.g. sulphate production	SO_2, H_2SO_4, SO_4^{2-} in ambient air and in cloud and rain water
	aerosol dynamics (activation, coagulation) aerosol cloud processing	aerosol mass and number size distributions
soil moisture	dust emissions, pollen emissions	surface soil moisture dust and pollen emission rates
	dry deposition (biosphere and soil)	deposition velocities, dry deposition rates (e.g. O_3, HNO_3, NH_3)
wind speed	transport of gases and aerosols on- vs. offline coupling interval, transport in mesoscale flows, bifurcation, circulations, etc.	U, V, (W)
	emissions of dust, sea salt and pollen	U, V dust, sea salt and pollen emission rates
atmospheric boundary layer parameters	turbulent and convective mixing of gases and aerosols in ABL, intrusion from free troposphere, dry deposition at surface	T, Q, TKE, surface fluxes (latent and sensible heat, SW and LW radiation) deposition velocities, dry deposition fluxe(O_3, HNO_3, NH_3)
lightning	NO emissions	NO, NO_2, lightning NO emissions
water vapour	OH radicals	Q, OH, HO_2, O_3

Effects of Chemistry on Meteorology

Chemical parameter	Effect on ...	Model variables
aerosols (direct effect)	radiation (SW scattering/absorption, LW absorption)	AOD, aerosol extinction, single scattering albedo, SW radiation at ground (up- and downward), aerosol mass and number size distributions, aerosol composition: EC (fresh soot, coated), OC, SO_4^{2-}, NO_3^-, NH_4^+, Na, Cl, H_2O dust, metals, base cations
aerosols (direct effect)	visibility, haze	aerosol absorption & scattering coefficients, RH, aerosol water content
aerosols (indirect effect)	cloud droplet or crystal number and hence cloud optical depth	interstitial/activated fraction, CCN number, IN number, cloud droplet size/number, cloud liquid and ice water content
aerosols (indirect effect)	cloud lifetime	cloud cover
aerosols (indirect effect)	precipitation (initiation, intensity)	precipitation (grid scale and convective)
aerosols (semi-direct effect)	ABL meteorology	AOD, ABL height, surface fluxes (sensible and latent heat, radiation)
O_3	UV radiation	O_3, SW radiation $<$ 320 nm
O_3	thermal IR radiation, temperature	O_3, LW radiation
NO_2, CO, VOCs	precursors of O_3, hence indirect contributions to O_3 radiative effects	NO_2, CO, total OH reactivity of VOCs
SO_2, HNO_3, NH_3, VOCS	precursors of secondary inorganic and organic aerosols, hence indirect contributors to aerosol direct and indirect effects	SO_2, HNO_3, NH_3, VOC components (e.g. terpenes, aromatics, isoprene)
soot deposition on ice	surface albedo change	snow albedo

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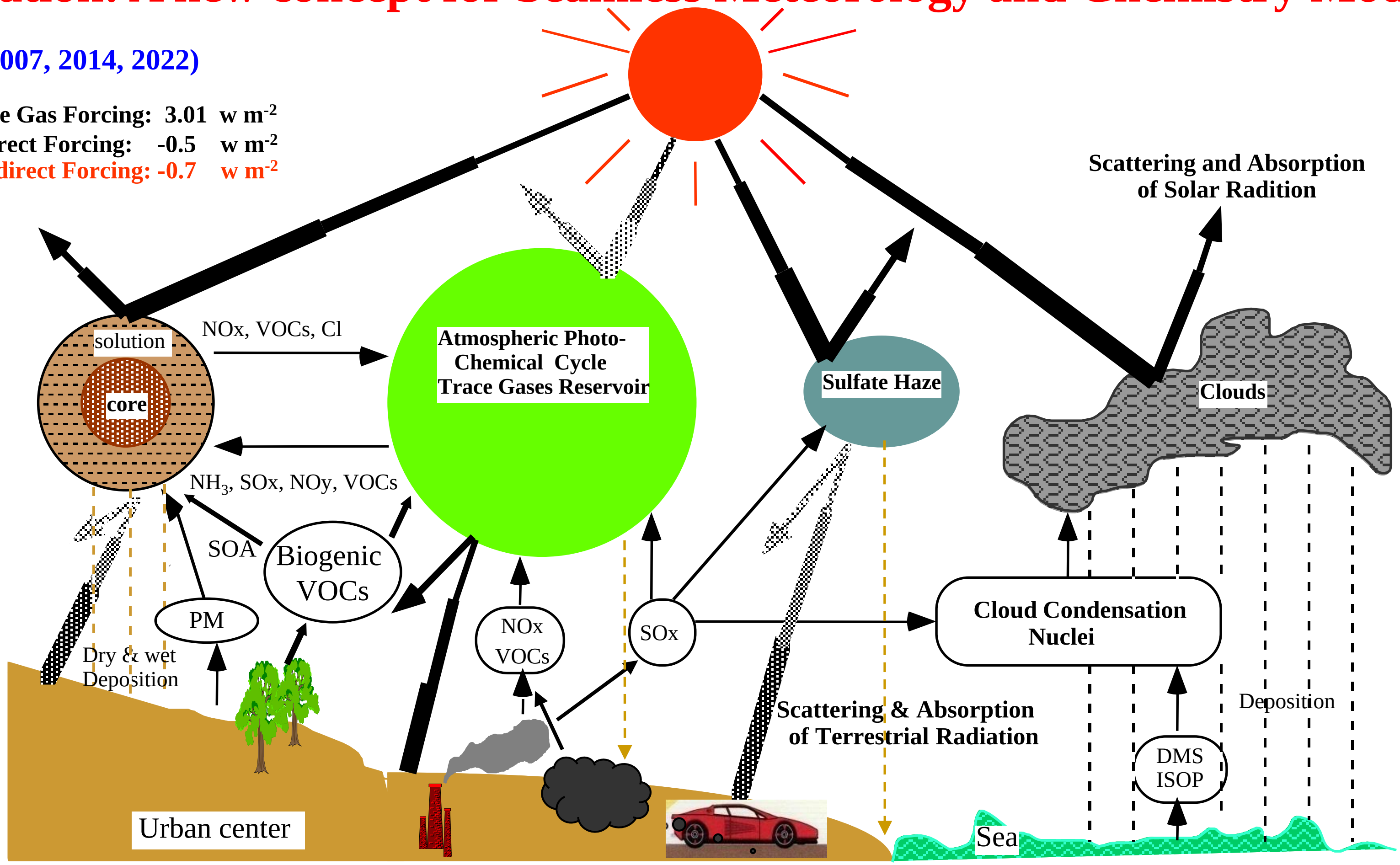
Baklanov et al., ACP, 2014

Atmosphere Interactions:
Gases, Aerosols, Chemistry, Transport, Radiation, Climate

Motivation: A new concept for Seamless Meteorology and Chemistry Modelling

IPCC (2007, 2014, 2022)

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, Copenhagen, 2007

Temperature → chemistry → concentrations → radiative processes → temperature
Aerosol → radiation → photolysis → chemistry
Temperature gradients → turbulence → surface concentrations, boundary layer outflow/inflow
Aerosol → cloud optical depth through influence of droplet number on mean droplet size → initiation of precipitation
Aerosol absorption of sunlight → cloud liquid water → cloud optical depth

Integrated chemistry-meteorology models

Advantages as compared to offline models

- meteorological fields accessible at every time step
- single executable, single simulation, single parallelization strategy
- consistent treatment of processes acting on chemical and meteorological variables, computed only once in one code
- possibility to consider interactions between chemistry and meteorology
- data assimilation affects at same time chemical and meteorological variables
- no meteo preprocessing, no need for reading meteo from disk

Challenges

- chemistry to be solved at same (high) resolution as meteorology
- meteorology changes when feedbacks are activated
- significant investment to ensure consistent treatment of processes (e.g. radiation, transport)
- development of chemistry and meteorology parts not separated; therefore strong co-ordination needed

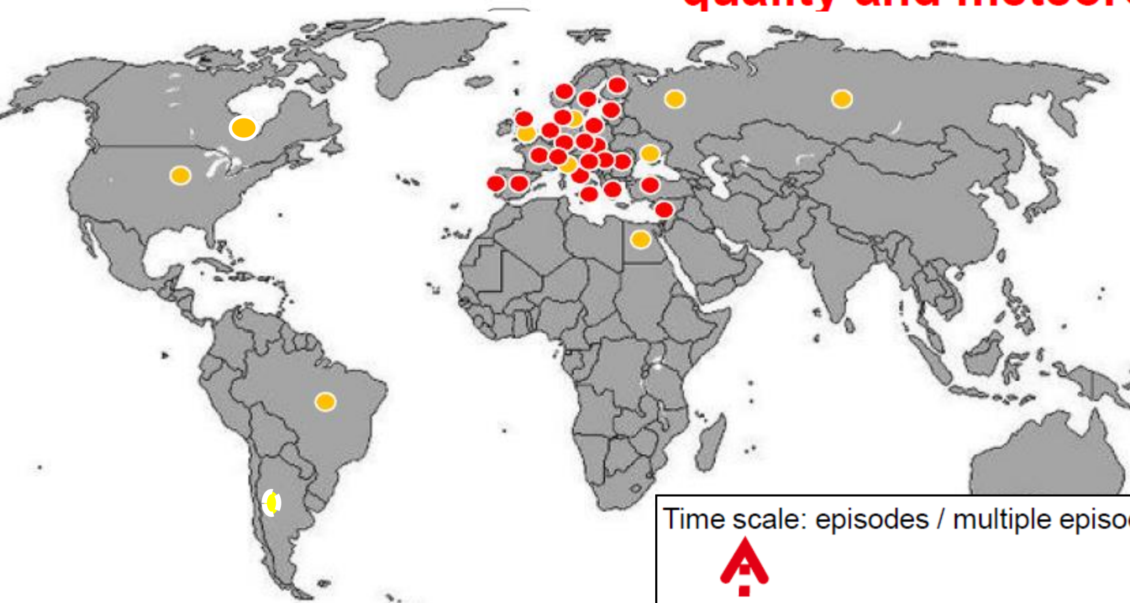
After Grell and Baklanov, AE, 2011

European Cooperation in the field of Scientific and Technical Research

www.cost.esf.org

Action COST ES1004

European framework for online integrated air quality and meteorology modelling (EuMetChem)



Base map: © 2004-2009 sc

- **Strategy and framework for online integrated modelling**
  - 17 experts (P. Suppan, J.M. Baltasano, G. Grell).
- **Interactions, parameterisations and feedback mechanisms**
  - 22 experts (M. Gauss, A. Maurizi, Y. Zhang).
- **Chemical data assimilation in integrated models**
  - 13 experts (Ch. Seigneur, H. Elbern, G. Carmichael).
- **Evaluation, validation, and applications**
  - 33 experts (D. Brunner, K.H. Schlünzen, S. Galmarini, S.T. Rao).

(Duration: 02.2011 … 02.2015)

Chair: A. Baklanov,
Co-chairs: S. Joffre, H. Schluenzen

23 COST countries
4 COST neighbour countries
3+2 COST partner countries
3 EU institutions
18 online models analysed =>

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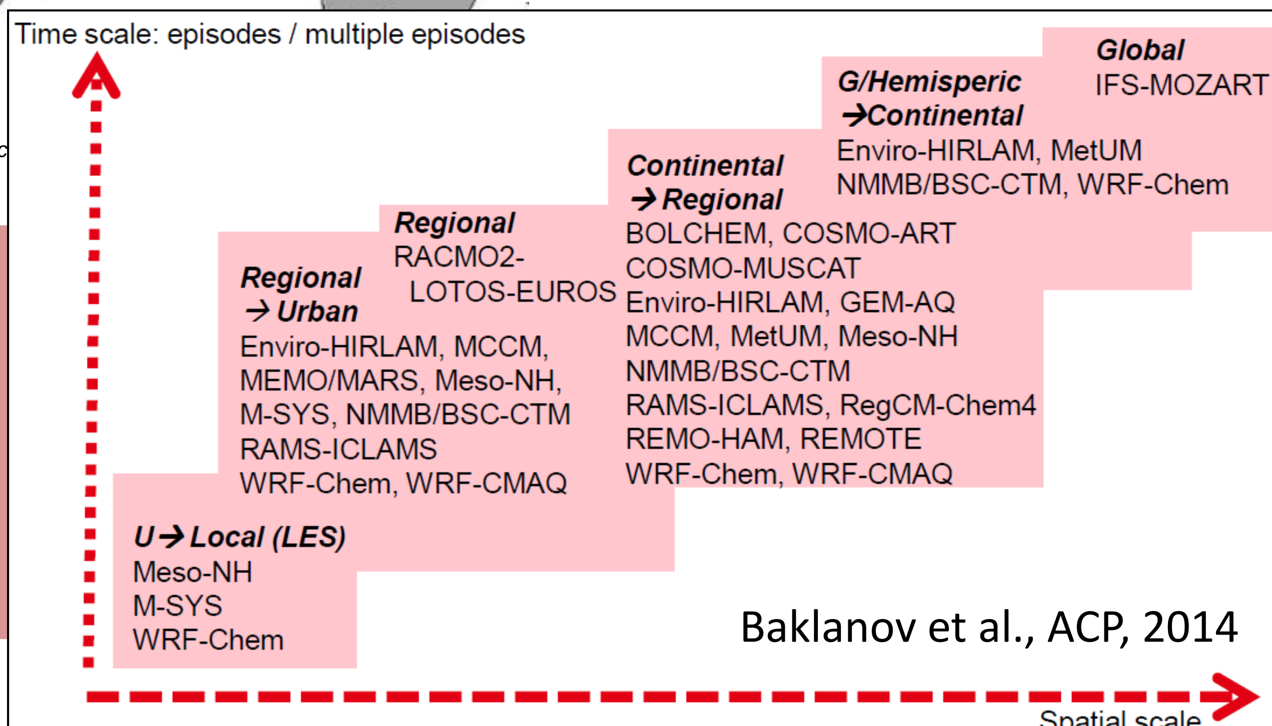


Baklanov et al., ACP, 2014

Overview of fully online CCM models (not online-access)

Model name	Dynamical model	Country ; Institutions / Consortia
ATTILA	ECHAM4	Germany; DLR
BOLCHEM	BOLAM	Italy; ISAC-CNR
COSMO-ART (Bott)	COSMO	Germany; COSMO Community
COSMO-ART (Semi-Lagr. (SL))	COSMO	Germany; COSMO Community
C-IFS / IFS-MOZART	IFS	ECMWF; MACC
ECHAM-HAM	ECHAM6	Germany; MPI-met
Enviro-HIRLAM / HARMONIE	HIRLAM-C	Denmark; DMI, HIRLAM
ICON-ART	ICON	Germany; DWD, MPI-met
MCCM	MM5	Germany; IMK-IFU
Meso-NH	Meso-NH	France; Lab. d'Aerologie, CNRM GAME
MetUM	Unified Model	UK; Met Office / Hadley Centre
M-SYS	METRAS	Germany; Univ. Hamburg
NorESM	CAM4	Norway; MetNo, Oslo Univ.
RegCM-Chem4	~MM5 - hydrostatic	Italy; ICTP
SOCOL	MA-ECHAM	Switzerland; ETHZ plus more
WRF-Chem	WRF	WRF-Community (US & Worldwide)

(See more in Zhang & Baklanov, 2020)

Integration of chemistry & aerosol modules

in ECMWF's integrated forecast system (IFS)

C-IFS

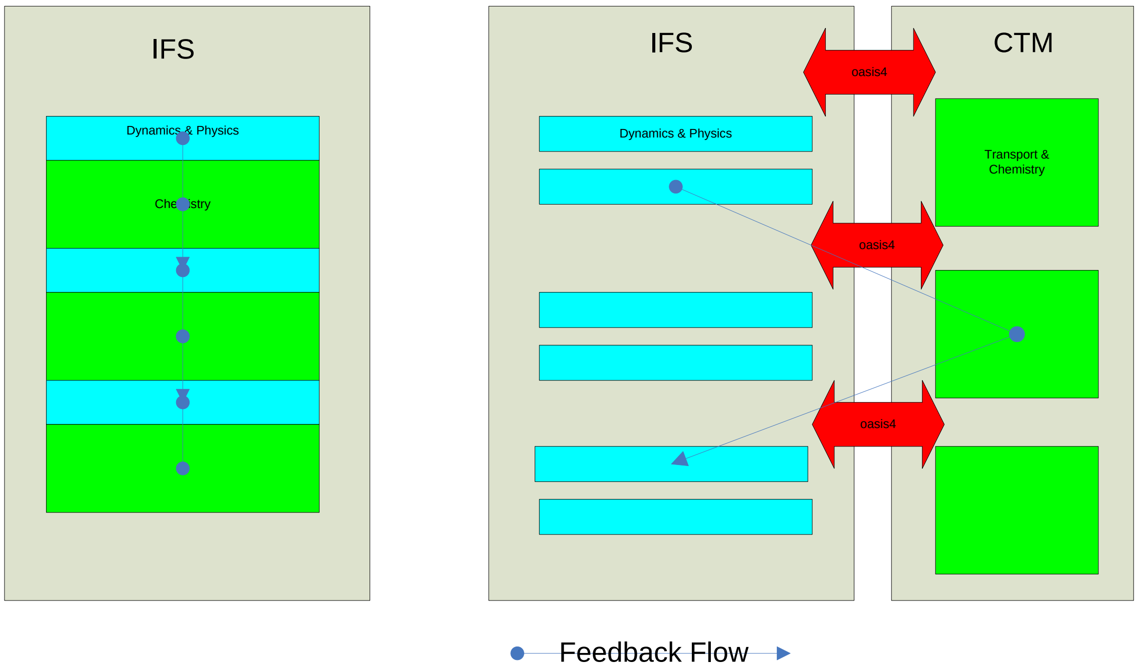
On-line Integration of Chemistry in IFS

Coupled System

IFS- MOZART3 / TM5

Developed in MACC

10 x more efficient than Coupled System



Developed in GEMS
Used in MACC

Integrated System
Feedback: fast
Flexibility: low

Coupled System
Feedback: slow
Flexibility: high

Flemming et al. 2009

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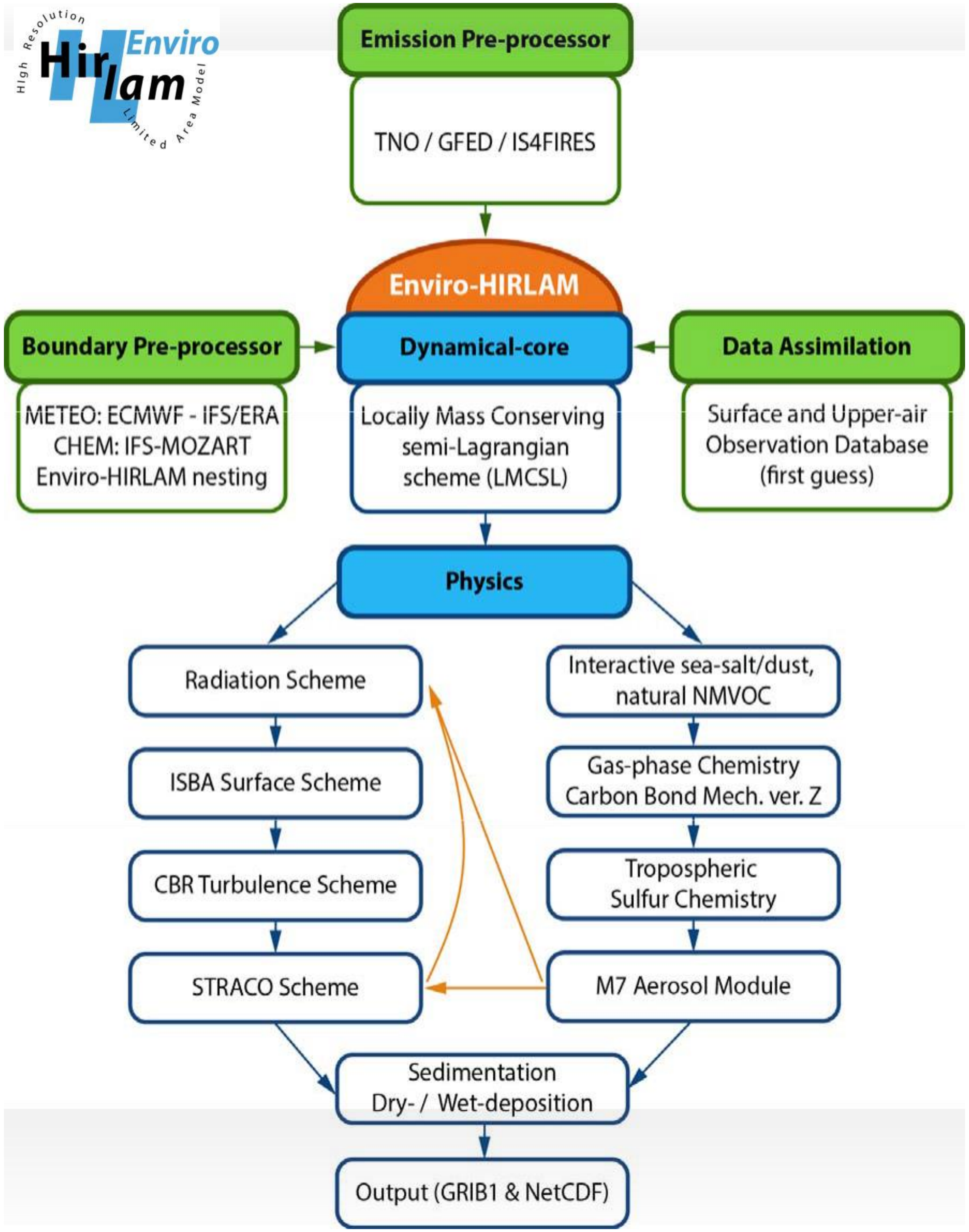
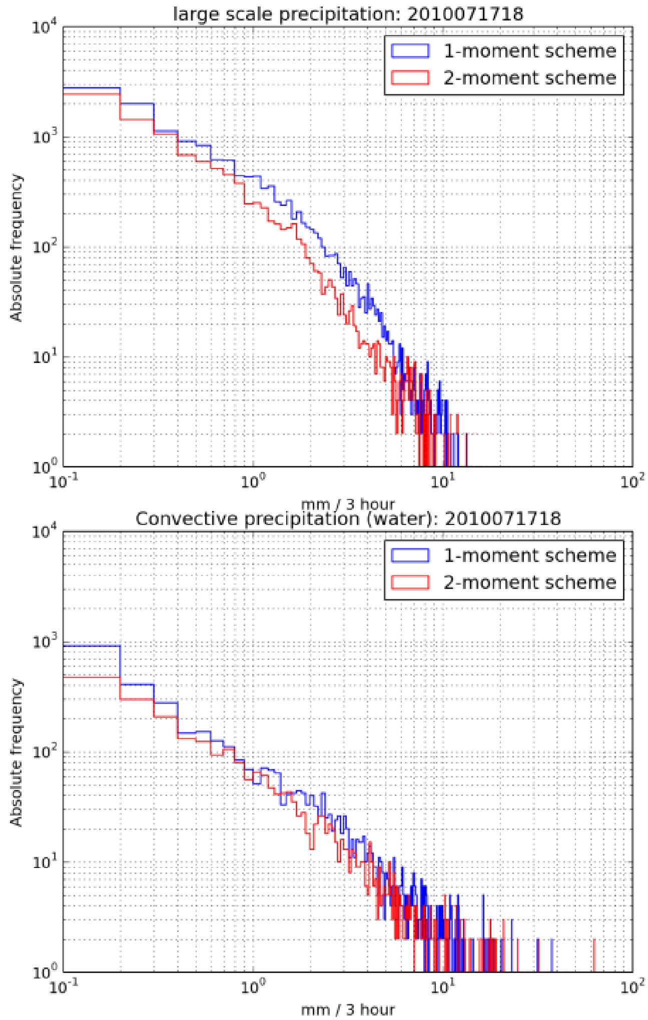


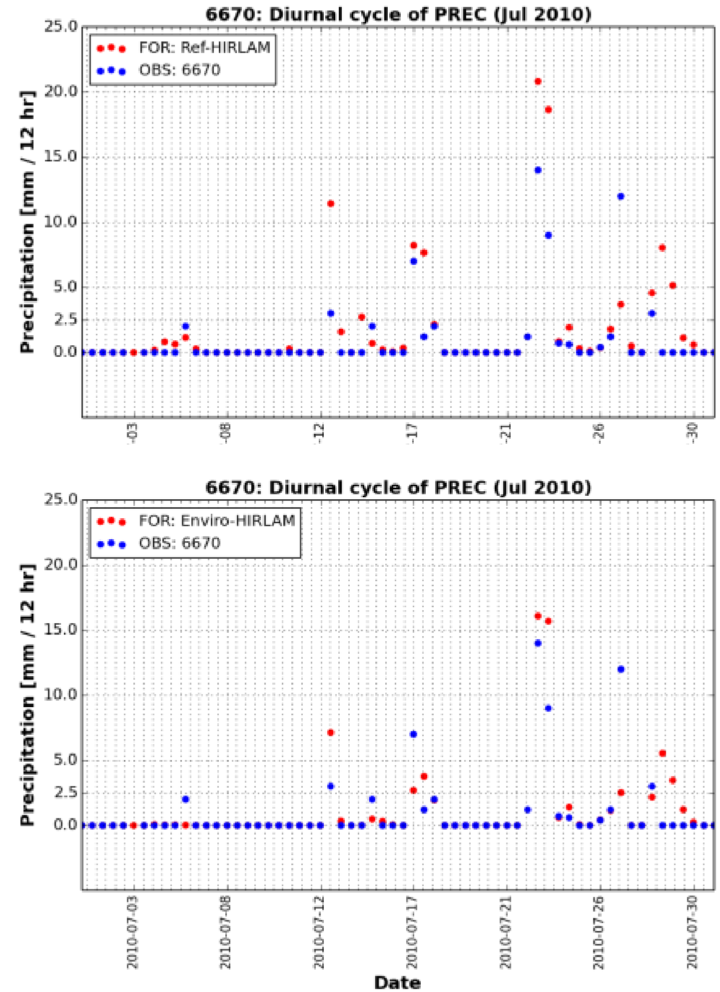
Enviro-HIRLAM (Environment – HIgh Resolution Limited Area Model)

- **Seamless / online coupled integrated meteorology-chemistry-aerosols downscaling modelling system for predicting weather and atmospheric composition**

(Baklanov et al., GMD, 2017)

Enviro-HIRLAM: aerosol–cloud interactions



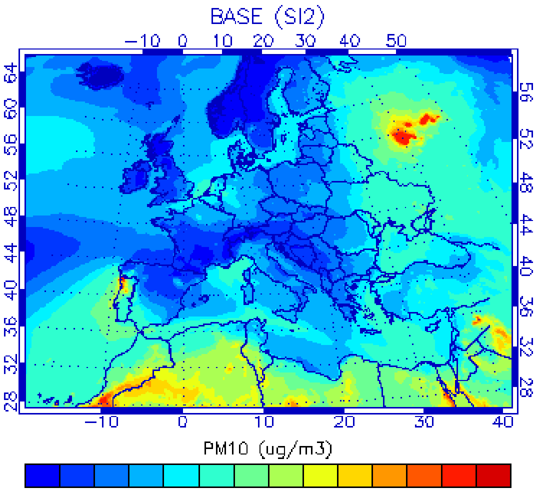


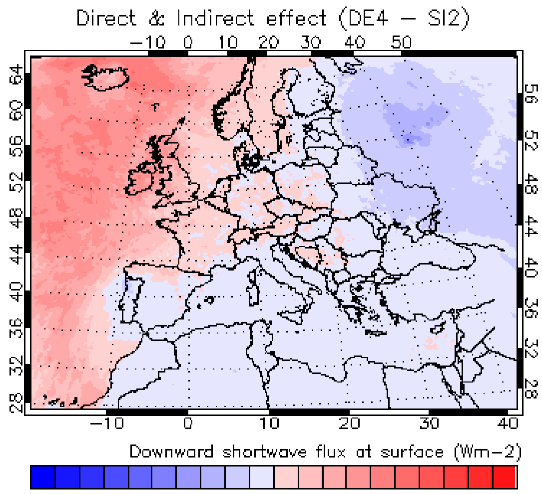
Frequency distribution in [mm/ 3 hour] of stratiform precipitation (top) and convective precipitation (down). Comparison of 1-moment (Reference HIRLAM) and 2-moment (Enviro-HIRLAM with aerosol–cloud interactions) cloud microphysics STRACO schemes.

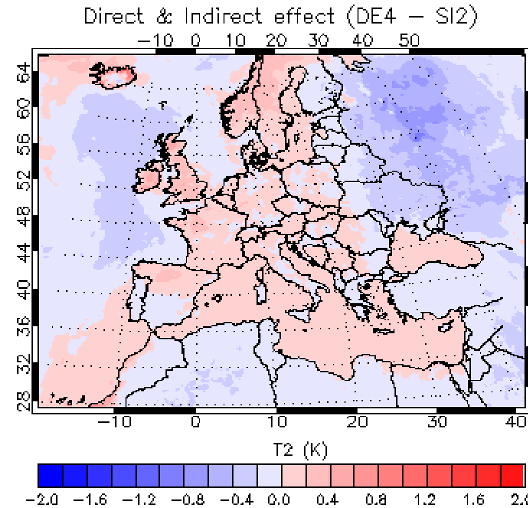
Precipitation amount (12 hrs accumulated) of reference HIRLAM (top) and Enviro-HIRLAM with aerosol–cloud interactions (down) vs. surface synoptic observations at WMO station 6670 at Zurich, Switzerland during July 2010.

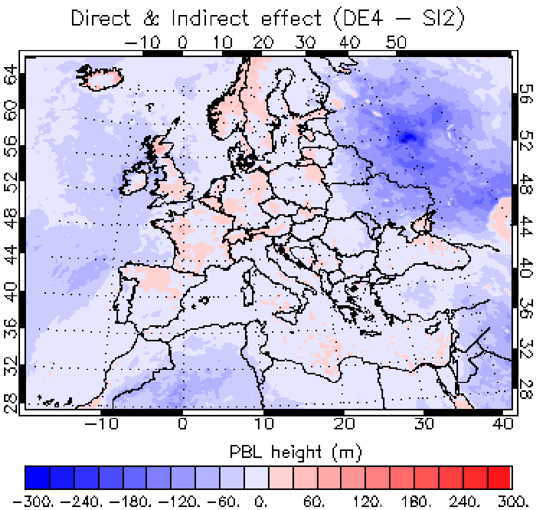
Nuterman et al, 2014

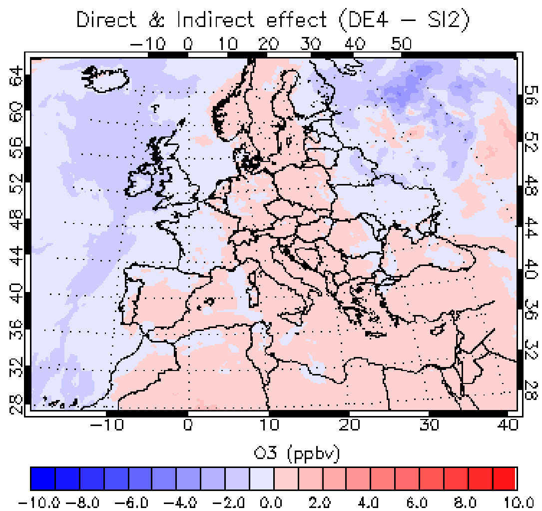
WRF-Chem Sensitivity Runs on 2010 Russian Wild Fires Case Study: Chains of aerosol direct & indirect effects on meteorology











- Significant aerosol direct effects on meteorology (and loop back on chemistry).
- Reduced downward short wave radiation and surface temperature, and also reduced PBL height. It in turn reduced photolysis rate for O3
- The normalized mean biases are significantly reduced by 10-20% for PM10 when including aerosol direct effects.
- Indirect effects are less pronounced for this case and more uncertain.

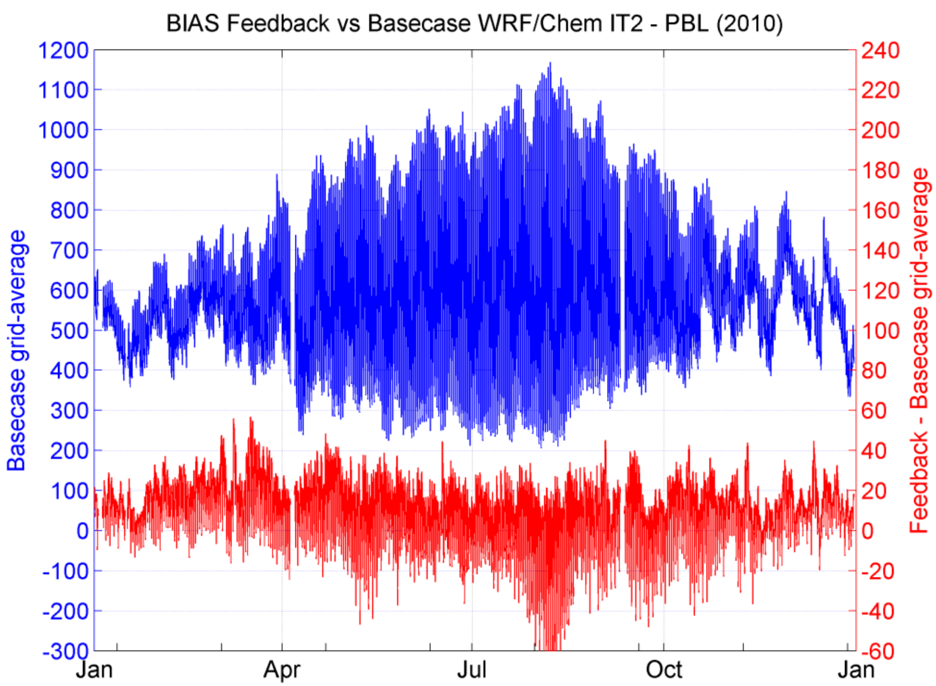
WMO OMM

Kong et al, AE, 2015

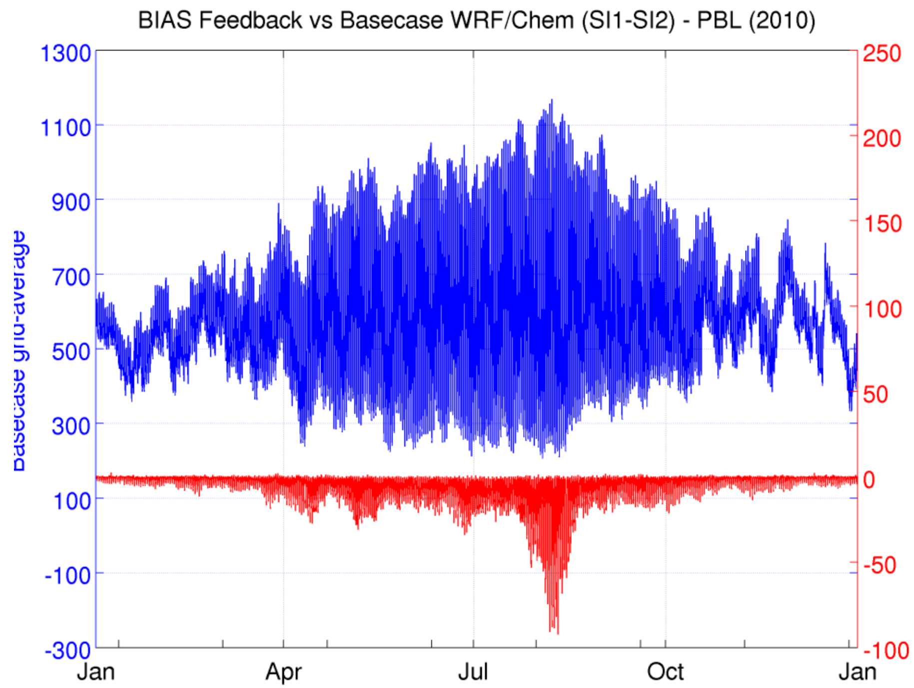
PBL Height [m]

Grid-average Feedback-Basecase (**WRF-Chem, EU**)

direct & indirect effects



direct effects



Zabkar, Curci et al., 2014

DIRECT&INDIRECT:

- **Feedbacks increase PBL in winter, in summer feedbacks may both increase and decrease PBL height. Range [-60 : 40]**

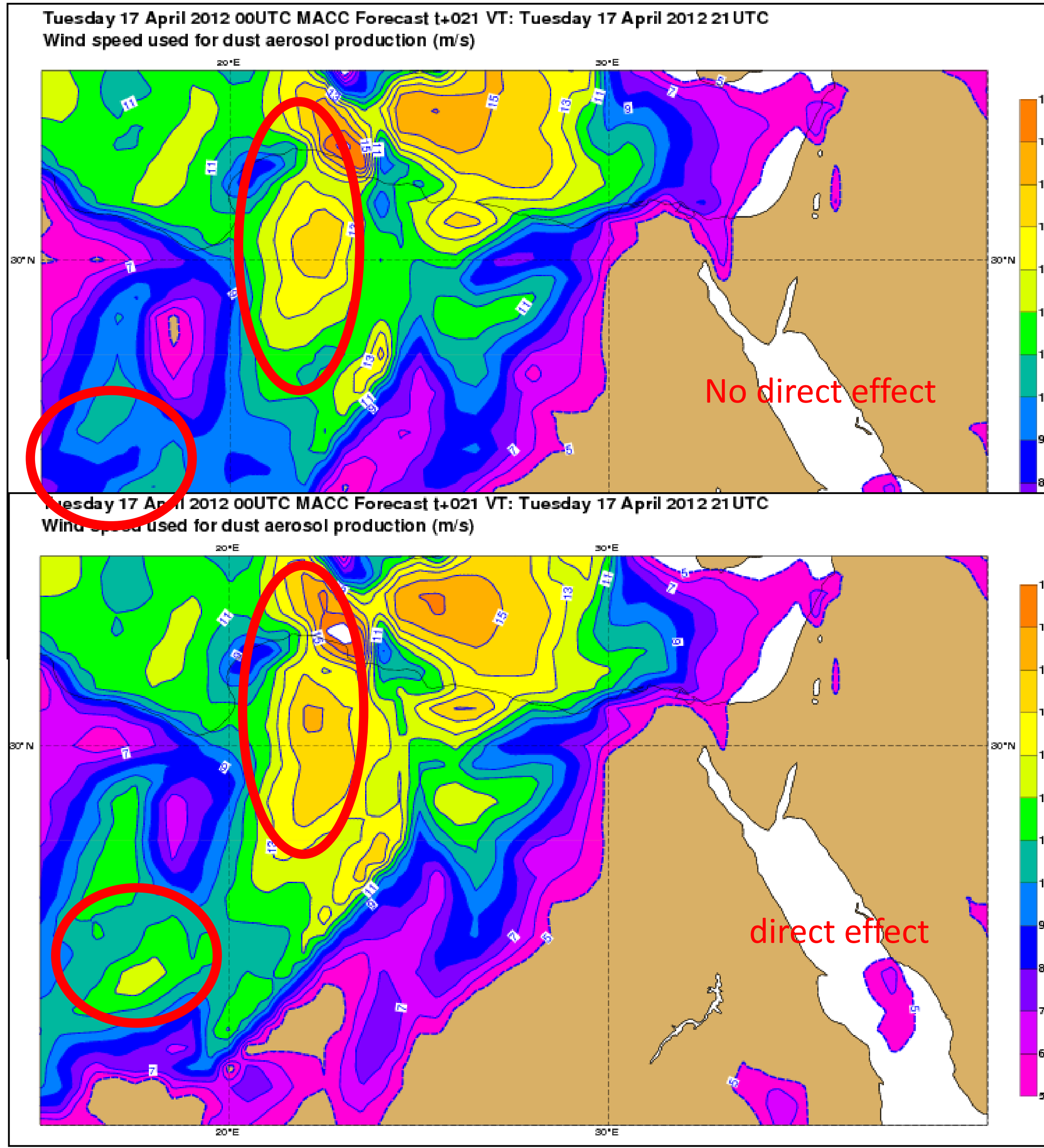
DIRECT:

- **Feedbacks decrease PBL, range [-80 : 0], highest decrease in August.**

Dust storm: Comparison of the aerosol sources

- **WMO WGNE study of aerosol impacts on NWP in an extreme dust event** 17/4/2012
- AODs are larger when taking into account the direct effect
- Because 10m wind speed is larger when taking into account the direct effect
- A small increase in 10m wind speed brings a large increase in dust aerosol production through saltation (power 3 dependency to 10m wind speed)

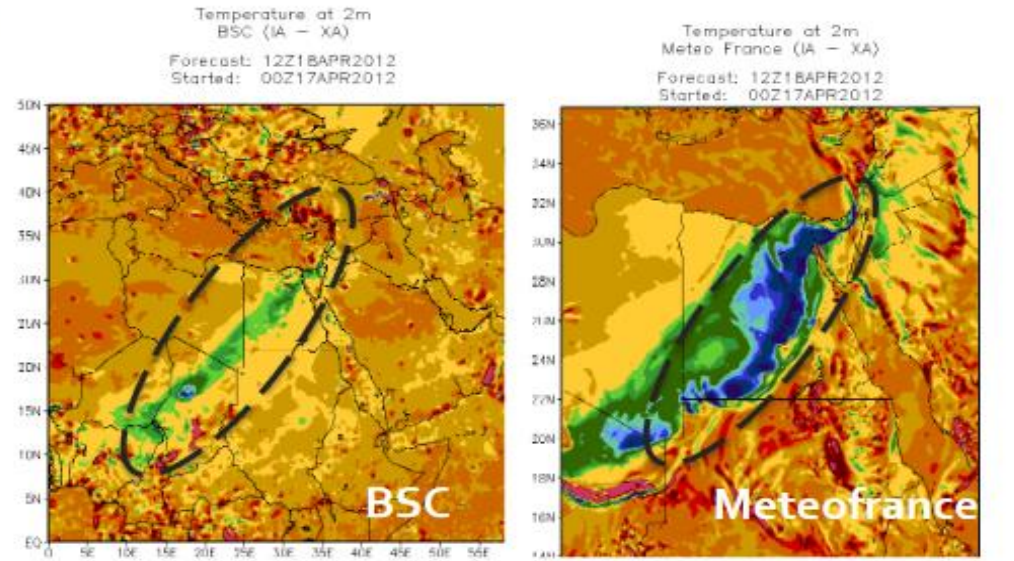
Courtesy of Samuel Rémy, Angela Benedetti, Miha Razinger, Luke Jones and Thomas Haiden



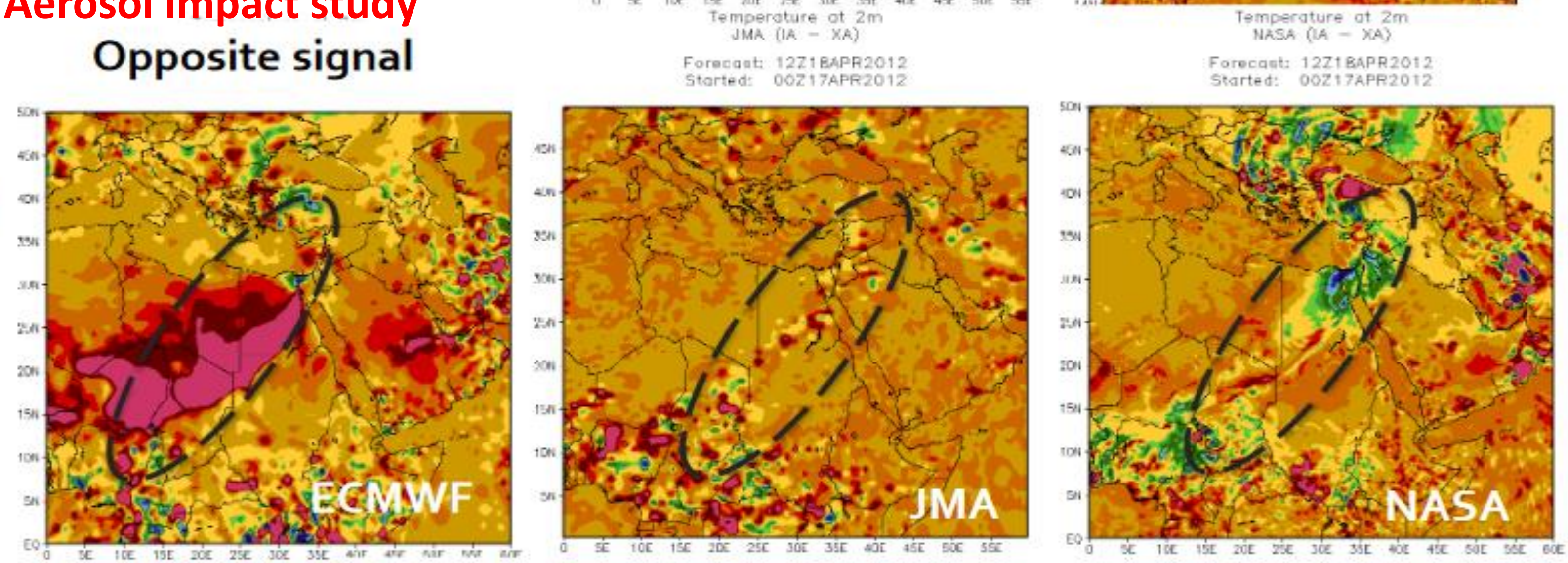
DIFF of Temp @ 2-m AER-NOAER

- 12 UTC (morning)
- Large discrepancies among centers

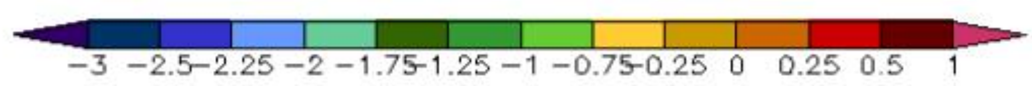
Welcome to join the 2nd phase of WGNE Aerosol impact study



Opposite signal



Location of the plume



Freitas et al., 2015

Online coupling for (i) NWP and MetM, (ii) AQ and CWF, (iii) Climate and Earth System modelling

- Relative importance of online integration and level of details necessary for representing different processes and feedbacks can greatly vary for these related communities.

- **NWP** might not depend on detailed chemical processes but considering the cloud and radiative effects of aerosols can be important for fog, visibility and precipitation forecasting, surface T, etc.

- For **climate modelling**, feedbacks from GHGs and aerosols become extremely important. However in some cases (e.g., for long-lived GHGs on global scale), fully online integration of full-scale chemistry is not critically needed. Still too expensive, so models need to be optimized and simplified.

- For **chemical weather forecasting and prediction of atmospheric composition**, the online integration definitely improves AQ and chemical atmospheric composition projections.

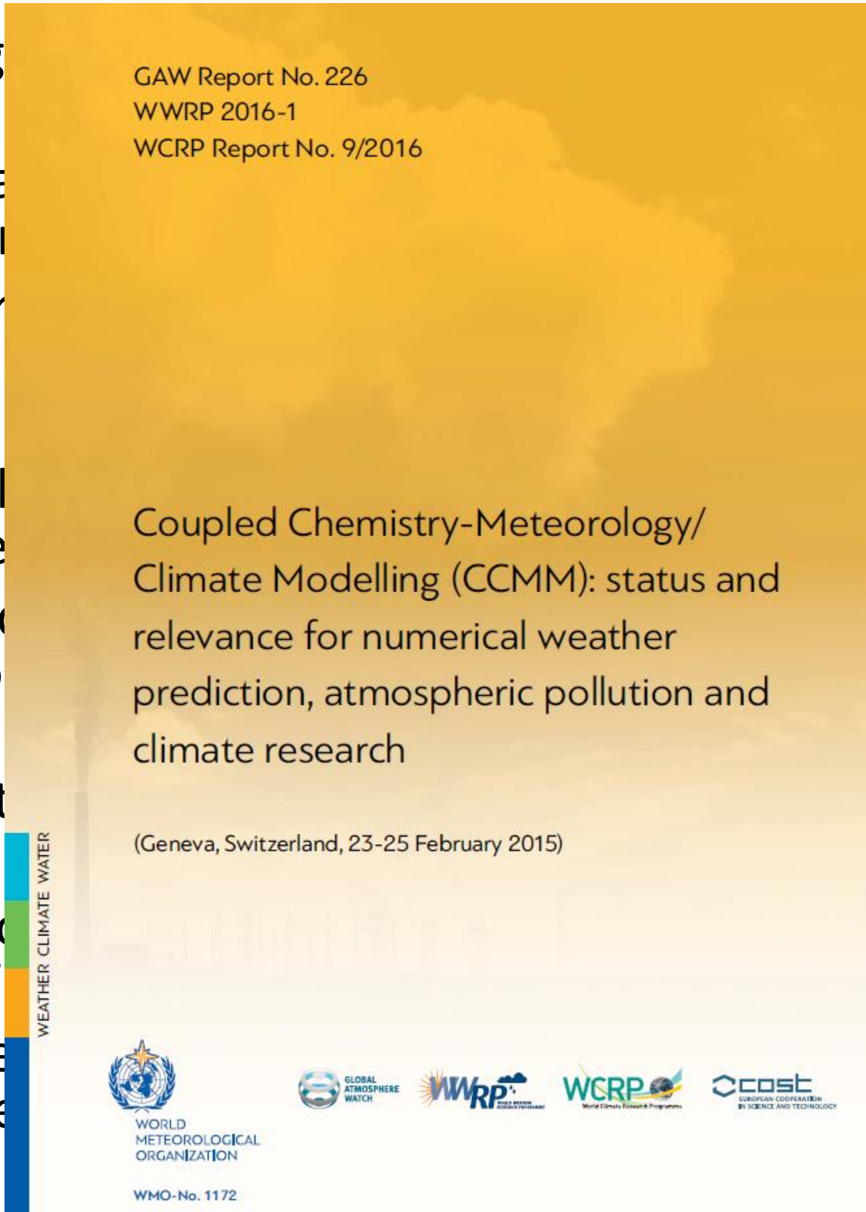
- **Main gaps**:
  - Understanding of several processes: aerosol-cloud interactions are poorly represented;
  - data assimilation in online models is still to be developed;
  - model evaluation for online models needs more (process) data and long-term measurements – and a test-bed.

WMO EUMetChem CCMM, 2016

CCMM key scientific questions:

https://library.wmo.int/doc_num.php?explnum_id=7938 and [Baklanov et al., BAMS, 2017]()

- What are the advantages of integrating chemical/aerosol processes in coupled
- How important are the two-way feedba meteorology, climate, and air quality si
- What are the effects of climate/meteor properties (chemical, microphysical, an urban/regional/global scales?
- What is our current understanding of cl well are radiative feedbacks represente
- What is the relative importance of the as well as of gas-aerosol interactions fo NWP, air quality, climate)?
- What are the key uncertainties associat feedback effects?
- How to realize chemical data assimilati improving NWP and air quality simulati
- How the simulated feedbacks can be ve observations/datasets? What are the re the three modelling communities?



GAW Report No. 226
WWRP 2016-1
WCRP Report No. 9/2016

Coupled Chemistry-Meteorology/Climate Modelling (CCMM): status and relevance for numerical weather prediction, atmospheric pollution and climate research

(Geneva, Switzerland, 23-25 February 2015)

WEATHER CLIMATE WATER

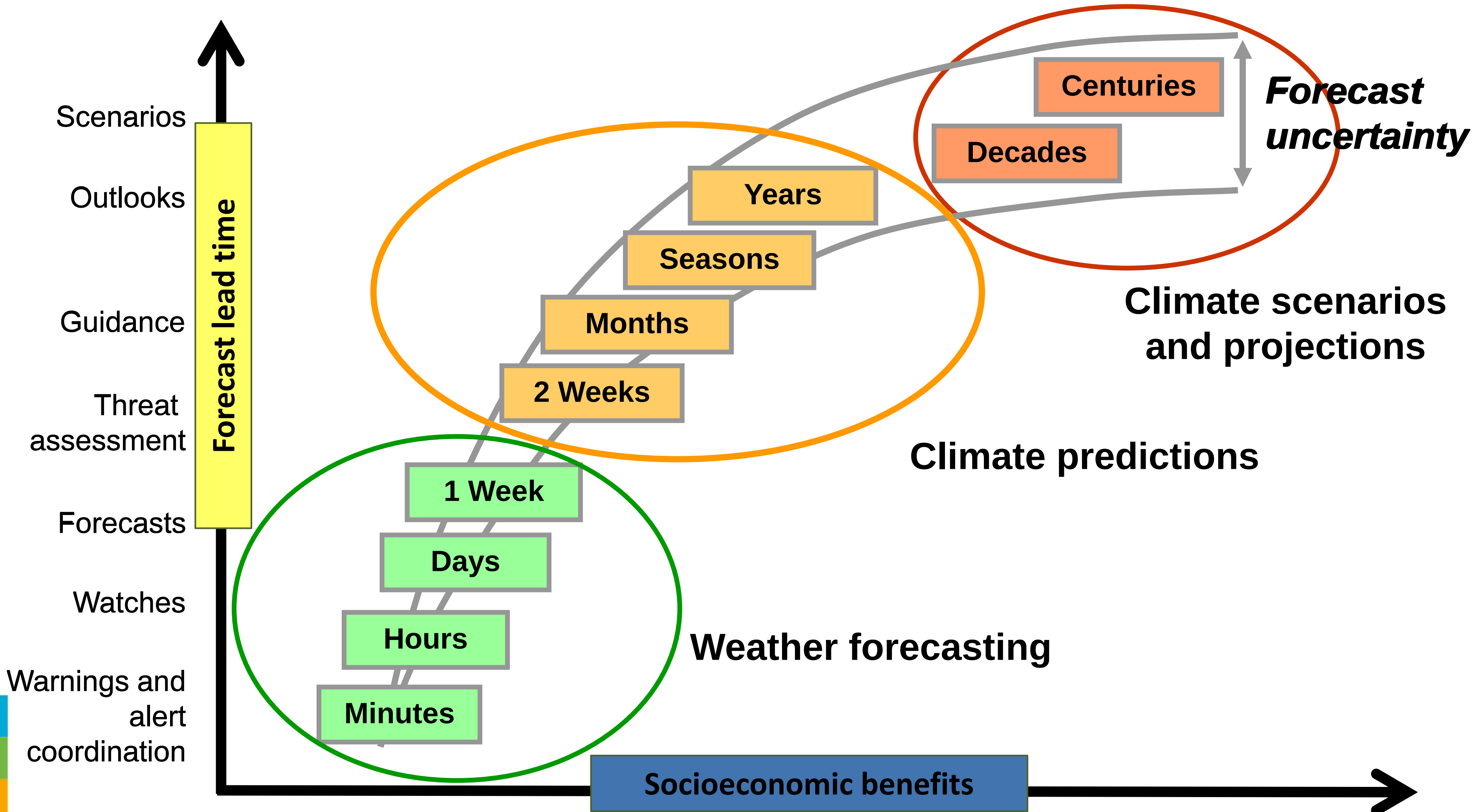
WORLD METEOROLOGICAL ORGANIZATION

WMO-No. 1172

(iii) Multi-scale prediction approach

- Monitoring, analysis and forecasting systems should operate at different spatial scale from the global scale to the regional, national, urban and sub-urban scales
- Zooming or special nesting grid techniques (e.g. WRF-Chem, COSMO-Art, EnvHIRLAM
- One-way nesting (sometimes referred to as downscaling), when values of the modelled variables at a coarse resolution are used as boundary conditions for finer (subscale) resolution runs.
- Two-way nesting, when information from the higher resolution scale is in addition transmitted across the boundaries to the coarser resolution
- Street level AQ the downscaling with microscale models (e.g., obstacle-resolved computational fluid dynamics (CFD) type or parameterized).
- Seamless unified modelling system on a single platform across-scales is a substantial advancement in both the science and efficiency (e.g. MPAS-A, MUSICA)
- Major challenges include globalization/ downscaling with consistent model physics and two-way nesting with mass conservation and consistency.
- Unified global-to-urban scale modelling provides a new scientific capability for studying problems that require a consideration of multi-scale feedbacks.

Weather-climate: seamless framework



Adapted from NOAA 2011

WMO OMM

(iv) Multi-platform observations and data assimilation (DA)

- **Meteorological and Chemical Concentration Observations**
  - **Surface networks**
  - **Upper air measurements (e.g., sounding)**
  - **Aircraft measurements**
  - **Satellite-Based Observations**

- **Data Assimilation Methods *– pioneering works of Marchuk, Penenko et al. for 3DVar, 4DVar***
  - **Meteorological data assimilation**
  - **Chemical data assimilation**
  - **Inverse modeling using data assimilation**
  - **Multiscale DA, challenges with urban DA**
  - **Combined chemical DA and ensemble forecasting**

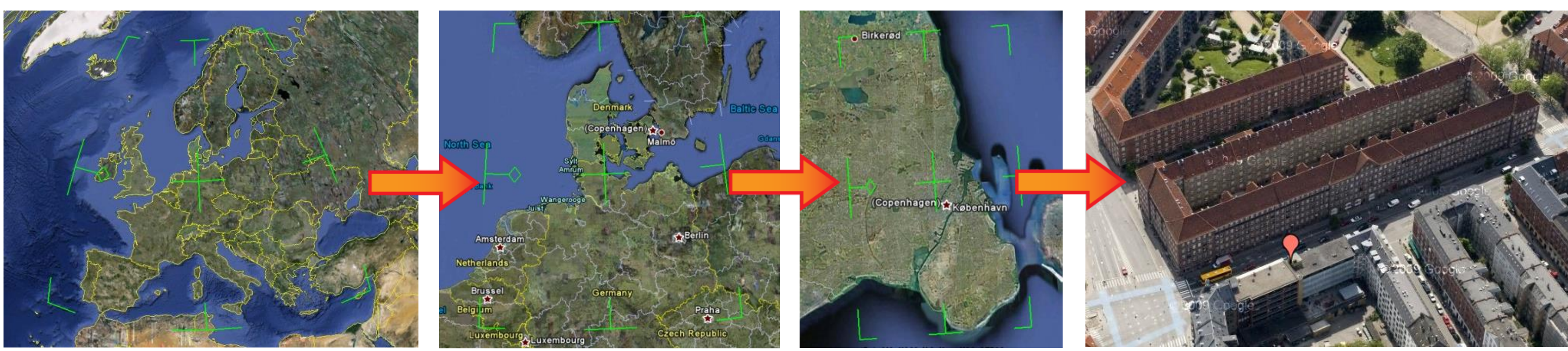
Overview by Bocquet et al., ACP, 2015

(v) Data fusion, machine learning methods and bias correction techniques

- Tremendously growing number and different types of observations became available now, require and give a strong impulse for development of new methods for measurement-model fusion to improve AQF
- Other than DA types of data fusion algorithms, such as the statistical methods, optimal interpolation, objective analysis, bias correction, as well as relatively new artificial intelligence, neural network, machine learning and hybrid methods, are actively developing
- Statistical methods are simple, but require a large amount of historical data and highly depend on them. Artificial intelligence, neural network and machine learning methods have better performance, but can be unstable and also depend on data.
- Hybrid or combined methods have a better quality. Such methods can also improve AQF utilising additional observational data.
- More advanced bias correction methods, e.g. the Kalman Filter (KF) and Kolmogorov-Zurbenko (KZ) filter technique.

Part 2: Urban cross-cutting focus and IUS

i. Why the urban focus?
ii. Urban meteorology and air pollution modelling and prediction;
iii. Urbanization of NWP, climate and AQ models;
iv. From urban NWP & UAQIFS to MHEWS;
v. Integrated Urban Hydrometeorology, Climate & Environment Systems;
vi. Integrated Urban Services (IUS) for sustainable cities.



CAMS/MACC regional domain (resolution - 20km) | Denmark-scale domain (3km) | City-scale domain (1km) | Street-scale selected domain (Jagtvej) (5m)

WMO OMM

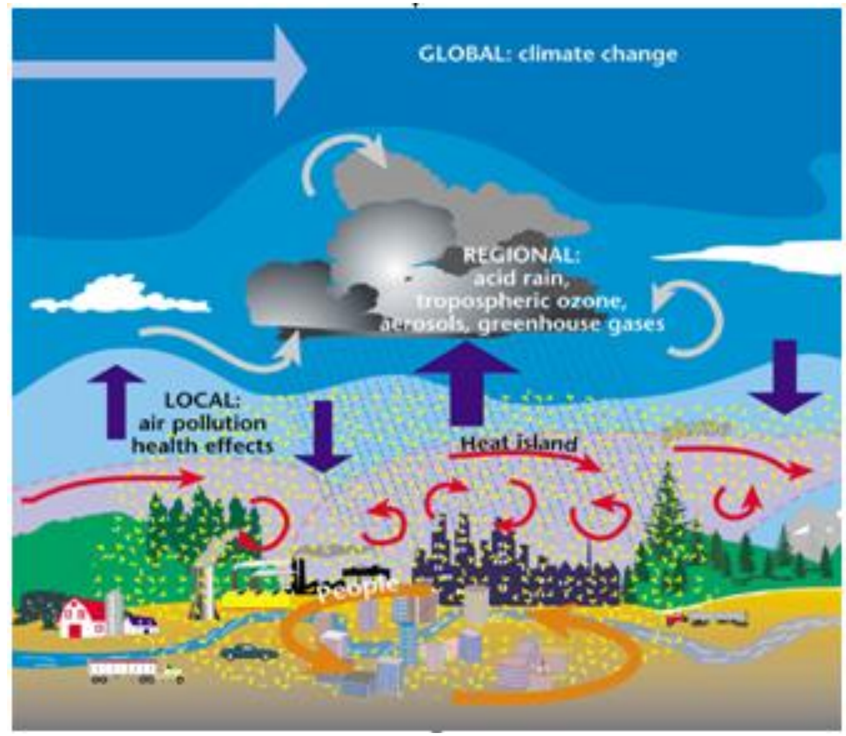
11 SUSTAINABLE CITIES AND COMMUNITIES

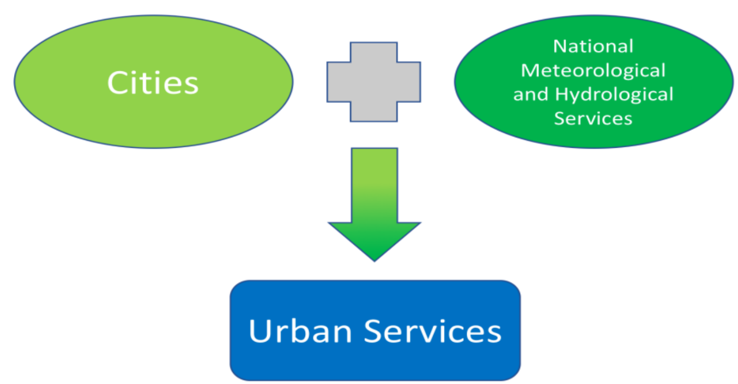
HABITAT III
QUITO - OCTOBER 2016

CITIES
2018·CONFERENCE
IPCC

Statement of the Problem

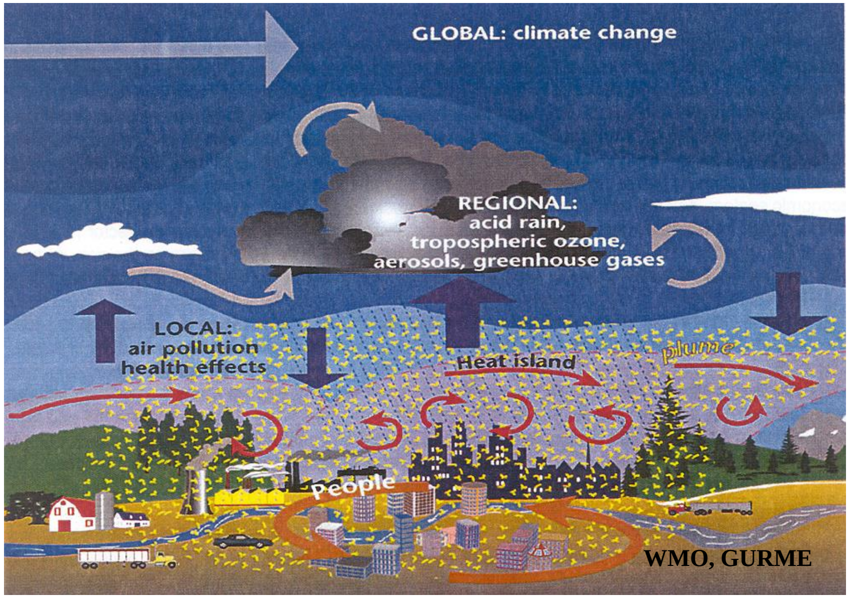
- 90% of disasters for urban areas are of hydro-meteorological nature
  - increased with climate change
- 70% of GHG emissions generated by cities
- Strong feedback
  - Two phases should not be considered separately
- Critical need to consider the problem in a complex manner with interactions of climate change and multi-hazard disaster risk reduction for urban areas
- Mitigations, adaptation, early warning
- Impact based prediction and solutions



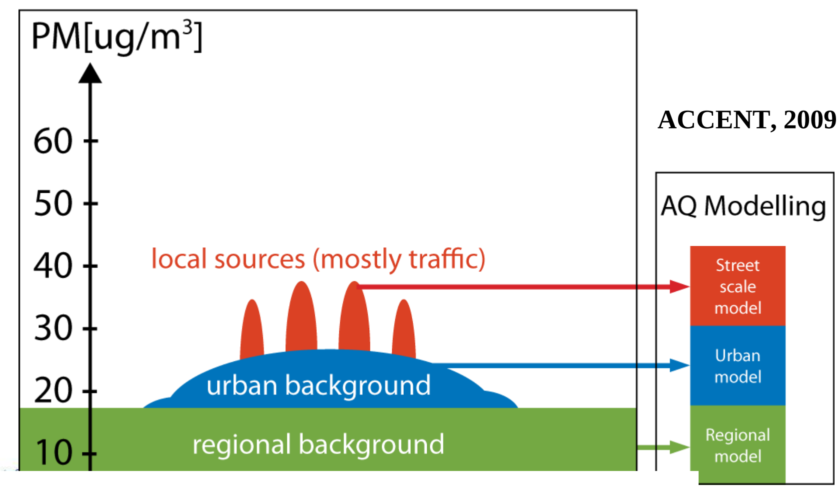


WMO OMM

Urban features in focus for UC, NWP and AQ models:



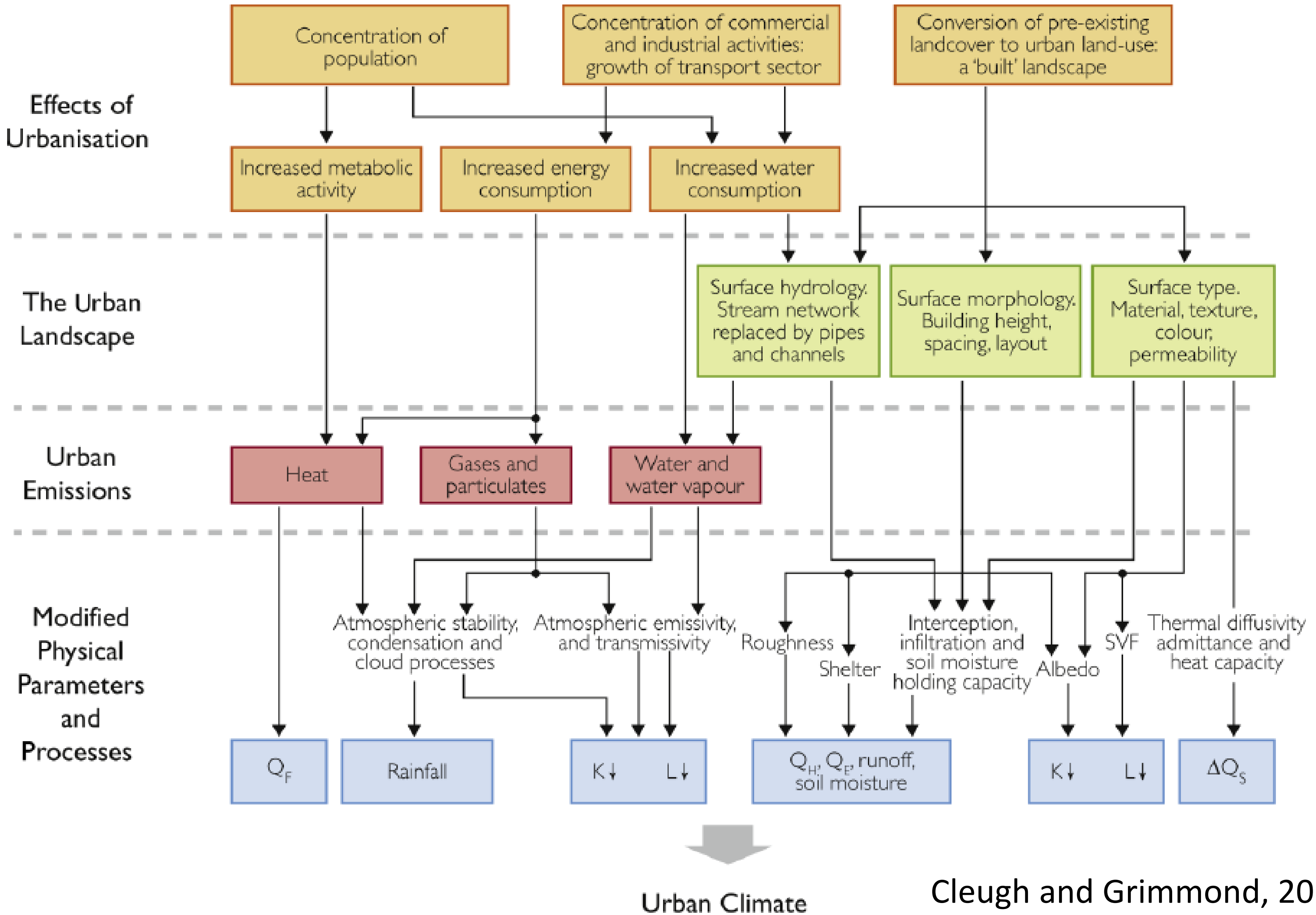
Why do cities have a different climate ?



…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.

Urban Atmospheric Processes



Cleugh and Grimmond, 2012

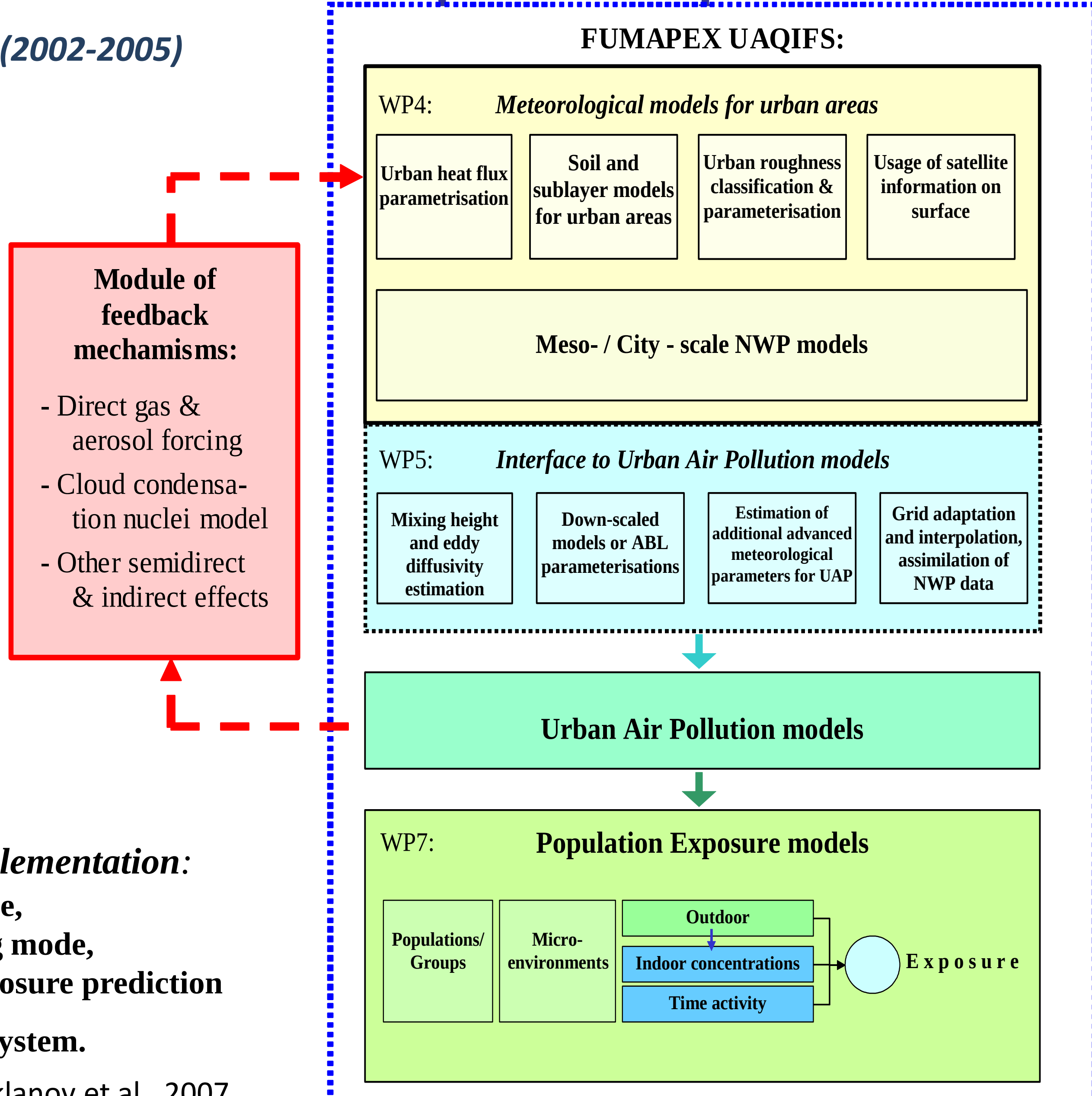
FUMAPEX: Integrated Systems for Forecasting Urban Meteorology, Air Pollution and Population Exposure

EU 5FP Project *(2002-2005)*

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

Urban AQ information and Forecasting systems (UAQIFS) are 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

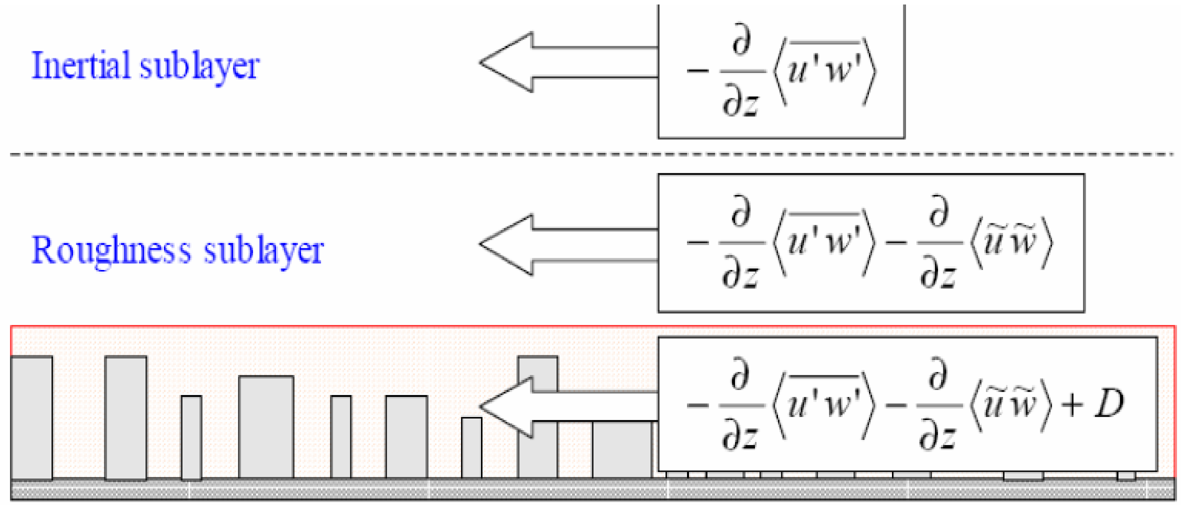


Different ways of the UAQIFS implementation:

(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.

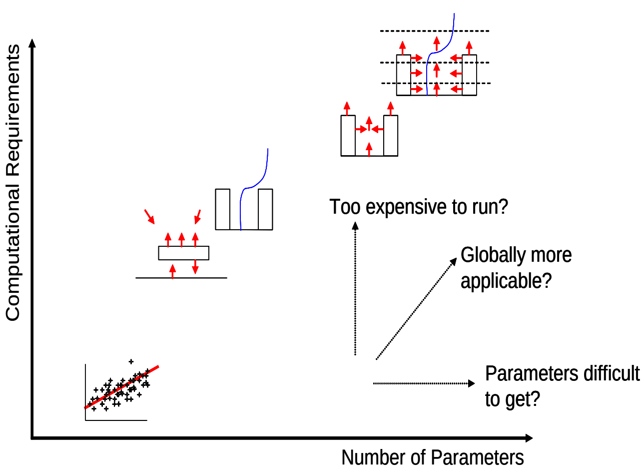
Baklanov et al., 2007

Strategy to urbanize different models



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

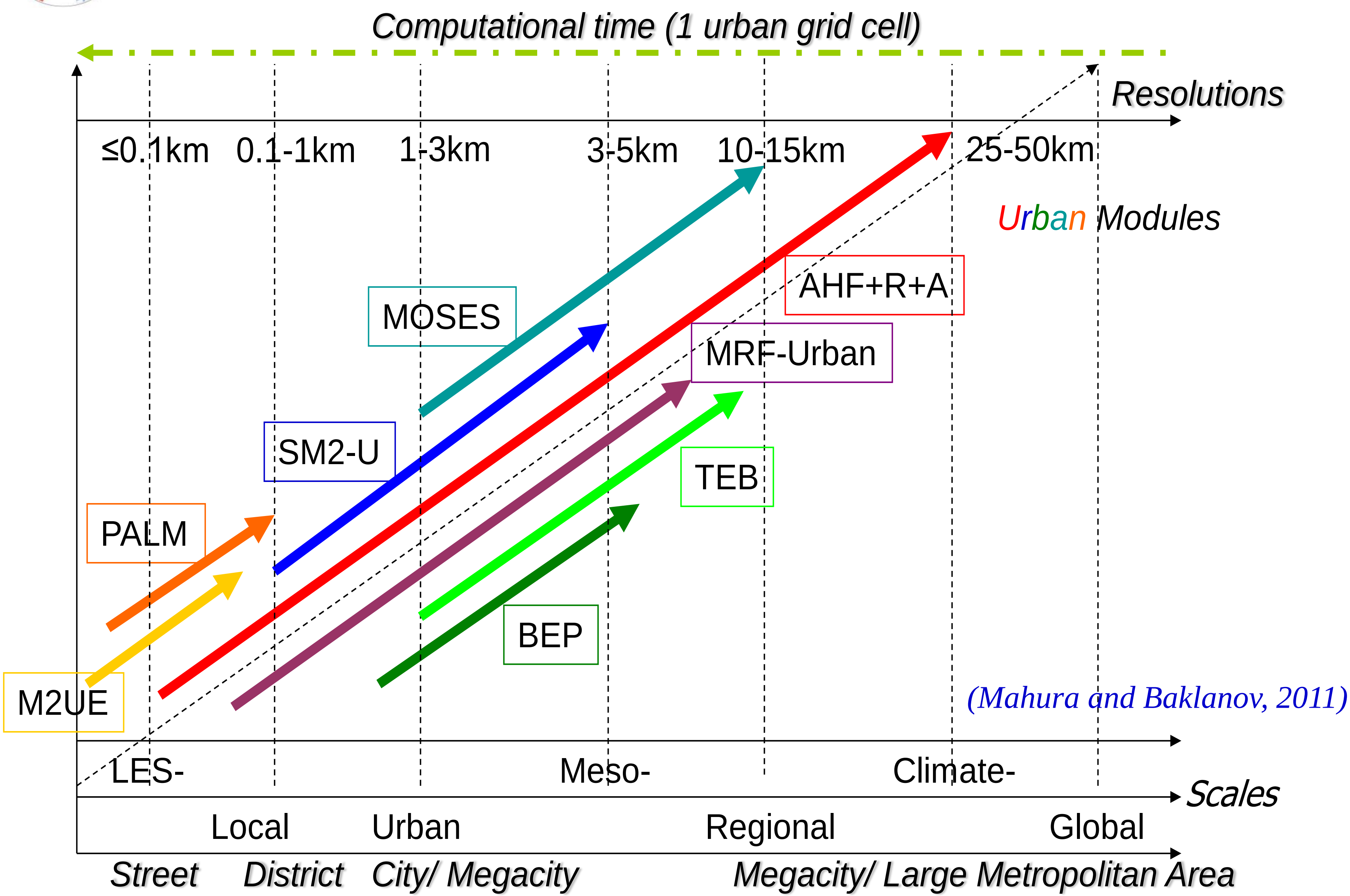
Testing with Different Urbanizations:



- 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)

Hierarchy of Urbanization Approaches

Urban canopy schemes for different type & scale models:

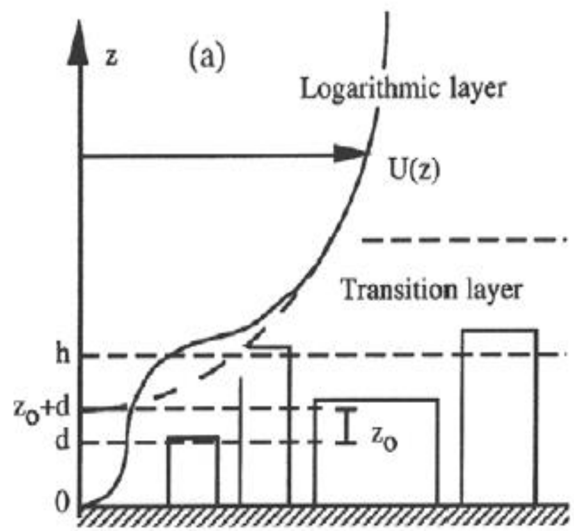


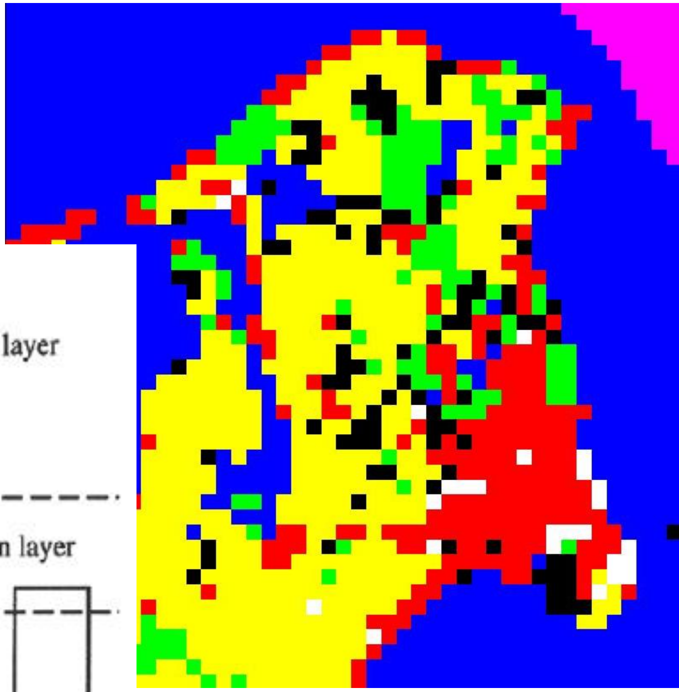
Urban Parameterisations for Enviro-HIRLAM

1. Regional to global scales: Anthropogenic Heat Flux & Roughness – AHF+R (Baklanov et al., 2008)
2. Meso & city-scale: BEP - Building Effects Parameterization (Martilli et al., 2002)
3. Research for city-scale: SM2-U - Soil Model for Submeso Scale Urban Version (Dupont et al., 2006ab)
4. Obstacle-resolved approach (downscaled M2UE model, Nuterman et al., 2008)

1. DMI urban parameterisation:

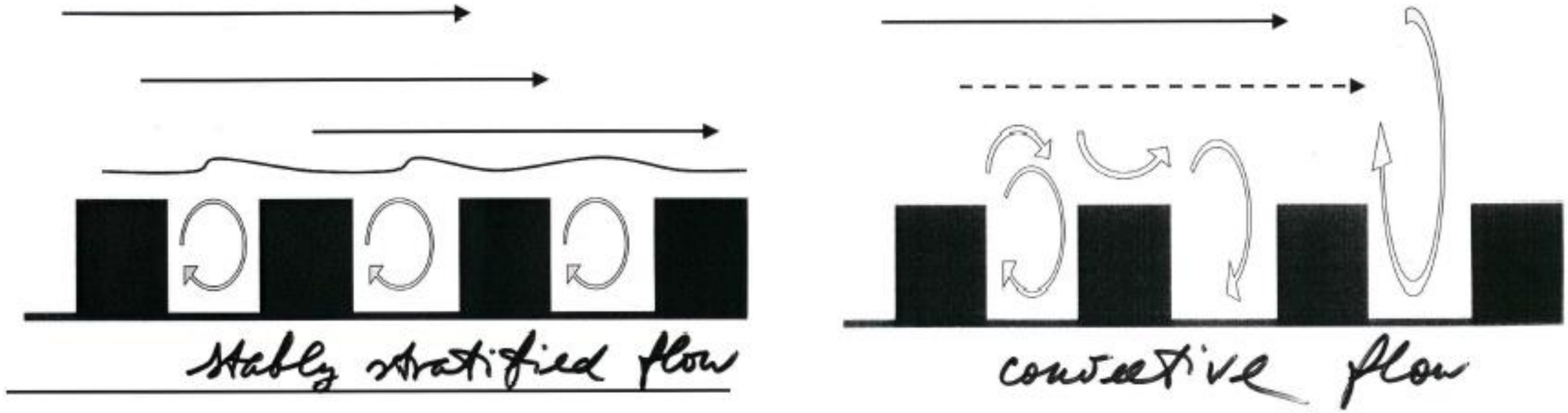
- Displacement height,
- Effective roughness and flux aggregation,
- Variation of building heights impact
- Effects of stratification on the roughness (Zilitinkevich et al., 2008),
- Different roughness for momentum, heat, and moisture;
- Calculation of anthropogenic and *storage* urban heat fluxes;
- Prognostic MH parameterisations for UBL (Zilitinkevich & Baklanov., 2002);
- Parameterisation of wind and eddy profiles in canopy layer.





(Baklanov et al., 2008, 2017; Mahura et al., 2007)

Stability Dependence of Roughness Length



For urban and vegetation canopies with roughness-element heights (20-50 m) comparable with the Monin-Obukhov turbulent length scale, *L,* the surface resistance and roughness length depend on stratification

Neutral ⇔ stable

$$\frac{z_{0u}}{z_0} = \frac{1}{1 + C_{SS} h_0 / L}$$

Neutral ⇔ unstable

$$\frac{z_{0u}}{z_0} = 1 + C_{US} \left(\frac{h_0}{-L} \right)^{1/3}$$

Constants: $C_{SS} = 8.13 \pm 0.21$, $C_{US} = 1.24 \pm 0.05$

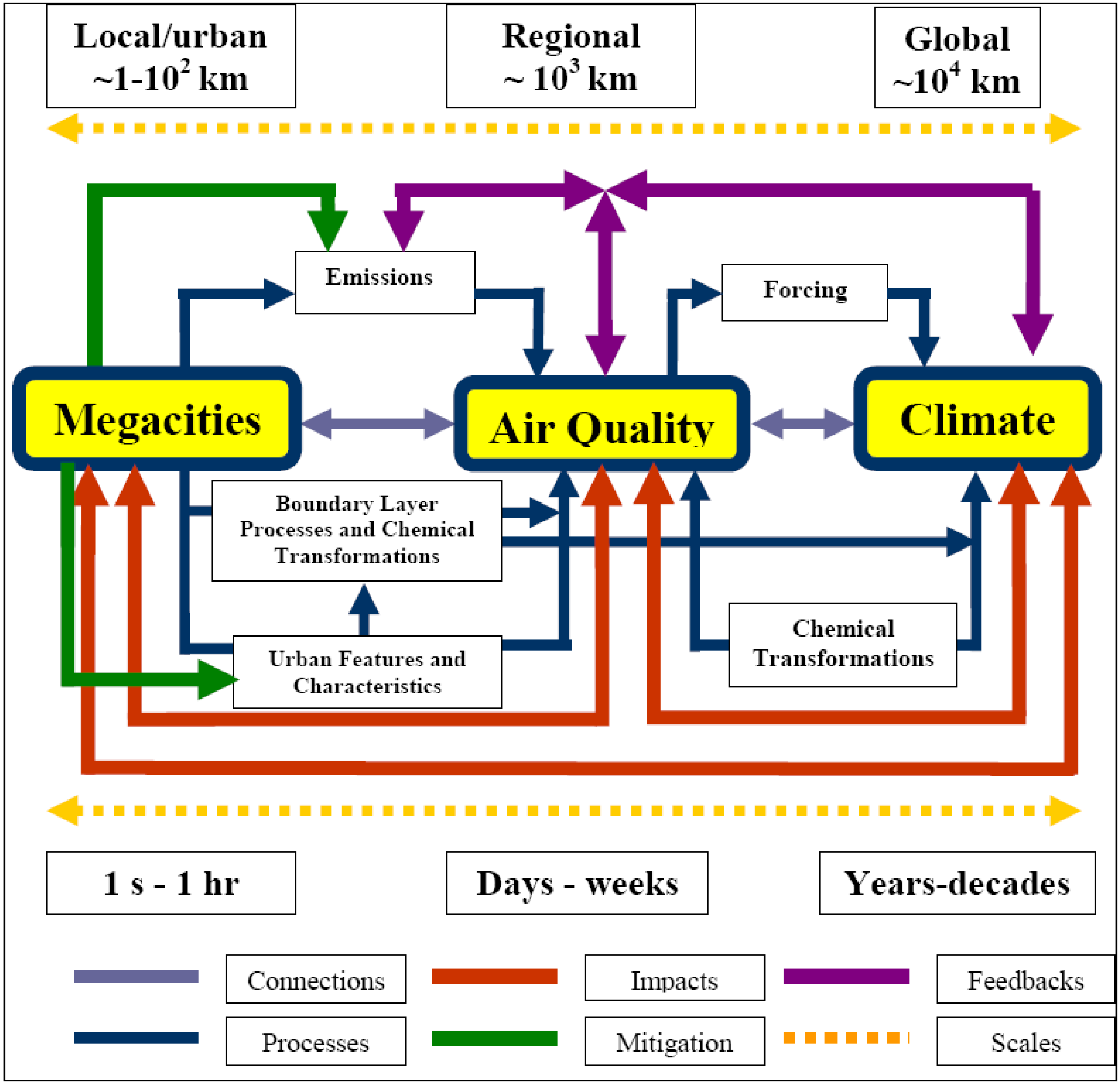
WMO OMM

Zilitinkevich, Mammarella, Baklanov, Joffre, BLM, 2008

Connections between Megacities, AQ, Weather and Climate

main feedbacks, ecosystem, health & weather impact pathways, mitigation

- Science - nonlinear interactions and feedbacks between 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

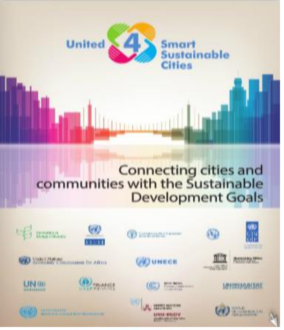


Nature, 455, 142-143 (2008)
Baklanov et al., 2010, AE 2016
Web-site: megapoli.info

Hazards and Risks in the Urban Environment

- Poor air quality and peak pollution episodes
- Extreme heat/cold and human thermal stress
- Hurricanes, typhoons, extreme local winds
- Wild fires, sand and dust storms
- Urban floods
- Sea-level rise due to climate change
- Energy and water sustainability
- Public health problems caused by the previous
- Climate change: urban emissions of GHG
- **Domino effect:** a single extreme event can lead to new hazards and a broad breakdown of a city's infrastructure

WMO OMM



Climate smart and sustainable cities

Resilient

Sustainable

Multi-Hazard Early Warning Systems for Weather, Hydrology, Air Quality at Urban Scales

Long Term Planning
Climate Services for Weather, Hydrology and Air Quality at Urban Scales

World Meteorological Organization
Weather • Climate • Water

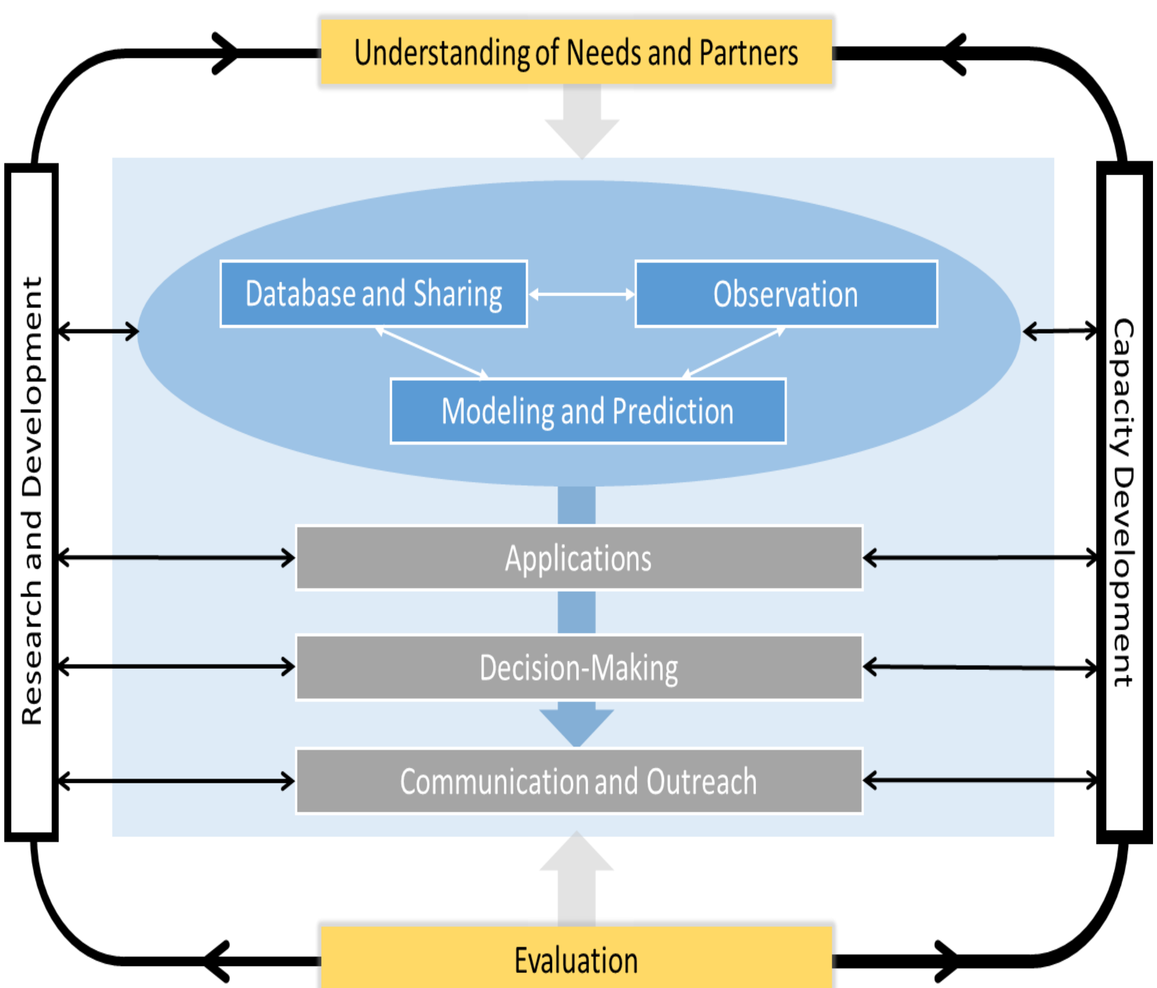
Goal: Science-based Integrated Urban Hydro-Meteorological, Climate and Environmental Services (IUS)

Benefits of IUS - Useful, Usable, Used

1. Resiliency through Multi-Hazard Early Warning Systems
2. Sustainability through urban long term planning
3. Capability and capacity through cross-cutting services
4. Efficiency through infrastructure cross-cutting services
5. Consistency (hence, effective and efficient) through integration
6. Effective service through Partnerships / Risk Communication

WMO OMM

Components of the development an Integrated Urban Weather, Environment and Climate Service (IUS)



UIS focuses on improving and integrating the following main elements and sub-systems:

- **Weather** (especially high impact weather prediction at the urban scale),
- **Climate** (urban climate, climate extremes, sector specific climate indices, climate projections, climate risk management and adaptation),
- **Hydrology** and water related hazards (flash river floods, heavy precipitation, river water stage, inundation areas, storm tides, sea level rise, urban hydrology),
- **Air quality** (urban air quality and other larger scale hazards: dust storms, wildfires smog, etc.)

WMO OMM

IUS Guidance: Volume I: Concept and Methodology; adopted by 70th WMO Executive Council
Volume II: Demonstration Cities; adopted by 71st WMO Executive Council

Mexico City

air pollution, hydrometeorological hazards, heatwaves, associated health and geophysical risks (e.g. flooding, landslides, wildfires)

Paris

heatwaves, river flooding, air quality

Toronto

extreme rainfall (convective weather), strong winds, thermal stress (heat/cold waves), air quality episodes, lake/river flooding

Hong Kong

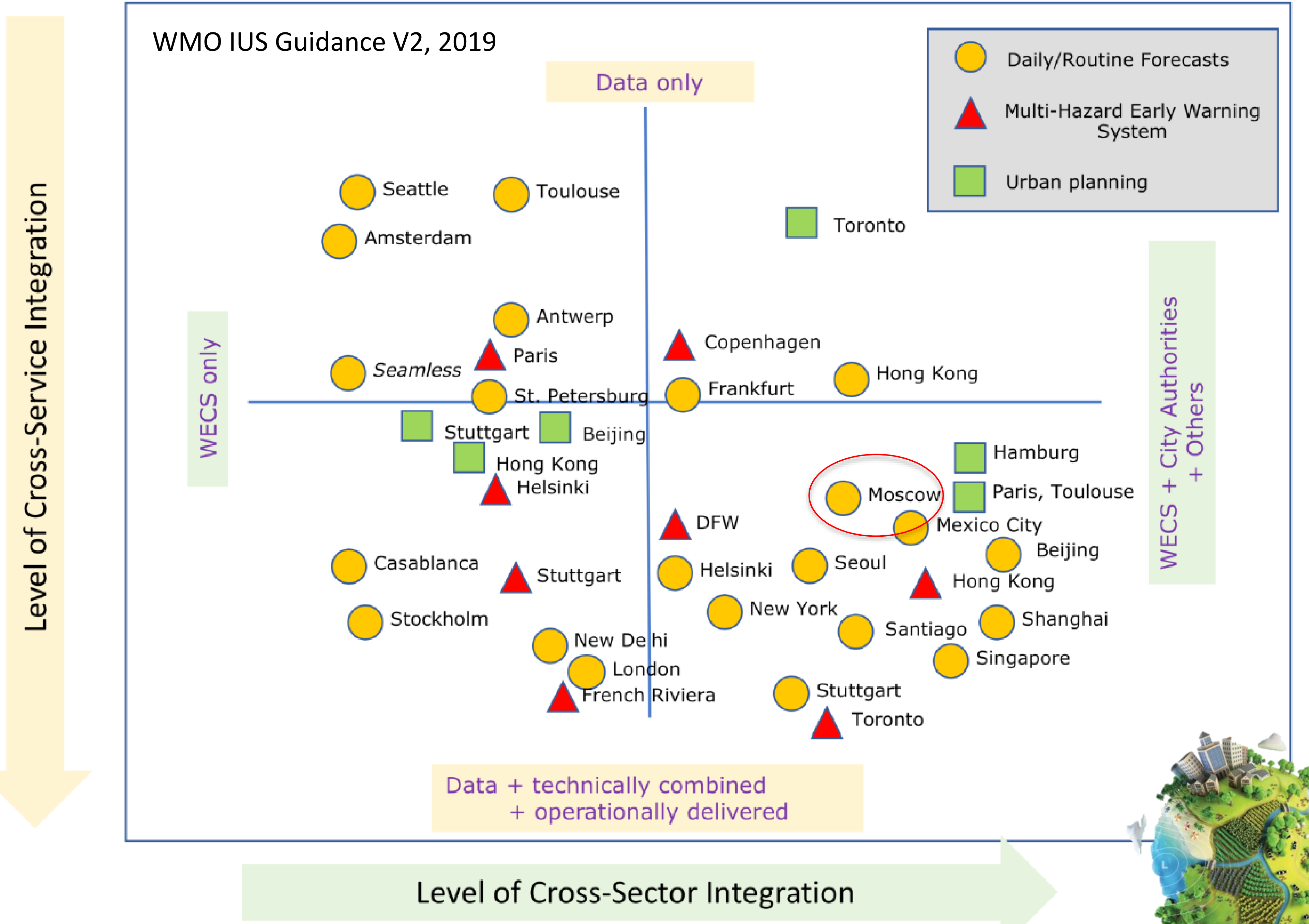
tropical cyclones, convective weather events, extreme temperatures, coastal inundation and flooding, water scarcity, air pollution

* CityIPCC 4 cities case studies (*Baklanov et al., 2020*)

* IUS Guidance Vol. II: 87 countries analyzed, 30 demonstration cities (*WMO, 2019*)

Examples of Integrated Urban Service Realisation

Demonstration Cities assessed by the UET, based on data provided



Moscow as a Demonstration City for Integrated Urban Services (IUS)

- **WMO GURME Pilot Project for Moscow (2004):**

МЕТЕОРОЛОГИЧЕСКОЕ ОБЕСПЕЧЕНИЕ УСТОЙЧИВОГО РАЗВИТИЯ МОСКОВСКОГО МЕГАПОЛИСА

- Демонстрационный проект, посвященный измерениям и моделированию связей между погодой, качеством воздуха и климатом для окружающей среды Москвы.

- **EU FP7 MEGAPOLI & RF MEGAPOLIS projects (2008-11):**

Megacities: Emissions, urban, regional and Global Atmospheric POLlution and climate effects, and Integrated tools for assessment and mitigation

- Цель российского проекта «Мегаполис» – разработка технологии комплексного анализа временных серий наземных данных для оценки состояния и динамики изменения атмосферы и окружающей среды в крупных городах (Москва).

- **Moscow Goverment & Hydromet project of Moscow AQF in collaboration with WMO GURME (2019):**

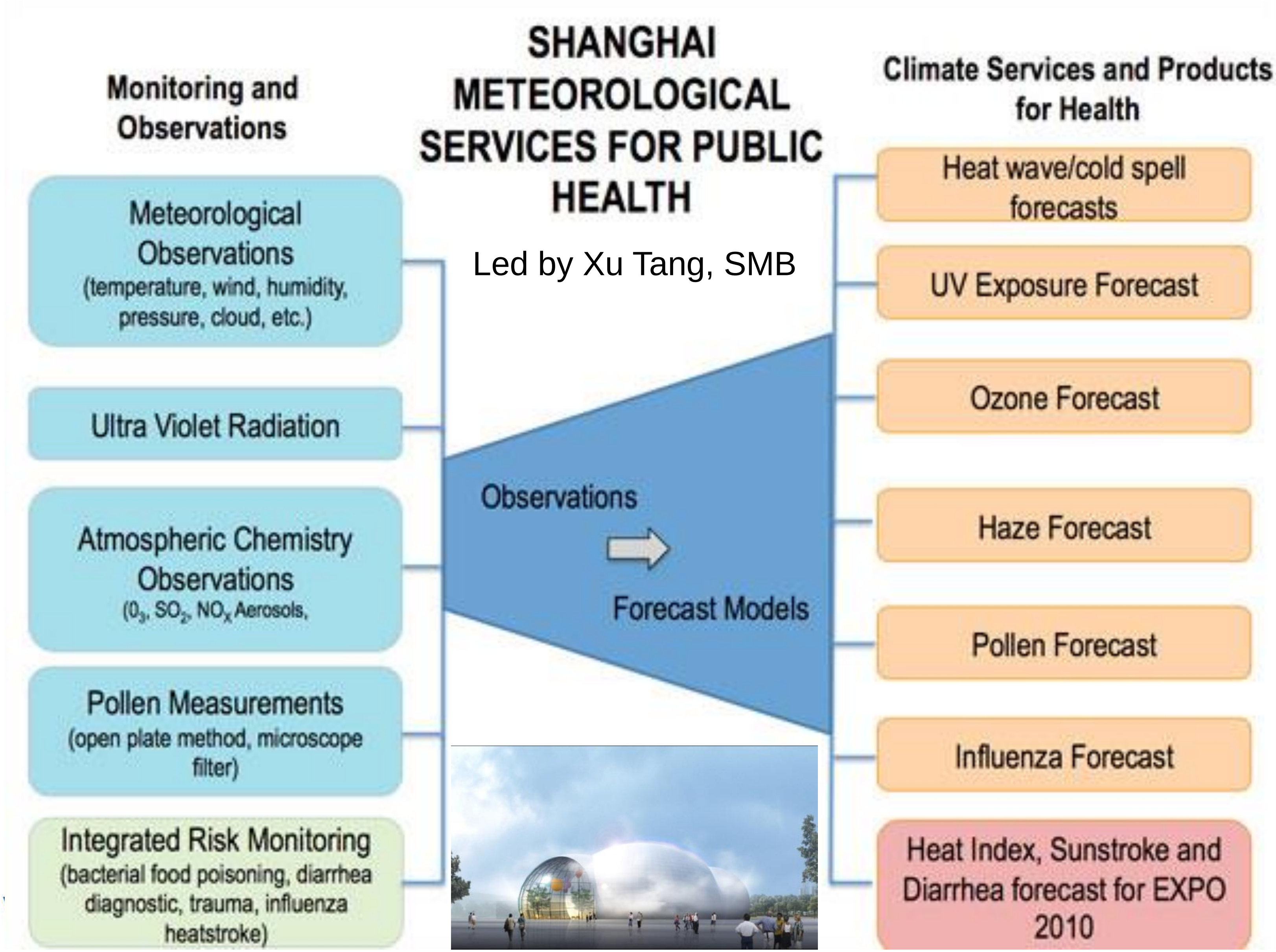
- Innovative operational high resolution air pollution forecasting system for Moscow.

- **Moscow is considered as a Demonstration IUS Project for smart city** (initial MoU signed)

WMO OMM

GURME
The WMO GAW Urban Research Meteorology and Environment Project

GURME Pilot Project part of Shanghai Multi-Hazard Early Warning System (MHEWS) (by SMB/CMA)



Led by Xu Tang, SMB

Hong Kong Local Experiences on IUS

Urban Integrated Services and Urban Design, Planning and Construction

Extreme Weather Events (HKO)
- Tropical cyclone and storm surge
- Thunderstorm and lightning
- Rainstorm, flooding and landslide
- Extreme hot & cold weather events
- Drought

Air quality modeling and forecast (EPD)
- Air Quality Health Index

Utilization of climate information (HKO)
- Climate change
- Disaster risk reduction (DRR)
- Urban climate evaluation

Evaluation
(Some examples)
- Wind load on buildings and infrastructures
- Coastal structure design
- Drainage system and slope safety
- Lightning safety
- Thermal comfort and health impact
- Energy demand / saving
- Water resources
- High air pollution area detection
- City resilience and disaster preparedness
- Urban heat island
- Air Ventilation Assessment (AVA)

Examples of Urban Planning & Infrastructure Construction
- Design standard and code of practices for buildings and infrastructures (e.g. "Building Wind Code", Drainage Master Plan, Port Work Design Manual, etc.)
- Mitigation measures to natural terrain landslides
- Drainage tunnels and Underground Stormwater Storage Tanks
- Blue-Green infrastructure
- Total water management strategy
- Climate change mitigation and adaptation measures
- Road networking design and urban density control
- Implementation of AVA and Urban Climatic Map into planning of new development and old district renewal

HKO - Hong Kong Observatory

EPD - Environmental Protection Department

* WMO Urban Expert Team

for the WMO Urban Guidance (GIUS) is vailable on:

Volume I: Concept and Methodology; adopted by the 70th WMO Executive Council

Volume II: Demonstration Cities; adopted by the 71st WMO Executive Council

WEATHER CLIMATE WATER
TEMPS CLIMAT EAU

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Open scientific questions relevant to development of Integrated Urban Services

- Understanding how to take and use of observations in urban areas
- Representation of urban character in models
- Urban atmosphere scales requirements, coupling with hydrology
- Impact of cities on weather/climate/water/environment
- Impact of changing climate on cities and adaptation strategy
- Major geophysical hazards – dust storms/earthquakes/volcanic eruptions/space weather - interactions with meteorology
- Development of Integrated Decision Support Systems
- Communication and management of risk, multidisciplinarity
- Evaluation of integrated systems and services
- Understanding of the critical limit values
- New, targeted and customized delivery platforms

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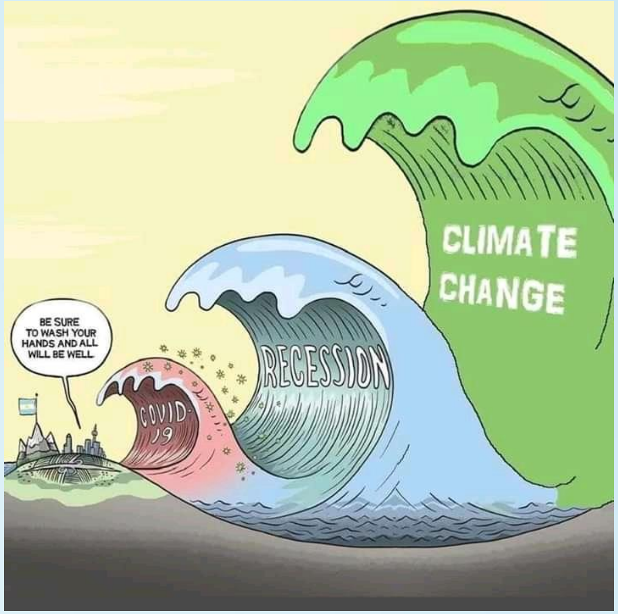
Thank you

Gracias

Merci

Спасибо

谢谢



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WMO OMM

World Meteorological Organization
Organisation météorologique mondiale

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