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We are entering a new era in technological innovation and in use and integration of different sources of information for improving well-being and the ability to cope with multi-hazards. New predictive tools able to detail weather conditions to neighbourhood level, to provide early warnings a month ahead, and to forecast weather-related impacts such as flooding and energy consumption will be the main outcomes of the next ten years research activities in weather science. A better understanding of small-scale processes and their inherent predictability should go together with a better comprehension of how weather-related information influences decisional processes and with better strategies for communicating this information. Within this perspective, this book is intended to be a valuable resource for anyone dealing with environmental prediction matters, providing new perspectives for planning and guiding future research programmes.

For more information, please contact:

World Meteorological Organization

7 bis, avenue de la Paix – P.O. Box 2300 – CH 1211 Geneva 2 – Switzerland

Communications and Public Affairs Office

Tel.: +41 (0) 22 730 83 14/15 – Fax: +41 (0) 22 730 80 27

E-mail: cpa@wmo.int

www.wmo.int

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**World
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Weather · Climate · Water

WMO-No. 1156



SEAMLESS PREDICTION OF THE EARTH SYSTEM: FROM MINUTES TO MONTHS

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$$\frac{\partial q}{\partial t} + J(\psi, q) + \beta \frac{\partial \psi}{\partial x} = 0$$

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Chairperson, Publications Board
World Meteorological Organization (WMO)
7 bis, avenue de la Paix
P.O. Box 2300
CH-1211 Geneva 2, Switzerland

Tel.: +41 (0) 22 730 84 03
Fax: +41 (0) 22 730 80 40
E-mail: publications@wmo.int

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FOREWORD

The World Meteorological Organization (WMO) has always attached great importance to the global coordination of research efforts required to develop and improve weather, climate, water and related environmental services. In this regard, the World Weather Research Programme (WWRP) has made significant contributions relating to high-impact weather systems such as tropical cyclones, in particular to the application by Members of research results aimed at further improving not only early warning systems for extreme events but also reducing the damaging effects of natural weather hazards. WMO has taken the lead and co-organized the World Weather Open Science Conference (Montréal, Canada, 16-21 August 2014), the first-of-a kind event bringing together a diverse community in order to foster the science needed to make society less vulnerable to weather-related impacts.

This conference has brought together the entire weather science and user communities for the first time to review the state-of-the-art and map out the scientific frontiers for the next decade and more. The outcomes of the debates and discussions have been synthesized in this book through a peer-reviewed process.

We are entering a new era in technological innovation and in use and integration of different sources of information for the wellbeing of society and their ability to cope with multi-hazards. New predictive tools that will detail weather conditions down to neighbourhood and street level, and provide early warnings a month ahead, and forecasts from rainfall to energy consumption will be some of the main outcome of the research activities in weather science over the next decade. A better understanding of small-scale processes and their inherent predictability should go together with a better comprehension of how weather related information influence decisional processes and with a better communication strategy.

I wish to take this opportunity to sincerely thank the members of the International and Local Organizing Committees, the chairs, rapporteurs, participants and all those who assisted in the preparation of this book, for their valuable collaboration.

Finally, I would like to thank the host country, Canada, and to express my appreciation to the other sponsors for providing supplementary support. I hope that this book will serve as a useful source of information and inspiration as well as a road map for weather research worldwide in the years to come.



(M. Jarraud)
Secretary-General

PREFACE

New sources of atmospheric observations, faster supercomputers and advances in weather science together have revolutionized weather forecasting in the latter part of the 20th century. On the global scale, we can today predict out to six days ahead as accurately as we could do for four days 20 years ago. This means society has much more advance warning of weather hazards than before, allowing people to prepare and, thereby, limit the loss of lives and property.

As weather science advances, critical questions are arising such as about the possible sources of predictability on weekly, monthly and longer time-scales; seamless prediction; the development and application of new observing systems; the effective utilization of massively-parallel supercomputers; the communication, interpretation, and application of weather-related information; and the quantification of the societal impacts. The science is primed for a step forward informed by the realization that there can be predictive power on all space and time-scales arising from currently poorly-understood sources of potential predictability.

Consequently the time was right in 2014 for a major Open Science Conference to examine the rapidly changing scientific and socio-economic drivers of weather science. This conference was designed to draw the whole research community together to review the frontiers of knowledge and to act as an international stimulus for the science and its future. The first World Weather Open Science Conference (WWOSC-2014 “The weather: what’s the outlook?”) was held in Montréal, Canada from 16 to 21 August 2014.

WWOSC-2014 was designed to consider both the state-of-the-art and imagine the future evolution of weather science and also the related environmental services and how these need to be supported by research. The timing of the conference was also chosen to coincide with the end of the ten-year THORPEX programme of the World Weather Research Programme, enabling the knowledge arising from that initiative to be synthesised. It was particularly exciting to bring together the international community - those starting out in science and those with longer experience - to review progress and set the long-term agenda. There has never been a more important time for weather science, which is poised for further breakthroughs. Society is extremely vulnerable to weather-related impacts and desperately needs that science

The research presented at WWOSC-2014 reviewed the state of knowledge in weather and weather-prediction science. In addition it explored the many applications of weather prediction to the natural environment. The Earth System Prediction approach for weather and environmental phenomena is seen as an effective way to better address the rapidly changing and increasing socio-economic requirements for weather services. A new generation of research scientists attended the conference and will contribute to new and advanced Earth system prediction models. WWOSC-2014 raised the visibility and importance of a strong and vibrant world weather science research activity, in harmony with the needs of operational weather services and their stakeholders, in the public and the private sectors.

This book collects together White Papers that have been written to describe the state of the science and to discuss the major challenges for making further advances. The authors of each chapter have attempted to draw together key aspects of the science that was presented at WWOSC-2014. The overarching theme of this book and of WWOSC-2014 is “Seamless Prediction of the Earth System: from minutes to months”. The book is structured with chapters that address topics regarding: Observations and Data Assimilation; Predictability and Processes; Numerical Prediction of the Earth System; Weather-related Hazards and Impacts. This book marks a point in time and the knowledge that has been accumulating on weather science. It aims to point the way to future developments. We hope it will be of great interest to researchers and practitioners alike. We also hope that it stimulates and excites the next generation of weather scientists. Finally, we would like to thank the authors who have contributed so much in creating this volume.

Michel Béland
(past-President of the Commission
for Atmospheric Sciences)

Alan Thorpe
(Director-General of ECMWF)

CHAPTER 12. SEAMLESS METEOROLOGY-COMPOSITION MODELS: CHALLENGES, GAPS, NEEDS AND FUTURE DIRECTIONS

Alexander Baklanov, Véronique Bouchet, Bernhard Vogel, Virginie Marécal, Angela Benedetti and K. Heinke Schlünzen

Abstract

Aiming at eventually migrating from separate meteorology and chemistry-transport modelling systems to seamless meteorology-composition-chemistry models (SMCM) has several advantages: It allows the consideration of two-way interactions (i.e. feedbacks), the consistent treatment of, e.g. water vapour in chemistry and meteorology, and ensures synergies in research, development, maintenance and application. This paper offers a review of the current research status of seamless meteorology and atmospheric chemistry modelling (or seamless meteorology-composition models (SMCM) for short) and recommendations to evolve from separate to seamless meteorology-composition models to address limitations in weather, climate and atmospheric composition fields whose interests, applications and challenges are now overlapping. SMCMS describe the relevant processes to investigate long-standing scientific questions on the interactions between atmospheric constituents and atmospheric processes and support the creation of new environmental prediction services. “Seamless” is introduced in the paper in relation to two aspects: 1) at the process-scale where it refers to the coupling within a model of meteorology and composition processes to represent for example the two-way interactions between composition and radiative processes or microphysics, or the consistent treatment of water vapour; and, 2) in terms time and space where it refers to the absence of discontinuities in model behaviour when used at multiple temporal or spatial resolutions to have for example consistent treatment of black carbon for air quality and climate applications. Starting with a survey of relevant processes responsible for the interactions between atmospheric physics, dynamics and composition, the paper highlights the challenges of this evolution towards seamlessness and presents priority areas for research to further this path.

12.1 INTRODUCTION

‘meteorology’ is used as the generic terminology that encompasses both weather and climate

During the last two decades or so, some major research initiatives have independently investigated the role of atmospheric composition in weather forecasting (Grell and Baklanov, 2011; EuMetChem; ICAP; WGNE), the real-time forecasting of air quality (Baklanov, 2010; Kukkonen et al. 2012; Zhang et al. 2012 a&b), the generation of chemical analyses through the assimilation of composition data (Monitoring Atmosphere Composition and Climate (MACC): Hollingsworth et al. 2008; Bocquet et al. 2015) and the interactions between atmospheric composition and climate (Alapaty et al. 2012; Liu et al. 2013; World Climate Research Programme (WCRP) Working Group on Coupled Modelling (WGCM)). These different projects have converged towards similar approaches by coupling meteorology and composition-chemistry models in order to better address the different model application problems, resulting in seamless models (SMCMs) where the treatment of meteorology, composition and composition-meteorology interactions is combined in one model through either an online integrated or online access coupling. Online integrated models simulate meteorology and chemistry over the same grid in one model using one main timestep for integration while Online access models use independent meteorology and chemistry modules that might even have different grids, but exchange meteorology and chemistry data on a regular and frequent basis (Baklanov et al. 2014).

Online integrated models are not new. They recently became available in the mainstream meteorological and atmospheric composition and chemistry research community. This is catalysed by ever increasing computing power and permits new forays into long-standing scientific questions on the interactions between atmospheric constituents and atmospheric processes. It also allows the implementation of new operational environmental prediction services (e.g. Copernicus in Europe: <http://atmosphere.copernicus.eu/>; Air Quality Health

Index (AQHI) in Canada: AQHI, 2013; Stieb et al. 2008). The level of coupling, the processes represented and the level of complexity of their representation, amongst other things, vary widely between models. While different applications can commend different choices, dedicated efforts are needed to address the challenges that are encountered in seamless models. This also extends to considerations of spatial and temporal scales as it is to be expected of modelling systems to produce consistent responses across all scales. Multi-scale capable models will have to be seamless. Discussions held at the World Weather Open Science Conference (WWOSC-2104) took stock of the current status, gaps and challenges of this integration and explored the needs and future research requirements towards a seamless representation of the atmosphere for the full range of atmospheric modelling systems.

12.2 EXISTING EXPERIENCE, MAIN TRENDS AND MOTIVATION

National Meteorological and Hydrological Services (NMHS) are now looking at bringing representations of atmospheric composition into different parts of their operational forecasting systems resulting in a wide range of efforts for various applications and as many levels of complexity in the representations. NMHSs have invested in the following areas: Volcano ash forecasting, warning and impacts; Sand and dust storm modelling and warning systems; Wild fire impact on atmospheric pollution, health and visibility; Chemical weather / air quality forecasting and reanalyses; Numerical Weather Prediction (NWP) for precipitation, visibility, thunderstorms, etc; Urban and environmental meteorology; High-impact weather and disaster risk management; Effects of short-lived climate pollutants; Earth system modelling and projections; Data assimilation for air quality and NWP; Weather modification and geo-engineering. The SMCs developed have reached different levels of maturity and are at varying stages of operational implementation. Climate services are an additional application area of SMCs.

Several major research and development projects have been initiated to support these new interests. In recognition of the rapid development of coupled meteorology and composition modelling, the Action ES1004 (EuMetChem) in the European Cooperation in Science and Technology (COST) Framework was launched in February 2011 to develop a European strategy for coupling air quality (AQ) and meteorology modelling (www.eumetchem.info). The Action aimed to identify and review the main processes coming into play in the coupling and to specify optimal modular structures for SMCs to simulate specific atmospheric processes. The COST Action developed recommendations for efficient interfacing and integration of new modules, keeping in mind that there is no one best model, but that the use of an ensemble of models simulations is likely to provide the most skilful result (Baklanov et al. 2014, 2015).

Other collaborative efforts are ongoing at the international level. The Air Quality Model Evaluation International Initiative (AQMEII), coordinated by the European Commission Joint Research Centre (JRC) and the US- Environmental Protection Agency (EPA), primarily addresses the fundamental issue of model evaluation through collaboration between the European and North American regional scale air quality communities. In the first phase of AQMEII (2010-2012), uncoupled chemical transport models (CTM) were extensively evaluated (Galmarini et al. 2012), while the models participating in Phase 2 (2013-2014) were online coupled meteorology-composition-chemistry models (Galmarini et al. 2014).

In the operational aerosol prediction community, the International Cooperative for Aerosol Prediction (ICAP, <http://icap.atmos.und.edu/>) initiative was set to address common challenges among operational centres related to the prediction of aerosols at the global scale, including their interactions with other Earth system's components. Its latest work proves the benefit of using a multi-model ensemble approach for the near-real-time production of aerosol forecasts based on the latest generation of models (Sessions et al. 2015).

On the European Union side, one major effort is the Copernicus Atmosphere Monitoring Service (CAMS) that will start in fall 2015. CAMS will consolidate many years of preparatory research (Global and regional Earth system Monitoring using Satellite and in situ data (GEMS), MACC, MACC-II and MACC-III projects) and development and deliver a large set of operational services.

Among them, there is the provision of daily forecasts and analysis of air composition (reactive gases and aerosols) at the global scale (<http://www.gmes-atmosphere.eu/>) and provision of boundary conditions for the regional prediction of air quality at the European level. For this a tropospheric chemistry scheme and an aerosol scheme is coupled with the Integrated Forecast System (IFS) that is used for the operational NWP at the European Centre for Medium-range Weather Forecasts (ECMWF). Further, work is underway to explore the benefits of a multi-model ensemble approach based on three state-of-the-art tropospheric/stratospheric schemes, taking into account scientific and computational cost issues. More generally, CAMS integrates all the components (emissions, observations, assimilation and forecasts systems both at global and regional scales, verification, data access, and documentation) needed to generate atmospheric composition products accessible to a large variety of worldwide users (policy users, solar energy and commercial applications and research). At the regional scale, a state-of-the-art multi-model ensemble approach is used for air quality operational forecasts over Europe. In this case, separate meteorology and chemistry-transport modelling systems are used.

In addition, several programmes and initiatives of the World Meteorological Organization (WMO) are moving towards seamless modelling, such as the WMO Working Group for Numerical Experimentation (WGNE), the GAW (Global Atmosphere Watch) Urban Research Meteorology and Environment (GURME) project (<http://mce2.org/wmogurme/>), the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS), and the WCRP Chemistry-Climate Model Initiative (CCMI, Eyring et al. 2013). In particular, the WGNE recently initiated a specific online integrated modelling case study on Aerosol Effects on NWP (see:

http://www.wmo.int/pages/prog/arep/wwrp/new/documents/03_Freitas_Aerosols.pdf and Arlindo daSilva's WWOSC-2014 presentation at: <https://www.wmo.int/pages/prog/arep/wwrp/new/wwosc/presentations.html>).

Most of the above-mentioned programmes are approaching the issues with the seamless meteorology-composition modelling approach since they are interested in 2-way interaction mechanisms with a focus on aerosol feedbacks. Direct processes and feedback relevant to meteorology, composition and chemistry have been reviewed in detail by Zhang (2008) and Baklanov et al. (2014).

The potential impacts of aerosol feedbacks can be broadly explained in terms of four types of effects: direct, semi-direct, first indirect and second indirect. For example, the reduction due to aerosols in solar radiation reaching the Earth's surface is an example of a direct effect (Jacobson et al. 2007). Changes in surface temperature, wind speed, relative humidity, clouds and atmospheric stability that are caused by this reduced radiation due to absorbing aerosols are examples of the semi-direct effect (Hansen et al. 1997). A decrease in cloud drop size and an increase in cloud drop number as a result of more aerosols in the atmosphere are named as the first indirect effect (Twomey, 1977). These changes might enhance cloud albedo. An increase in liquid water content, cloud cover and lifetime of low level clouds and suppression or enhancement of precipitation are examples of the second indirect effect (Albrecht, 1989). However, this simplified classification is insufficient to describe the full range of two-way chains and loops of interactions between meteorological, composition and sometimes chemical processes in the atmosphere. For example, clouds modulate boundary layer outflow/inflow by changes in the radiative and turbulent fluxes as well as alterations of temperature profiles and thereby vertical mixing and the water vapour modulates radiation. The vertical temperature gradient also influences cloud formation and controls turbulence intensity and the evolution of the atmospheric boundary layer (ABL). Similar feedback mechanisms exist for altered chemistry impacts on chemistry. On a more general level, a number of chains and loops of interactions take place and should be properly simulated in a seamless model.

The relative importance of the seamless meteorology-composition modelling and of the priorities, requirements and level of details necessary for representing different processes still varies with the applications and communities (AQ forecasting, AQ assessment, NWP, climate and Earth system models). Against the backdrop of the separate development of meteorological models (MetMs) and CTMs together with the continued increase in computing power, a more detailed modelling

description of physical and chemical processes and their interactions calls for a strategic vision. Such a vision will help to provide shared goals and directions for the research and operational communities in this field, while still having a multiple model approach to respond to diverse national and institutional mandates.

The next 10 years will need to see a much higher level of meteorology-composition models as multi-scale models will be more widely used to better describe the atmospheric processes. However, combining two modelling systems for operational applications, each of which has high CPU time and memory requirements, poses many challenges in practice. An assessment of the challenges, gaps and requirements is presented below. In the following Sections 12.3-12.7, the main sub-themes that need to be considered for further developments of SMCs are discussed. Each sub-theme is structured as background info, underpinning research, main linkages and requirements for further research and realisations.

12.3 MAJOR CHALLENGES AND NEEDS FOR INTERACTING PROCESSES AND FEEDBACK MECHANISMS

Background

Numerous feedbacks exist between the dynamical and thermodynamic state of the atmosphere and gaseous and particulate compounds. Although most feedbacks have been identified for a long time several of them are yet not well quantified or characterised. In addition, their relative importance for seamless meteorology-composition forecasting and predictability are not quantified yet. Tables 1 and 2 summarize these feedback processes.

Table 1. The impact of atmospheric variables and processes on trace gases and aerosols

<i>Temperature</i>	Modulates chemical reaction and photolytic rates
	Modulates biogenic emissions (isoprene, terpenes, dimethyl sulphide, etc.)
	Influences biogenic and anthropogenic emissions (isoprene, monoterpenes, VOCs from solvents and fuel)
	Influences the volatility of chemical species
	Determines aerosol dynamics (coagulation, condensation, nucleation)
	Determines atmospheric stability, turbulence and mixing potential
<i>Temperature and humidity</i>	Affect aerosol thermodynamics (e.g. gas-particle partitioning, secondary aerosol formation)
	Influence pollen emissions
<i>Water vapour</i>	Modulates OH radicals, size of <i>hydrophilic aerosol</i>
<i>Liquid water</i>	Determines wet scavenging and aqueous phase chemistry
<i>Wind vector</i>	Determines horizontal and vertical transport of trace gases and aerosols
	Influences dust-, sea-salt-, and pollen emissions
<i>Atmospheric turbulence</i>	Determines turbulent diffusion of trace gases and aerosols
<i>ABL height</i>	Influences concentrations
<i>Radiation</i>	Determines photolysis rates
	Determines biogenic VOC emissions
<i>Cloud processes</i>	Affect in-cloud scavenging of aerosols and trace gases
<i>Precipitation</i>	Determines the wet removal of trace gases and aerosol
<i>Surface-vegetation-atmosphere exchange processes (depending on soil type, vegetation cover, soil moisture and leaf area)</i>	Affect natural emissions (e.g. dust, sea salt, pollen, nitrogen compounds, biogenic VOCs, CO ₂ , water vapour) and dry deposition
<i>Lightning</i>	Contributes to natural NO _x emissions

Table 2. Impacts of trace gases and aerosols on atmospheric variables and processes

<i>Aerosols</i>	Modify radiation transfer (SW scattering/absorption, LW absorption, LW scattering by large particles like dust)
	Affect ABL meteorology (temperature, humidity, wind speed and direction, stability)
	Affect haze formation and atmospheric humidity
	Modify physical properties of clouds (size distribution, extinction coefficient, phase function and single scattering albedo)
	Influence cloud droplet and ice crystal number concentrations
	Influence precipitation (initiation, intensity)
<i>Soot</i>	Influences surface albedo (e.g. ice surfaces)
<i>Trace gases</i>	Modify radiation transfer

These feedback processes show that seamless meteorology-composition model systems can improve the current state of knowledge and the capability of future seamless prediction atmospheric models. The relative importance and necessity of seamless meteorology-composition models and the related level of detail required for representing different processes and feedbacks vary greatly between the three application fields: NWP, air quality and chemical weather forecast, and climate/Earth system modelling, as was also confirmed in an expert poll conducted among the members of the EuMetChem COST Action (Baklanov et al. 2014; Kong et al. 2014).

Emissions and deposition interact with the meteorological part within online coupled models. The most interesting emissions are those which depend on meteorology as they can be treated more accurately and consistently than in offline coupled models. Natural emissions (e.g. isoprene, terpenes and pollen) strongly depend on meteorology and are in general already calculated online even in offline models using the meteorological input driving the CTM model. Sea spray is the dominant aerosol source over the oceans and therefore, its proper quantification is highly relevant for simulating chemical reaction in offshore and coastal areas and thus is more realistically to be calculated in a seamless meteorology-composition-model. Wind-blown dust refers to particles from a broad range of sources. Due to their direct relationship with meteorology, such emissions must be calculated with the seamless approach.

A large variety of chemical mechanisms are currently in use in SMCMs. Nevertheless, the most commonly-used mechanisms have converged in terms of the state of the science included in their formulation. Modifications of the chemical mechanisms, which not only affect gas phase chemistry but also the coupling with aqueous-phase and aerosol mechanisms, have faced practical difficulties in the past. Methods of updating chemical mechanisms make updates much easier as illustrated in the MECCA module (Sander et al. 2005).

In comparison to conventional weather forecasting models, SMCMs may require huge computational efforts depending on the involved processes. Therefore, one main challenge will be identifying the degree of representativeness and complexity required with respect to 3D-composition fields, chemistry, aerosol dynamics and aerosol chemistry, and the feedbacks between gaseous compounds, aerosols, clouds and radiation for the next generation of seamless meteorology-composition models. Nevertheless, these needs and challenges are scaled by the differing degree of requirements of the various applications and users with as the main aim to improve forecasting skills for all meteorological parameters and relevant concentrations.

Underpinning research

Although it is the final goal of seamless meteorology-composition model systems to include all relevant processes describing the feedback between atmospheric composition and weather and climate one might think of intermediate steps.

In case of air quality model systems that include mineral dust and biomass burning aerosol would be an improvement of the current situation. This requires research in the fields of the emission of mineral dust, the emission of biomass burning aerosol, and of plume rise models.

Mineral dust is one of the most abundant aerosols. Mineral dust particles strongly modify atmospheric radiation. Taking this effect into account would be relevant step for seamless prediction. The calculation of the optical properties of aerosols is required to simulate the impact of mineral dust on the radiative fluxes. The refractive index is a crucial input parameter for such calculations. The refractive index depends on the chemical composition. Improved wavelength dependent measurements of the optical properties of mineral dust particles are needed. The nonsphericity of the mineral dust particles, often neglected needs further attention.

As long as bulk schemes are used in numerical weather forecast models to treat cloud microphysics an improvement would be including aerosols in a simplified way in such schemes. An example would be the process of auto-conversion which transfers cloud droplets to rain droplets. This transfer depends on the number concentration of cloud droplets which depends on the number of cloud condensation nuclei. In-cloud and below-cloud scavenging, sedimentation and deposition at the surface could be taken into account by such models. As sea salt and mineral dust are the most abundant aerosol particles in many regions of the world the simulated number concentrations of those particles could serve as an input to drive the auto conversion in microphysical bulk schemes. This requires the development of parameterizations.

A further step forward would be the replacement of bulk microphysical schemes by more sophisticated ones as for example two moment schemes and the inclusion of secondary aerosol particles as sulphate and nitrate or secondary organic compounds. Several aerosol processes such as nucleation, coagulation, condensation, and evaporation should then be included. The interactions of aerosols with gas phase chemistry and their impacts on radiation and cloud microphysics depend strongly on their physical and chemical properties. Although several models are available in the research community there is still a strong need for research before such model systems can be transferred into seamless meteorology-composition forecast models. Accurate parameterization of the ability of aerosol particles to act as ice nuclei and the quantification of their relevant freezing processes within clouds are needed. A quantification of the level of complexity which is needed in case of atmospheric chemistry is required; this can be achieved by performing sensitivity studies and comparisons with observations. Disentangling the role of aerosols for cloud formation and precipitation needs further research efforts, before the level of complexity that has to be included in SMCMs is clear. This has to be done focussing on different cloud types (low level, mixed phase, deep convective) and weather systems.

Linkages

The strategy to advance on the research topics listed above requires an understanding of the atmospheric processes as a whole. For this, it is necessary to promote close collaborations at the international level between the different research areas involved: meteorology, atmospheric chemistry, and aerosol science. Interdisciplinary basic research projects towards this goal should be promoted with dedicated observing and modelling strategies depending on the specific meteorology-composition process and feedbacks to be studied.

Requirements

Migration from offline to seamless and, more specifically, to online integrated modelling systems is recommended for many applications as this approach can guarantee a consistent treatment of processes and allow two-way interactions of physical and chemical components of SMCMs, particularly for chemical weather forecasting (CWF) and NWP communities. In particular, the following steps should be taken:

- A challenge for most SMCMs is the adequate treatment of indirect aerosol effects. Its implementation with affordable computational requirements and evaluation against

laboratory/field data would greatly facilitate the transition to seamless meteorology-composition models.

- The understanding and therefore the parameterization of aerosol-radiation-cloud-chemistry interactions is still incomplete and further research on the model representations of these interactions is needed.
- Key aerosol properties (size, phase, hygroscopicity, mixing state, optical properties) and processes (chemistry, thermodynamics for SOA and dynamics) need to be better represented for seamless meteorology-composition-chemistry forecasts.
- Cloud properties (droplet number concentrations, size distribution, optical properties), processes (microphysics, dynamics, wet scavenging, aqueous phase chemistry) and cloud-aerosol interactions for all types of clouds need to be better represented.
- As more meteorological and chemical variables are assimilated into a model, one must be cautious about possible diminishing returns and possible antagonistic effects due to the interactions between meteorological variables and chemical concentrations. Consequently, the development of optimal methods for data assimilation is warranted, including the estimation of model and observation uncertainties.
- Create a unified central database of chemical mechanisms, where mechanism owners can upload relevant codes and provide updates as necessary.
- Enable interfacing of this database using, e.g. the Kinetic Pre-Processor (KPP) to develop a set of box model intercomparisons including evaluation against smog chamber data and more comprehensive mechanisms and moreover an analysis of the computational cost.

12.4 SEAMLESS COMPOSITION REPRESENTATION

Background

As presented in Hurrell et al. (2009), “the global coupled atmosphere-ocean-land-cryosphere system exhibits a wide range of physical and dynamical phenomena with associated physical, biological, and chemical feedbacks that collectively result in a continuum of temporal and spatial variability”. This recognition, which implies that the traditional boundaries between atmospheric, oceanic and earth sciences are by and large artificial, sparked a new area of research for seamless weather, composition and climate predictions, which was actively discussed at the WWOSC-2014. Within the same conference, many scientists recognized that the concept extends beyond weather and climate prediction to chemical weather and chemical climate. As it is the case for physical and dynamical processes, there is a continuum of chemical phenomena and interactions with the physical and dynamical state of the atmosphere across all time and spatial scales. Models need to aim for numerical representations whose results are consistent across those scales. This is a particularly difficult challenge with chemistry where hysteresis is frequent, yet even more important to avoid divergence in the predictions of atmospheric constituents.

The representations of atmospheric composition in each of the three main atmospheric disciplines (weather, climate and air quality) are constrained by the associated cost of such representations and have different priorities. As a result, the heterogeneity and different levels of maturity in each field are major challenges to overcome in order to evolve towards a seamless framework. Recognizing that the atmospheric community at large aims to model the same chemical phenomena and can leverage each other’s advancement is key to the development of a next generation of models where the simplest to the more explicit representations of composition provide the same consistent scientific results. In doing so, the community will need to revisit the computing performance of chemical representations and take advantage of the upcoming computing capacities, an area that has seen a lot less attention compare to their dynamic and physic counterparts.

Finally, the spatial transitions cannot be forgotten as numerical models are bound to achieve sub-kilometre resolutions on an operational basis within the next two decades. To stay in step with this trend, the chemical community will need to participate in emerging research efforts focusing on scale-independent and scale-aware parameterizations (Grell et al. 2014), and understand how these concepts extend more broadly to chemical composition.

Linkages

It is fairly evident that to expand the seamless framework to atmospheric composition, synergistic efforts are required within the communities currently dedicated independently to weather, air quality and climate. Overarching initiatives such as the CCMM symposium (http://eumetchem.info/ccmm/Agenda_CCMM.pdf) are developing to gather and foster a scientific dialogue across the disciplines; this needs to be further supported through dedicated joint research efforts. Likewise, a similar integration is required in data assimilation and is further discussed in Section 12.7 and in Chapter 3.

Requirements

- The chemical modelling and climate research communities are evolving rapidly towards adopting SMCs as the tool of choice for development in the next decade. The NWP community is not requiring implementation of full chemistry and mostly needs the implementation of aerosol interaction processes. Using common platforms is a critical component to establish an engaged dialogue across weather, climate and air quality modellers and facilitate the harmonization of the chemical composition representations.
- Scale-independent and scale-aware parameterizations are examples of the new concepts that emerge from pushing the scientific thinking beyond the artificially established boundaries; research efforts along the same concepts need to be fostered and applied broadly to chemical composition.
- Accelerating developments that address the seamless challenges will require the support of joint research initiatives with international recognition and participation; the benefits of modelling experts of different background working alongside will extend well beyond the objectives of the initiatives as it pushes each party to reassess their working assumptions.

12.5 NUMERICAL AND COMPUTATIONAL ASPECTS

Background

With the increase of computational resources, more complex numerical models are becoming feasible, and an increase of the spatial resolution is affordable. Consequently, SMCs are experiencing closer attention. Key points in such models are (i) the numerical schemes (especially those for the transport of composition species), (ii) the seamless treatment of the coupling or integration between meteorology and chemistry, (iii) the role of initial and boundary values and (iv) the efficient performance of the system in a specific high performance computing (HPC) environment.

Underpinning research

A number of different numerical techniques have been used and proposed for the transport of aerosols and other chemical species in seamless meteorology-composition-models. Some of them are able to maintain consistency of the numerical methods applied for both meteorological and chemical variables, while others apply different transport schemes for meteorology and chemistry species, partly because the transport requirements for chemical species are stronger than those for hydrometeors in NWP (see overview in Baklanov et al. 2014; model inventory at mi.uni-hamburg.de/costmodinv). This may be a relevant deficiency when explicitly treating aqueous phase chemistry. Rasch and Williamson (1990) listed the following desirable properties for

transport schemes: accuracy, stability, computational efficiency, transportability, locality, mass conservation and shape-preservation (positive definiteness, monotonicity, etc.). The last two are of particular interest in composition modelling. It is important also to mention the so-called wind mass inconsistency problem, which turns out not to be trivially resolved in SMCMs.

Among technical aspects, one should also consider the basic structure of the code. When using SMCMs the number of prognostic variables in the model increases dramatically. To make sure that the code is still efficient, the numerical schemes must be highly multi-tracer efficient (Lauritzen et al. 2010).

The current state of online coupled models is that they are run on state-of-the-art supercomputers and are written in a mixture of Fortran 2008/2003/95/90/, C and C⁺⁺ and some Fortran 77. The mixture of different languages is a result of the enormous efforts needed to develop a robust code, which easily extends more than 100 man-years. The models are using either Message Passing Interface (MPI), Open MultiProcessing (OpenMP), or a combination of the two for the parallelisation of the code. Both methods have advantages and disadvantages, but by combining the two methods, one can ideally optimize the code for use on all types of machine architectures.

Linkages

The numerical and computational aspects for seamless meteorology-composition models are also extremely important and common to AQ, NWP and climate modelling communities, so this work should be done together and involving numerical mathematics experts and computer scientists.

Requirements

The most relevant properties to be considered when developing integrated models and especially for considering feedback mechanisms are mass conservation, shape-preservation and prevention of numerical mixing or unmixing. Eulerian flux-based schemes are suitable for mass conservation. Recently, several semi-Lagrangian schemes have been developed that are inherently mass conservative. Such schemes are applied in some integrated models.

- A detailed analysis of the numerical properties of SMCMs is recommended. A particularly relevant set of tests has been described by Lauritzen and Thuburn (2011), which shifts the focus from traditional, but still important, criteria such as mass-conservation to the prevention of numerical mixing and unmixing. Not maintaining the correlations between transported species is similar to introducing artificial chemical reactions in the system.
- A clear trend towards seamless meteorology-composition model development is becoming perceptible with several modelling systems that can be considered as online integrated models with main relevant feedbacks implemented. Complementing those, there are several ones that are built using an online integrated approach, but some major feedbacks are not included yet. A third group of models, the online access models, is characterised by applying an external coupler between meteorology and composition/chemistry. All the information is passed through the coupler. Depending on the approach used, wind and mass consistency problems may arise in the last case. In this sense, online integrated models are desirable to avoid inconsistency problems.
- Numerical performance is an important issue for SMCMs. The current parallelisation is based on well-established MPI and OpenMP programming models. Beyond these approaches, there is no clear trend towards new parallelisation paradigms, even though supercomputers are experiencing a huge increase in computing power achieved mainly through an increase in the number of computing units rather than an increase in clock frequency. New processor types such as GPU's and MIC's are only beginning to be explored.
- To adopt newer technologies, a conversion programme that transfers existing code to the new technology would be advantageous. The transferred code would need to be still

readable and maintainable. This would be very useful since a seamless meteorology-composition-chemistry model takes several decades of work to develop, and without software based support, transfers can take years to be completed reliably.

12.6 EVALUATION OF COUPLED MODELS

Background

There is a crucial need for more advanced evaluation of methodologies and output data. Model validation and benchmarking are important elements of model development as they help identify model strengths and weaknesses. Model validation has a long tradition in the NWP and AQ modelling communities, and many concepts can be applied to SMCs as well. The MetM community has the necessary tools, for example, to analyse whether including certain feedbacks has a positive effect on weather forecast skill. Demonstrating these benefits however, requires running a model with and without feedbacks and specific combinations of feedbacks over extended periods of time - rather than for selected episodes - in order to draw statistically significant conclusions. Furthermore, reliable comparison data need to be available, at least for the most relevant processes.

Underpinning research

Evaluating whether relevant feedback processes are treated accurately by a model is challenging. The effects of aerosols on radiation and clouds, for example, depend on the physical and chemical properties of the aerosols. Thus, comprehensive measurements of aerosol size distributions, chemical composition, and optical properties are needed. Such observations should ideally be collocated with detailed radiation measurements (e.g. WMO GAW, AERONET), with aerosol lidars probing the vertical distribution and with radiosondes providing profiles of temperature and humidity. Evaluating indirect aerosol effects on clouds and precipitation is even more challenging and requires additional detailed observations of cloud properties such as cloud droplet number concentrations. Measurements from polarimetric radars, disdrometers, and cloud particle imagers can provide information on hydrometeor phases and size distributions but are only sparsely available. SMCs can also be beneficial for AQ modelling. Surface-based observational networks are available for the validation of classical air pollutants such as O_3 or NO_x and satellite observations (column values) of NO_2 , O_3 , SO_2 and CO, and the aerosol optical depth (AOD). Note that surface networks are not uniformly distributed around the world, with very sparse observations in the southern hemisphere and over the oceans. Aircraft data also represent an important resource for observations of trace gases and aerosols for evaluation and possibly data assimilation.

Linkages

To advance the aforementioned research objectives it will be necessary to promote synergetic work between NWP, climate, and chemistry communities in order to define new strategies for model evaluation of all its components as a whole.

Requirements

For SMCs, the evaluation can no longer be conducted for meteorology or composition separately. Interacting processes will need specific attention to avoid the situation where the “right” results are obtained for the wrong reasons. In this regard, efforts should focus on conducting dynamic evaluation to establish the models’ credibility in accurately simulating the changes in weather and air quality conditions observed in the real world. To achieve this, attention should be given to:

- An international test bed for evaluation of urban, regional and global SMCs. The first step in this direction has been taken by the AQMEII consortium for the regional scale, but extension to higher resolution models is important. At the European level, model evaluation

activities are currently conducted for AQ under the FAIRMODE initiative. Involving the meteorology community in such activities could help to ensure that model results are right for right reasons.

- Overall evaluation methodologies for model application objectives outside the European AQ directives (EC, 2008) as suggested by Schlünzen (1997) and updated by Schlünzen and Sokhi (2009) are needed to ensure that relevant meteorological targets (e.g. very high temperatures, extreme precipitation) are also simulated correctly for the right reasons. Dynamic as well as diagnostic evaluation as defined by Dennis et al. (2010) should be considered.
- The quality measures used for evaluation need to be reconsidered in order to include uncertainty of the comparison data in them (Schlünzen et al. 2015).
- A target specific evaluation concept using operational data should be developed and applied globally to be able to compare (and exchange) model results.
- Extending quantitative evaluation approaches developed for meteorology to climate models (Schoetter et al. 2012) is an additional necessary extension of current evaluation attempts.
- Non-standard variables (e.g. shortwave and longwave radiation, photolytic rate of NO₂, AOD, Cloud Optical Thickness (COT), Cloud Condensation Nuclei (CCN), Cloud Droplet Number Concentration (CDNC), precipitation) should be included routinely into model evaluations for SMCMs. Reliable measurements are needed on a routine basis.
- Routine, long-term measurements of aerosol size distributions, chemical composition and optical properties in operational ground-based networks are urgently needed to verify meteorology/climate-composition-chemistry feedbacks.
- Ground-based and satellite remote-sensing measurements of aerosol and cloud properties (e.g. optical depths, CCN, CDNC and shortwave and longwave radiation) are very important to study aerosol indirect effects and should be included for validation of meteorology chemistry feedbacks.
- Last but not least, there is a need to evaluate routinely the atmospheric mixing processes in models, in particular within the Atmospheric Boundary Layer (ABL), using measurements on fluxes of meteorological parameters and chemical species in all three directions. These data need to be gained, evaluated and provided for evaluation.

12.7 DATA NEEDS AND ASSIMILATION

Background

Experience with chemical data assimilation (CDA) in SMCMs is still limited but it has become subject of much investigation (see an overview in Bocquet et al. 2015). Most applications of CDA use CTMs, rather than SMCMs, to improve the simulated concentration fields or model parameters such as emissions. Initial efforts have been made with integrated systems (IFS-MOZART and Weather Research and Forecasting Model (WRF)-Chem) to assimilate composition and meteorological observations in SMCMs. There is some evidence that CDA can also improve the assimilated meteorological variables, for example the assimilation of ozone can have a positive effect on the assimilated wind fields (Semane et al. 2009).

Underpinning research

CDA will be beneficial in SMCMs if it improves the realism of the composition/concentration fields which are used to simulate the interaction between atmospheric composition and meteorology. The most common approach is the adjustment of initial conditions through CDA in a manner similar to meteorological data assimilation. Optimal interpolation, variational approaches, Ensemble Kalman filter (EnKF) or hybrid techniques combining the advantages of both variational and EnKF techniques are all applicable. Other methodologies such as inverse modelling of emission fields appear as a promising technique to improve the skill of SMCMs and may have a stronger impact for short-lived pollutants than CDA has on initial conditions. However, it is

debatable whether the results of inverse modelling should be used directly to correct emission fields or only to provide insights for the development of improved emission inventories.

Linkages

An important aspect of seamless composition modelling has been the development of data assimilation systems that include also chemical species and particulate matter. Several global and regional models currently provide analysis of gases and aerosols. As an example, among others, the global MACC system incorporates retrieved observations of ozone, CO, SO₂, NO₂ and aerosol optical depth in its analysis to provide initial conditions for the prediction of these species. Currently, the emissions are not part of the analysis but are specified either from established inventories or from satellite observations as it is the case for the emissions of biomass burning aerosols, CO and other species from wild fires (Global Fire Assimilation System (GFAS), Kaiser et al. 2012). Estimation of emissions through data assimilation will be the next step for global models. This has already been successfully tried by regional models (e.g. Elbern et al. 2007) and in off-line models (i.e. Huneus et al. 2012).

Requirements

Several data assimilation techniques are currently used in the analysis of atmospheric constituents such as 3D and 4D-Var, EnKF and Optimal Interpolation. More research is needed for the correct definition of the background error covariance matrices for the chemical species, including errors deriving from the incorrect specification of the emissions. Hybrid 4D-Var/EnKF systems could be used for CDA and research towards that end is definitely encouraged. There is also the need to invest in research related to the inclusion of the full tangent linear and adjoint of the chemical processes in variational methods. In most current systems, these processes are not included in the minimization and this may limit the impact of the assimilation. Independent of the specific assimilation framework, some general recommendations related to data assimilation observational needs can be made:

- Observations of key variables have to be timely and accurate. In particular, especially for chemical weather forecasting and air-quality applications, the data to be fed in the assimilation system need to be in near-real-time (NRT), with correct timing and have a characterization of the observation errors at the pixel level.
- More research is needed to make full use of raw products such as satellite radiances. This involves the development of higher-complexity observation operators. The benefits will be the more efficient exploitation of the observations, and the lower dependency on a priori assumptions external to the system.
- Several data sources are needed to ensure resilience of the system and wealth of observation-based information. Currently most centres rely on satellite data for the analysis of the atmospheric composition. The next generation of satellite measurements is designed to provide more information on the vertical distribution of gas pollutants and of their precursors, in particular in the lower troposphere, which will be most useful. Efforts are also under way to use ground-based (CO₂, PM, etc.) and aircraft measurements.
- Accurate measurements to verify the model prediction are also needed. These could have longer data latency than the data to be used for assimilation. However it is important that these observations are also delivered timely, to ensure the possibility of a routine verification of the chemical model prediction. Validation datasets are mostly those coming from ground-based observing networks such as GAW, Aerosol Robotic Network (AERONET), European Aerosol Research Lidar Network (EARLINET), Micro Pulse Lidar Network (MPLNET) (www.iagos.fr) etc. Aircraft data also provide invaluable independent observations for validation. High quality, validated datasets are essential also for the verification of the SMCMs run in climate configuration.
- Observations have to be available in a format that is easily accessible, and should also be as compatible as possible with model fields. To this end, close collaboration between data providers and modellers is encouraged to make the process of data acquisition and assimilation more efficient and successful.

12.8 WHAT DO NMHSS NEED FOR SPECIFIC APPLICATIONS AND SERVICES?

In this section, we address the aspect that research is needed on the SMCM systems to have consistent representation of composition constituents regardless of application.

It is clear that the seamless modelling approach is a prospective way for future single-atmosphere modelling systems, providing advantages for all three communities: meteorological modelling including NWP, AQ modelling including CWF, and climate modelling. However, there is not necessarily one seamless modelling approach/system suitable for all communities.

Comprehensive SMCM systems, built for research purposes and including all important mechanisms of interactions, will help to understand the importance of different processes and interactions and to create specific model configurations that are tailored for their respective purposes.

Regarding CWF and atmospheric composition modelling, the SMCM approach will certainly improve forecast capabilities as it allows a correct way of jointly and consistently describing meteorological and chemical processes within the same model time steps and grid cells. This also includes harmonised parameterizations of physical and chemical processes in the ABL. There are many studies and measurements supportive of this conclusion (Grell et al. 2004; Grell, 2008; Zhang, 2008; Korsholm et al. 2009; Grell and Baklanov, 2011; Forkel et al. 2012; Saide et al. 2012; Zhang et al. 2013). In particular, due to the strong nonlinearities involved, separate models for meteorology and atmospheric composition can lead to inaccuracies in composition simulations.

For meteorological modelling, the advantages of SMCM approaches are less evident and need to be further investigated and justified. The results of process studies with very detailed comprehensive SMCM systems will serve as a benchmark for reducing physical and chemical processes. Operational forecast centres will rely on the results of those efforts to decide on the practical usage of such next generation seamless prediction models. Here a strong interaction with academia and operational forecast centres is required (e.g. Bangert et al. 2012; Rieger et al. 2014; Vogel et al. 2014). The main improvements for NWP that are possible through an online integrated approach will be related to improvements in (i) meteorological data assimilation (first of all remote sensing data, radiation characteristics, which require detailed distributions of aerosols in the atmosphere) and (ii) description of aerosol-cloud and aerosol-radiation interactions, yielding improved forecasting of precipitation, visibility, fog and extreme weather events and radiation (including Ultraviolet). While these improvements might not be statistically significant as averaged over longer periods of time, it is clear that for specific episodes and high-impact weather events (e.g. aircraft icing, dust storms, vegetation fires, clear summer skies) there are large potential benefits. In summary, meteorology modelling including NWP should benefit from including such feedbacks as aerosol-cloud-radiation interactions and aerosol dynamics.

For climate modelling, the feedbacks (forcing mechanisms) are the most important and the main improvements are related to climate-chemistry: Greenhouse Gas (GHG)/aerosol-radiation and aerosols-clouds interactions. However, the online integration approach is not strictly necessary for all purposes in this field. Many GCMs or RCMs use an offline approach (separate meteorological and chemical composition models) for describing GHG and aerosol forcing processes (by chemistry/aerosol parameterizations or prescription or reading outputs of CTMs). For climate studies, in the EU project MEGAPOLI (<http://megapoli.info>), a sensitivity study compared the seamless versus offline approaches and showed that for long-lived GHG the seamless approach did not give large improvements (Folberth et al. 2011). On the other hand, for short-lived climate pollutants, especially aerosols and for regional or urban climate, the outcome was very different, with online integration modelling being of substantial benefit. The seamless approach for climate modelling is mostly important for studies of short-lived climate pollutants, which represent one of the main uncertainties in current climate models and are in particular at the core of political and socio-economic assessments of future climate change mitigation strategies. It will be impossible to answer the main questions about aerosol short-lived climate pollutants and mitigation strategies

without employing SMCM systems that include aerosol dynamics and feedbacks.

Proceeding from the above analysis and results of several overall publications (Zhang, 2008; Grell and Baklanov, 2011; Kukkonen et al. 2012; Zhang et al. 2012a,b; Baklanov et al. 2011, 2014, 2015), we suggest aiming at eventually migrating from separate MetM and CTM systems to integrated SMCM systems. Only this type of model allows the consideration of two-way interactions (i.e. feedbacks) in a consistent way. The integration has not only the advantage of a single-atmosphere model, for instance where water vapour and other atmospheric gases are no longer treated numerically differently, simply because of historical separation of the different disciplines. Furthermore, the integration has the advantage of saving computational resources, since several processes (e.g. vertical diffusion) have to be described in both MetMs and CTMs. It will also reduce the overall efforts in research and development, maintenance and application leading to cost savings for both types of models. However, adding new components (chemistry, detailed aerosol for instance) in NWP for operational applications still raises the issue of timeliness for product delivery when running a more complete and therefore computationally costly model.

To achieve the objective of seamless meteorology, composition and chemistry simulation in forecast models some specific aspects should be considered:

- National weather centres should consider progressively including aerosol-composition interactions into NWP systems which will lead to potential improvements and extending them to CWF using SMCMs for cross evaluations, benefitting both disciplines.
- The seamless approach is well suited for applications where frequent feedbacks/communication/interactions between meteorology and composition-chemistry models are required to properly account for the effects of mesoscale events in high-resolution CTMs.
- The online integration of meteorology, physics and emissions and their accurate representations are essential for CWF; the implementation of aerosol feedbacks is important mostly for specific episodes and extreme cases.

Administrative problems might hinder progress of CWF models. On a national level environment and meteorology are often handled in separate ministries, which might hinder merging Meteorological and Composition data sets as needed in the future. Thus, different regional and national data centres might have to be used.

Last but not least, the further development and use of SMCMs needs deep-rooted experts. Thus, universities should extend and update their education programmes to be tailored for the future needs of seamless modelling. The basic education in physics, (numerical) mathematics and atmospheric sciences has to be extended and include chemistry and computing knowledge in order to be able to create and maintain SMCMs. Since most programme codes are developed and used over decades, a good education of the future scientists is essential.

12.9 CONCLUSION

The paper presented a synthesis of advances in atmospheric dynamics and composition modelling and provided recommendations to evolve from separate to seamless meteorology-composition models to address limitations in weather, climate and atmospheric composition fields where interests, applications and challenges are now overlapping.

Seamless modelling is a prospective way for future single-atmosphere modelling systems with advantages for applications at all timescales of NWP, atmospheric composition and climate models.

A variety of SMCM systems is needed for different applications. Different model versions should contribute to different targets with respect to temporal as well as spatial scales, but also to processes under focus. The relative importance of online integration and of the priorities, requirements and level of details necessary for representing different processes and feedbacks can greatly vary for these related communities.

For NWP: full scale gas chemistry is less important, chemical mechanisms can be simplified focusing mostly on chemistry influencing aerosol formation and cloud interactions; aerosol feedbacks improve ABL characteristics and precipitation in very polluted episodes or over cities. Statistically the effects are not strong in average, but significant for specific episodes. 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.

For AQ: the SMCM approach improves AQ forecasting, and an extended chemistry is needed; aerosol feedbacks effects are not always relevant, they need to be studied further. For AQ forecasting, the key issue is usually the ground-level concentration of pollutants, whereas for weather and climate studies model skill is typically based on screen level temperature, wind speed and precipitation. For chemical weather forecasting and prediction of atmospheric composition, the seamless meteorology-composition modelling definitely improves AQ and chemical atmospheric composition projections.

For climate studies: suitable only for understanding the forcing and feedback mechanisms, it is still too expensive to include the full chemistry in climate runs. Chemistry is important, the models need to be optimised and simplified. For climate modelling, feedbacks from GHGs and aerosols are extremely important. However in some cases (e.g. for long-lived GHGs on global scale), fully online integration of full-scale chemistry and aerosol dynamics is not critically needed, but SMCMs should include composition change projections.

Remaining gaps: Understanding of several processes e.g. aerosol-cloud interactions are poorly represented and need further research; data assimilation in SMCMs still needs to be developed to avoid over-specification and antagonistic effects; model evaluation for SMCMs needs more (process) data, long-term measurements and a test-bed.

Several applications are likely to benefit from seamless modelling though they do not clearly fall under one of the three above-mentioned main communities, e.g. forecasting of bio-weather (e.g. pollen concentration), monitoring and forecasting plumes from volcano eruptions, forest fires, oil/gas fires, nuclear explosions or accidental releases, wind and solar energy production assessments and forecasting, weather modification and geo-engineering techniques that involve changes in the radiation balance, etc.

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CHAPTER 18. URBAN-SCALE ENVIRONMENTAL PREDICTION SYSTEMS

C. Sue Grimmond, Greg Carmichael, Humphrey Lean, Alexander Baklanov, Sylvie Leroyer, Valéry Masson K. Heinke Schluenzen and Brian Golding

Abstract

Weather, climate, water and related environmental conditions, including air quality, all have profound effects on cities. A growing importance is being attached to understanding and predicting atmospheric conditions and their interactions with other components of the Earth System in cities, at multiple scales. We highlight the need for: (1) development of high-resolution coupled environmental prediction models that include realistic city-specific processes, boundary conditions and fluxes; (2) enhanced observational systems to support (force, constrain, evaluate) these models to provide high quality forecasts for new urban services; (3) provision of meteorological and related environmental variables to aid protection of human health and the environment; (4) new targeted and customized delivery platforms using modern communication techniques, developed with users to ensure that services, advice and warnings result in appropriate action; and (5) development of new skill and capacity to make best use of technologies to deliver new services in complex, challenging and evolving city environments. We highlight the importance of a coordinated and strategic approach that draws on, but does not replicate, past work to maximize benefits to stakeholders.

18.1 INTRODUCTION

From now until 2050 most population growth is expected to occur in cities and towns, especially in Asia and Africa. Urban environments are particularly sensitive to weather, air quality, climatic conditions and their variability, all of which have profound impacts, direct and indirect, on activities within cities (e.g. transportation, energy demand, construction, school access, tourism etc.) and beyond (especially if the city is of regional, national or global economic importance). Impacts also relate directly to human health and well-being, both acute (e.g. epidemics) and chronic (e.g. respiratory). Cities are also focal points for innovation driving economic and societal progress, locally, regionally and globally. Thus cities provide huge potential for mitigation and adaptation to changing atmospheric conditions, and sites where some of the greatest benefits will accrue from enhanced prediction through smarter models, data and climate services.

While urban areas range from extensive conurbations (e.g. the Pearl River Delta, Tianjin-Beijing, Yangtze River Delta, New York-Boston) to megacities (e.g. Tokyo, Sao Paulo, Jakarta, Manila, Los Angeles, Lagos) to large cities (e.g. London, Hanoi, Bangalore) to smaller urban areas, these settings have important features in common: dense populations, impervious built surfaces, significant emissions of pollutants, heat and waste, etc. However, atmospheric conditions and forcing factors vary significantly, within as well as between cities, and the needs of various stakeholders (e.g. private, public and third sector) for services, advice and warning, in terms of information and tools, differ considerably too. These factors must be recognized in the development of weather, climate, water and related environmental services in cities.

A number of recent reports have considered what is needed to enhance predictive capabilities for urban areas (e.g. Fisher et al. 2005, Martilli 2007, Hidalgo et al. 2008, Baklanov et al. 2009, Grimmond et al. 2010, 2013, 2014, National Research Council 2010, 2012, Zhu et al. 2012/2013, Dabberdt et al. 2013, Pelling and Blackburn 2013). This chapter, informed by these recommendations, considers the needs to improve model development and predictive capability.

18.2 MODELLING PHYSICAL PROCESSES IN THE ATMOSPHERE

18.2.1 Background

Operational mesoscale numerical weather prediction (NWP) models in many national meteorological services are now being run at grid lengths of the order of a few km. At this scale,

urban effects of larger cities can be seen, albeit crudely. For example, operational forecasts are run at 5 km (Japan Meteorological Agency (JMA), Japan), 3 km (National Centers for Environmental Protection (NCEP), continental USA), 2.8 km (Deutscher Wetterdienst (DWD), Germany), 2.5 km (Météo-France; Danish Meteorological Institute (DMI), Denmark; Environment Canada (MSC) Canada (south-west region)), and 1.5 km (Met Office, UK); with some including urban land surface schemes (e.g. Masson 2000, Best 2006, Mahura et al. 2008, Seity et al. 2011, Lane 2014).

Cities influence atmospheric flow, its turbulence regime, and create distinct microclimates which modify the transport, dispersion, and deposition of atmospheric constituents, both within and downwind of urban areas. Key urban features include the:

- Distribution and shape of roughness elements (notably buildings and trees) which affect the turbulence regime, speed and direction of the flow, as well as radiative and thermodynamic exchanges between different surface elements and the atmosphere.
- Extensive surfaces of impervious materials, with these and the concurrent reduction of vegetation and exposed soils affecting the hydro-meteorological regime and aerosol deposition.
- Release of anthropogenic heat by human activities (e.g. from vehicles and buildings) which affect the thermal regime.
- Release of pollutants (including aerosols) which affect radiation transfer, formation of clouds, and precipitation within the city and beyond.

The net result is a series of distinct urban weather, climate and related environmental features. The most well-known of these is the urban heat island - warmer urban canopy air temperatures than in nearby rural areas - that are most pronounced a few hours after sunset. Such thermal differences can influence regional air circulation.

Some of the features listed above are included in current numerical weather prediction models, but with higher resolution coupled systems the challenge is to greatly improve the precision and scope of predictions.

18.2.2 Underpinning research

NWP models make use of a wide range of urban land surface models (ULSM). These ULSM are undergoing rapid development and enhancement, and have been the focus of recent systematic evaluations (Grimmond et al. 2010). While existing ULSM include very different levels of complexity, currently no one scheme performs best for all surface exchanges, so significant scope for improvement remains (Grimmond et al. 2011, Best and Grimmond 2015).

Inclusion of ULSM in mesoscale models has improved performance both experimentally (e.g. Mahura et al. 2008, Porson et al. 2010, Trusilova et al. 2013, Leroyer et al. 2014) and operationally (e.g. Best 2006, Lane 2014). The challenge of modelling urban canopy processes is complicated by the increasing resolution of atmospheric models. Current research involves mesoscale models being run at greater spatial resolution than the operational scales (e.g. Chen et al. 2011, Bohnenstengel et al. 2012, Loridan et al. 2013, Masson et al. 2013, Schoetter et al. 2013, Leroyer et al. 2014, Lean et al. 2015). These models are capable of simulating obstacles and meso-scale features (Martilli et al. 2007, Baklanov and Nuterman 2009, Schlünzen et al. 2011). Routine experimental runs include the UK Met Office's 300 m model for Greater London (Boutle et al. 2015) and Environment Canada's 250 m NWP for Greater Toronto (Leroyer and Bélair 2014).

18.2.3 Linkages

Higher resolution numerical prediction models are being applied to applications such as air quality (AQ), chemical dispersion, urban hydrology and ocean models (for coastal cities). For example, the 250 m Environment Canada NWP model may contribute to the 2.5 km grid AQ forecasts for Greater Toronto in the context of the PanAm 2015 games.

By modelling at ≤ 1 km scale, models will require more detailed surface fluxes and will resolve more atmospheric physical processes, which will result in different requirements for sub-grid parameterizations. At such scales, more advanced microphysics schemes may be required and deep convection schemes may be deactivated, although that does not mean convection is perfectly represented (Stein et al. 2014). A fundamental issue is the need to better understand the behaviour of high-resolution NWP models as they start to resolve turbulence (the so called grey zone) so that the complementary role of sub-grid scale vertical mixing schemes may be revised (Honnert et al. 2011). In this regard, many lessons can be learnt from the LES (large eddy simulation) community. An example of the issues that may be encountered is the serious spin-up effects often observed as air enters the domain of ~ 100 m resolution models and spin up turbulence (Munoz-Esparza et al. 2014).

Evaluation of new models need to draw on observations, from the real world and laboratory studies (e.g. wind tunnel, water tunnel), and from higher resolution and more detailed numerical studies (e.g. DNS - direct numerical simulation). Consequently, different research communities need to work closely together to ensure that these data are collected appropriately and used effectively. Data mining of such rich data sets will be necessary to improve the understanding of the processes that are modelled.

18.2.4 Requirements

Careful analysis of all elements in integrated forecasting systems is required to define their importance, priorities, and needs for different applications. More research on the resolution required to provide suitable descriptions of urban effects for different applications (e.g. urban weather, pollution, climate comfort) is necessary.

Higher resolution NWP, combined with the presence of more tall buildings in many cities, challenges the limits of current understanding. Key questions that need attention include: do buildings need to be directly resolved in these models? What simplifications are appropriate to make the computations tractable in realistic modelling time? At what scale can the current land surface schemes and model physics be applied? When does the model type need to be changed and the traditional RANS (Reynolds Averaged Navier Stokes) models be replaced by LES models?

Higher resolution models will also require a great deal of development of the representation of the urban surface. Given current projections of computer power, it will still be many years before models can resolve buildings (i.e. be equivalent in resolution to current street scale CFD/LES/DNS modelling (computational fluid dynamics/large eddy simulation/direct numerical simulation)) for any reasonable sized city. This means that a key challenge moving forward will be the "building grey zone" (analogous to the often discussed convection grey zone) where buildings are not resolved but the assumption, in lower resolution surface schemes, that there are many in each grid-point also breaks down.

To improve model evaluation, a wider range of laboratory and CFD/LES/DNS studies are needed with structures that more closely resemble cities rather than idealized homogenous arrays. These are needed particularly to inform model development for urban Roughness Sub-Layer (RSL) turbulence. Higher resolution models will also mean that the vertical extent of buildings will have to be considered, with schemes correctly distributing effects of buildings on heat fluxes, drag etc. over the lower parts of the boundary layer (e.g. Masson 2000, Martilli 2007, Baklanov et al. 2008, Chen et al. 2012, Santiago et al. 2013, Husain et al. 2013), in conjunction with a number of other processes.

There is also a need to improve understanding of dynamically changing land cover for model parameters. Cities are dynamic, new structures are built and there is ongoing repair and regeneration of older buildings (e.g. new roofs, painting or resurfacing of walls, roads, green infrastructure), as well as growth and management of vegetation etc. These all affect the micro-scale features of the surface. Methods need to be developed to gather this information in a routine manner, ingesting the spatially explicit parameters appropriate to models.

Research is required to advance coupled models that simulate the feedback between human activities (e.g. energy use in buildings, traffic) and urban environmental conditions (e.g. air quality, anthropogenic heat fluxes). Multi-scale modelling will allow more thorough investigations into the effects of large-scale atmospheric turbulence on the neighbourhood or micro-scale turbulence below the canopy levels. These tools need to be more thoroughly developed for a wide range of applications (e.g. the interaction between natural and built areas; human comfort; building energy consumption; and urban design).

Furthermore, research is needed to better understand the air quality weather feedbacks at urban scales, and how sensitive predictability is to the complexity of the representations of these feedbacks. Research is also needed to further develop and evaluate data assimilation methods to support coupled prediction systems.

18.3 CHEMICAL MODELLING IN THE ATMOSPHERE

18.3.1 Background

Cities emit significant amounts of pollution into the atmosphere which can result in poor air quality and large negative impacts on human health (notably in megacities, such as Beijing and Delhi). The pollutants usually result from urban transport, power generation, industry, and various cooking and heating activities. They have effects on the environment and are harmful to health. However, this pollution is not confined by city boundaries but is transported over large distances and contributes to regional and even hemispheric background pollution (Anenberg et al. 2014). Many of these pollutants, along with greenhouse gases like CO₂, can also influence weather and climate directly and indirectly.

Urban air pollution involves both primary and secondary pollutants, and can occur throughout the year. Meteorology and emissions play important roles, which are not fully understood. For example, the rise in winter haze events in east China is thought to be influenced by changes in emissions and trends in temperature and relative humidity (Wang et al. 2014).

Due to the large impacts of urban air pollution on human health, and disruptions to transport and other services during haze episodes, more and more cities around the world are expanding their air quality forecast services. The demand for, and diversity of, services using air quality prediction systems (including health alerts and emission reduction management planning) are placing increased requirements for more model products and at higher spatial resolution. In addition, the need to also address climate services expands the scope of the prediction systems to include greenhouse gases and radiative forcing due to greenhouse gases and short-lived climate pollutants (e.g. black carbon).

18.3.2 Underpinning research

A number of recent international studies have been initiated to explore these issues^a. These aim to assess the impacts of megacities and large air-pollution hotspots on local, regional and global air quality; to quantify feedback mechanisms linking urban air quality, local and regional climates, and global climate change; and to develop improved tools for predicting air pollution levels in cities. The sources and processes leading to high concentrations of the main pollutants, such as ozone, nitrogen dioxide and particulate matter, in complex urban and surrounding areas are not fully understood. This limits our ability to forecast air quality accurately. Air quality prediction is strongly dependent on the estimates of emissions. Emissions impacting urban environments include those related to transportation, power generation, industrial, and cooking, heating and cooling. But wind-blown particulates and smoke from forest and agricultural fires also need to be considered. Air

^a See MILAGRO (www.mce2.org), MEGAPOLI (<http://megapoli.info/>), CityZen (wiki.met.no/cityzen/start), ClearfLo (www.clearflo.ac.uk), WISE (Seoul), and SUIMON (Shanghai). A comprehensive worldwide overview of impacts of megacities on air pollution and climate and corresponding projects is available at WMO/IGAC (2012).

quality forecasting activities place additional demand on the emission estimates, including representing near-real-time estimates of the contributions from fires and dust outbreaks. Substantial work has been done in recent years on emission estimates (e.g. Vermote et al. 2009, Kaiser et al. 2012). Comparison of three major global emissions inventories, alongside two city-level inventories, showed that the sources and degrees of emissions vary hugely between megacities, in particular, by geographical region (van der Gon et al. 2011). For example, much of the megacity emissions in Europe and the Americas are associated with traffic and road use, whereas in Asia and Africa the output currently largely stems from residential energy use.

Secondary air pollutants (e.g. ozone, and secondary inorganic (e.g. sulphate) and organic aerosols) can be major components of air pollution in urban environments. Improving the understanding of secondary aerosol formation has been an active research area, and improved treatments are now being incorporated into air quality models (Tulet et al. 2006). But more work is needed. Other research relates to aerosol interactions with clouds and radiation, data assimilation that includes chemical and aerosol species, dynamic cores with an efficient multi-tracer transport capability, and the general effects of aerosols on the evolution of weather and climate. All of these areas are concerned with an optimal use of models on massively parallel computer systems.

The numerical models most suitable for integrated operational urban weather, air quality and climate forecasting systems are the new generation of limited-area models with coupled dynamic and chemistry modules (so called Integrated Meteorology-Chemistry Models, IMCM). These models have benefited from rapid advances in computing resources, along with extensive basic science research (Zhang 2008, Baklanov et al. 2014).

Current state-of-the-art IMCMs encompass interactive chemical and physical processes, such as aerosols-clouds-radiation, coupled to a non-hydrostatic and fully compressible dynamic core that includes monotonic transport for scalars, allowing feedbacks between the chemical composition and physical properties of the atmosphere. These models are incorporating the physical characteristics of the urban built environment discussed earlier. Recent studies have shown that the effects of the built environment, such as the change in roughness and albedo, the anthropogenic heat flux, and the feedbacks between pollutants and radiation, can have significant impacts on the air quality levels (compare Yu et al. 2012, 2014).

However, simulations using fine resolutions, large domains and detailed chemistry over long time durations for the aerosol and gas/aqueous phase are computationally demanding given the models' high degree of complexity. Therefore, IMCM weather and climate applications still make compromises between the spatial resolution, domain size, simulation length and degree of complexity for the chemical and aerosol mechanisms.

A typical model run at the weather scale for an urban domain uses a reduced number of chemical species and reactions because of its fine horizontal and vertical resolutions, while climate runs generally use coarse horizontal and vertical resolutions with more detailed chemical mechanisms (Barth 2007). There are initiatives to expand the air quality related services of large forecast centres. For example the MACC-II - Monitoring Atmospheric Composition and Climate - Interim Implementation - project^b served has the pre-operational atmosphere service on the global and European scale, which is now being transitioned to operations. This activity could be extended and downscaled to megacities and urban agglomerations. This approach has successfully been applied in the research community and shows very local impacts within hot spots. However, a seamless prediction from global to local scales has not been achieved.

Large uncertainties remain in the predictions of air quality. Multi-model ensembles show promise in improving prediction skill (Zhang et al. 2012).

^b <http://www.gmes-atmosphere.eu/>

18.3.3 Linkages

The incorporation of urban effects into air pollution models is generally carried out through the “urbanisation” of meso-meteorological or NWP models (which act as driver models), or using special urban meteo-pre-processors to improve non-urbanised NWP input data. This is also the case in air pollution assessment studies following, for example, European directives (e.g. BMU, 2002).

The increasing resolution in NWP models allows more realistic reproduction of urban air flows and air pollution, and triggers interest in further experimental and theoretical studies in urban meteorology.

18.3.4 Requirements

Modelling air quality and chemical dispersion in the urban area will require improved modelling of the bio-geophysical and chemical features of the land surface and consequent exchanges of heat, moisture, momentum, radiation (the surface energy balance) and pollutants with the urban boundary layer (UBL). Research with CFD/LES/DNS codes jointly with physical modelling (wind tunnel experiments) will allow improved understanding of wind and pollutant transport in regimes other than skimming flow and with combined effects of wind and buoyancy. Research is needed so more realistic air pollution chemistry mechanisms can be incorporated into the models.

Of particular importance is the need to better represent local, time-dependent pollutant emissions. There are currently large uncertainties in urban-scale emissions that increase at higher resolutions. Additional demands are placed on the emissions inventories for use in forecasting activities, as such applications require up-to-date daily emissions. Emission inventories available for use in forecasting are typically produced using a bottom-up approach relying on statistics that are several years out of date. Continued efforts are needed to improve emission estimates needed by air quality prediction systems, and increased efforts are needed to design and incorporate emissions modelling/forecasts (especially those that are weather dependent) as a component of seamless prediction. The use of observations from satellite to rapidly update emissions is an area of active research (Streets et al. 2013).

Computational constraints have led to meteorological models being run at higher resolutions than chemical composition models. In the future, higher resolution chemical composition runs need to be evaluated. Some tests suggest resolutions below 1 km do not show clear improvements (e.g. Saide et al. 2011). This could relate to the dynamical model which was not built for such high-resolution. Investigations are needed to achieve better performance at fine resolutions. Different levels of chemistry sophistication are needed for different applications of urban integrated service modelling systems, e.g. for urban air quality, NWP and climate studies. Building on the tools and ongoing studies at different scales, often by distinct communities (weather/chemistry /AQ/Climate), studies are needed to provide guidance on the level of application awareness required at different scales, given the cost of including chemistry and aerosols in models. Likewise, guidance on prioritization of what is feasible, in what timeframe and within the context of regional issues (e.g. China vs Europe/North American AQ levels) would also be valuable. Further coordination between ongoing activities such as those taking place in ICAP (International Cooperation for Aerosol Prediction), where real-time comparison of global models and ensemble forecasts with aerosol representation are being undertaken, and the WGNE (Working Group on Numerical Experimentation) aerosol project are relevant examples.

Air quality services are being established in cities around the world, often stimulated by high-profile events (e.g. Olympics, Expos, etc.). Increased efforts to support and transfer knowledge gained from these efforts are needed so that lessons learned can be applied to other cities as they plan to initiate or expand urban-related services. The establishment of formal test-beds and legacy projects are possible mechanisms to support knowledge exchange. Satellite retrievals of atmospheric constituents at urban scales are becoming available (e.g. 1 km, Lyapustin et al. 2011) and are being used (e.g. Hu et al. 2014). However, they are not yet assimilated into models to improve predictions.

18.4 MODELLING URBAN HYDROLOGY

18.4.1 Background

A majority of the world's major cities are situated adjacent to water - either the sea or a major river or both. The building of cities disrupts the normal hydrological cycle of the land surface, creating impervious surfaces and culverted drainage networks, and modifying larger water courses through straightening, dredging, enclosing and damming. Cities depend on water for drinking, hygiene, manufacturing, power generation, waste disposal, heating and cooling and many other services. When there is too much or too little water the consequences can be very serious.

Floods are a recurrent hazard in many cities. Urban flooding may arise from windstorms that generate storm surges and storm waves. In October 2012, Superstorm Sandy raised a storm surge of up to 3 m along the eastern seaboard of the USA. This was sufficient at high tide to raise the sea level above the height of the sea defences, so that the waves of up to 6m, generated by the onshore winds, could run straight over the land, demolishing buildings and infrastructure for many km inland (Alves et al. 2015, Sullivan and Uccellini, 2013). Considerable damage was caused in New York from this combination of ocean surge and waves. The threat from storm surges is not confined to open ocean coastlines. Some of the most damaging surges have occurred on coastlines bordering semi-enclosed seas such as the North Sea between the Netherlands and the UK (Heaps, 1983). Cities on lakes with no tides may be built with little protection, so that a change in wind climate could lead to frequent damaging floods.

River flooding is a recurrent threat to a large proportion of major cities in all climates. Large rivers gather water from vast areas of land through networks of tributaries. Floods may be caused by unusually large amounts of rainfall or snowmelt in distant places, may be the result of unusual phasing of more modest amounts from multiple sources, or may occur due to extreme precipitation in the region of the city itself. In August 2011, flooding in rural areas of Thailand produced a massive flood that propagated down the Chao Phraya river inundating Bangkok for a period of several months (Nabangchang et al. 2015, Trigg et al. 2013). In 2009 torrential rain in Ouagadougou, amounting to a quarter of the annual average rainfall, produced a huge flood in the river destroying a dam in the reservoir in the city and forcing more than 100,000 residents to flee.

In the case of locally intense rainfall, smaller water courses and surface water flooding may be as important as the main river (Falconer et al. 2007). Whereas it may be clear which areas are at risk of flooding from major rivers, enabling defences to be constructed, flooding from local extreme rainfall will occur wherever the local natural and/or artificial drainage channels are overwhelmed, leading to flash flooding and landslides in steep topography and ponding of water in low areas, including underground shopping malls and transport corridors.

18.4.2 Underpinning research

Current hydrological forecasting capabilities depend on the use of a large number of tools developed for specific requirements (Sene, 2008). In the future there will be a move towards modelling the water cycle as an integrated whole, including water in ice, liquid and vapour phases, in the atmosphere, on the land surface, under the land surface and in the ocean. Climate models already deal with many parts of the cycle, but this integration is currently not well developed for weather forecasting timescales. In the atmosphere, the most intense rainfall is associated with convective storms, either in isolated forms or embedded in fronts and tropical cyclones. The latest generation of km-scale NWP models is able to reproduce the observed convective rainfall intensity on timescales of relevance to flood forecasting (Lean et al. 2008). However, the details of location, timing and intensity of such predictions are highly sensitive to details of the initial state, model parameterizations and representation of the surface topography, so that probabilistic prediction appears to be essential. Development of km-scale probabilistic prediction schemes is at an early stage and much more work is needed on all its aspects (Clark et al. 2010, Vie et al. 2011, Peralta et al. 2012).

Modelling the run-off in urban areas is an area of hydrology that needs considerable development. Conventional rainfall-runoff models are designed for rural land surfaces and do not take account of the routing of water by gutters, buildings or drains. Surface inundation models are designed mainly for prediction of flooding from river overtopping or breach and need further development for use with direct rainfall inputs. Drainage models deal with the highly important sub-surface water flows, but often with only a crude representation of the surface. In all of these models, the representation of sediment and detritus washed from flooded land upstream is excluded. There are major challenges to developing flood models that can include an affordable and consistent level of complexity across these different aspects (see e.g. Butler and Davies, 2010, Hedonin et al. 2013). Modelling coastal flooding from storm surges and waves has a long history in many susceptible locations. However, achievable resolutions have until recently limited such predictions to offshore conditions, from which the risk to the coastline must be inferred. New developments in variable grids, and improved physics, coupled with increased computation power are now allowing such models to forecast conditions in the surf zone, enabling a much more direct assessment of the risk of overtopping and breach of coastal defences (Alves et al. 2015). Models have been developed that integrate surge, waves and inundation across the coastline (e.g. Li et al. 2014). Achieving this in real-time forecasting will permit assessment of impact and hence of risk to be much more effective and localised.

Bringing all of these advances together so as to be able to predict the risk to inhabitants of a megacity will take many generations of modelling systems and new capabilities in observing and monitoring.

18.4.3 Linkages

Predictions of flooding from ocean surges and waves depend on detailed modelling of the interaction of ocean with coastal bathymetry. In many areas of the world the bathymetry changes as currents move sediment around the sea floor, especially during storms. Similarly, beaches and dune systems are an important component of the coastal defences of large areas of land, but these change with human activity and with waves action, especially in storms. In both areas there are requirements both for monitoring and updating of the models and for representation of the dynamical interactions during storms.

Predictions of flooding from rivers depends on knowledge of the upstream river network - the cross-section of the river, the sediment in its bed and carried in the stream, the vegetation etc. These change through the seasons, due to human activity, and due to storm water flows. A concern in many rivers is the likelihood that the river will change channel or create a new channel during a storm, leading to dramatic changes in the areas at risk from overtopping. Predictions of flooding from surface water, piped drainage and minor water courses depend critically on the (three-dimensional) topography of the urban landscape, which can change extremely rapidly. The presence of obstacles in gulleys or culverts can instantly divert water streams, while collection of detritus will modify the conveyance by piped drainage or water courses. These effects are not predictable and nor are they completely observable, so a stochastic approach to their representation seems likely to be needed.

Interactions between the different types of flooding are important. Tides and surges raising water levels in estuaries are a key contributor to flooding by rivers due to the restriction of outflow. This is well illustrated by the Thames Barrier which is more often used to restrict upstream propagation of a surge during high river flow conditions for this purpose than it is to protect London directly from a storm surge (Mikhailov and Mikhailova, 2012). Both surges and high river conditions can cause back flows in minor water courses and restrict outflows from sewers, leading to upstream flooding. These effects can only fully be dealt with in a completely coupled flood prediction system.

18.4.4 Requirements

Flooding and related land slippage is one of the most disruptive natural hazards in urban areas. City management requires fore-knowledge of the area likely to be affected, the level of impact, and its duration, so as to be able to plan resources allocations and to prioritise responses so as to

enable the continued functioning of the city as a whole (e.g. Speight et al. 2015). Individuals need to know the threat to them, their property and the infrastructure they depend on, so as to choose appropriately between evacuating, protecting and riding out the storm. In the case of some infrastructure impacts, such as roads, power and water supply, the flooding may not be local to those affected, making the communication process particularly difficult. An extreme example is the need to deter evacuation from low risk areas that on evacuation routes through areas of high flood risk.

The risk posed by flooding depends primarily on its depth, the water speed, and the duration of its stay. Water speed is the primary determinant of fatalities, not only due to drowning of individuals, but to vehicles being swept into water courses, and due to undermining and destruction of occupied buildings. Duration is significant in cutting people off from the resources needed to keep them alive - particularly, food, water and heating - and due to the growth and spread of disease. Advanced knowledge of the locations where the risk from such impacts is highest can enable both self-protection activities, such as sand bagging entrances and stocking up on food, as well as deployment of central city resources, such as pumps, boats, water tankers, generators, satellite communications etc, that might be difficult to move through the streets once floodwater has flowed through them carrying vehicles and other detritus with it.

The timescales for such deployments are critical for the usefulness of forecasts. Having sufficient staff resources to deploy will generally depend on a forecast before the end of office hours the day before the flood, while accessing equipment and getting them to the right places will require several hours. In the event of a major disaster, if support from outside the city will be required, several days warning of that level of impact will be needed. In contrast to these needs, the precise location and intensity of convective precipitation is currently predictable for only an hour ahead at best, while totals from organized bands of precipitation may be reliably predictable up to 12 hours ahead. While improvements to these capabilities will not doubt be achieved, the discrepancy indicates that decisions will need to be made predominantly on probabilistic information. This has major implications for the focus of development of prediction tools as well as in challenging the communication of information so as to achieve the most effective responses.

18.5 OBSERVATIONS TO SUPPORT URBAN-SCALE ENVIRONMENTAL PREDICTION SYSTEMS

18.5.1 Background

To evaluate model performance, improve model algorithms and provide data for forcing or assimilation, observational data are needed. Operational urban networks (within and around a city) need to be installed with attention to the optimal balance between resolution, resources and practicality. Such observational networks need surface-based instrumentation (e.g. soil moisture and air/soil/surface temperature, rainfall) and vertical profiles (from within the deep urban canopy layer to the top of the boundary layer) of temperature, humidity, wind, turbulence, radiation, air quality (gases and particles, precursors and secondary), reflectivity and refractivity.

As urban areas become larger, buildings often become taller. This is particularly the case in rapidly urbanising Asia. In Shanghai, for example, in 2012 there were >100 buildings taller than 30 stories, with one building (the second tallest building in the world) > 630 m tall (Tan et al. 2015). Such tall buildings, individually or clustered together, have implications both for the measurement of atmospheric variables and for the contexts for which the data are needed (e.g. the ability to predict conditions at a range of heights; a fire and smoke at floor 15 of at 30+ storied building disperses differently to a fire on floor 2 of a 3 storey building). As a consequence, new technologies are needed to gather observations in places where currently measurements are challenging or not possible at all. Investments are needed in conventional instrumentation, alongside high density sensor networks, mobile platforms, new remote sensing techniques and other data sources (e.g. real-time information from mobile phones and on-board computers in cars etc.), to enable improvements in technology to observe places and processes that currently are difficult. This also needs to include design and better integration of satellite observing systems.

Observations of the spread of flood water pose particular challenges in an urban environment. Flood extent is often monitored with aerial photography, but the urban canopy severely restricts the view and sub-surface flooding is not accessible to such approaches. Flow and level can be monitored in drainage pipes, but these measurements rarely give good information once flooding starts. The potentially widespread nature of urban flooding makes it difficult to adequately monitor a city with in situ instrumentation, though developments in the “Internet of Things” make cheap ubiquitous sensing a possibility for the future (e.g. Holler et al. 2014). Alternatively, crowd sourcing of flood information may provide the information required.

18.5.2 Underpinning research

Detailed guidance for observations, based on theoretical knowledge and experience gained from past studies, is available for standard urban surface observations (WMO 2008, see Chapter 11, <https://www.wmo.int/pages/prog/www/IMOP/CIMO-Guide.html>). However, numerous challenges exist in undertaking observations in the urban environment in many real world settings (e.g. Grimmond 2006, Barlow 2014) and using hardware models (e.g. Kanda 2006).

With an air quality focus, extensive field experiments in cities have provided highly resolved airborne and ground-based measurements (e.g. <http://discover-aq.larc.nasa.gov/>, Discover-AQ in Baltimore-Washington, California, Texas, Colorado). These studies have posed challenges to existing models, which are not able to resolve much of the fine structures measured nor to accurately predict pollution formation mechanisms. Future work needs to be undertaken utilizing these existing high-resolution datasets to keep advancing urban-scale models.

Satellites data are an important source of information for urban areas providing information on land use and other attributes (e.g. Jensen and Cowan 1999, Yang et al. 2003), population density (e.g. DeSherbinin et al. 2001) surface temperatures (e.g. Dousset and Gourmelon 2003), hydrology (e.g. Weng 2014) and atmospheric composition (Streets et al. 2014). Satellite derived data provide an effective way to track dynamic changes in the form (e.g. addition of taller buildings, Gamba et al. 2006) and materials (e.g. change in cladding, use of cool materials etc, e.g. Kotthaus et al. 2014) of cities. However the data often remain coarse and data at the building scale rarely are available. With a number of geostationary satellites set to launch in the next few years, the potential enhancement for a wide variety of purposes including AQ and chemical forecasts (Saide et al. 2013, Streets et al. (2014).

Most current urban observational networks fall into two groups: long-term measurements for a very limited number of variables or stations and short-term (or specific event) measurements of multiple variables for a large number of stations extending across an urban area. The former provides better data for model evaluations across seasons; the latter insights into spatial heterogeneity of urban influence and a better understanding of relations between meteorological variables. Short-term field experiments and wind tunnel studies also have been used successfully (Klein et al. 2007, 2011; Wood et al. 2009, Leidl et al. 2014). Very few urban areas are equipped with 4D measurement networks. Exceptions, include combinations of in situ surface and mast observations with radar in Hamburg (Wiesner et al. 2014), Light Detection and Ranging (LiDAR) in London (Bohnenstengel et al. 2015), and both in Shanghai (Tan et al. 2015) and Helsinki (Wood et al. 2013). More of these are needed for research within an operational context as only the latter two examples are run by meteorological agencies.

Evaluation of meteorological models using observations traditionally has been conducted in two modes: off-line (i.e. stand-alone ULSM) and on-line. In off-line mode, observations or an operational or coarser meteorological model provide the atmospheric forcing. Evaluations require verification of the urban surface description used as model input and the representation of physical processes (Leroyer et al. 2010, 2011, Grimmond et al. 2011). Analyses for several locations and variables provide the best insights into compensations of model errors or hidden meteorological features. Assessments of the performance of models does depend on the variables considered (e.g. Loridan et al. 2013) and model resolution (e.g. Leroyer et al. 2014), with differences being related to different physics in the schemes (e.g. convection representation Leroyer et al. 2014). This highlights the importance of nested observations of physical and chemical variables to ensure

that complete urban environmental prediction systems are evaluated as well as components models.

18.5.3 Linkages

Improvements of urban observational networks need to be closely linked to those in the region; the greatest benefits will come from coordinated nesting of observations (Dabberdt et al. 2013). Attention needs to be directed to the full range of modelling work that needs to be undertaken (and addressed elsewhere in this document); viz, improving physical, chemical and other application models, engaging the full suite of stakeholders and end-users. Given the difficulties of obtaining urban observations, collaborative data collection and mining (e.g. site provision, combined data systems) should aid all partners.

Another key linkage involves connecting the research community and citizen scientists. The research community are driving forward many model improvements that are needed (see other sections in this chapter), while citizens are becoming important providers of meteorological information (crowd-sourced data). For example, the Weather Observations Website (WOW) (<http://wow.metoffice.gov.uk/>), the Weather Observer Program (CWOP, <http://www.wxqa.com/>), and the Community Collaborative Rain, Hail and Snow CoCoRaHS network for precipitation (<http://www.cocorahs.org/>) all gather data, both currently and historically, that can be used to enhance modelling skill. Similarly, data from less traditional sources (e.g. mobile phones, Overeem et al. 2013) are likely to permit data collection in places not possible previously. These new data sources present major challenges for those involved in gathering and managing data. The use of this potentially transient data, with appropriate quality control, will yield useful data only through the combination of new data-mining techniques but also a good understanding of urban meteorology and atmospheric chemistry. If this expertise does not draw upon much of the rich history of study and understanding (which extends back at least over two hundred years e.g. Howard 1818) there will be unnecessary reinventing, relearning, and missed opportunities.

18.5.4 Requirements

To enhance seamless predictions in urban areas it is widely accepted that there is a need for long-term, multi-site urban observation networks reporting traditional meteorological variables, fluxes, and the vertical state of the physical and chemical properties of the atmosphere (e.g. Grimmond et al. 2010, National Research Council 2010, 2012). Advances are needed to develop methods and frameworks to analyse atmospheric data measured above and within complex urban surfaces. This needs to include attention to measurement source areas to ensure representative results and meaningful comparisons with models. Much more needs to be known about the outer layer of the urban boundary layer (UBL), the atmosphere above the ISL (inertial sub-layer). Further research is needed on the relation between urban morphology and flow (and exchanges) within the canopy, directly above, and with the UBL. Research is also needed to better understand the coupling of surface and air temperatures. Similarly, there is a need to improve our understanding of ventilation and pollutant removal mechanisms (vertically and laterally) for three-dimensional street canyons.

Design of observation networks, for multiple-scales of interest from a larger region to the key areas of particular interest will be essential to improve model prediction times for extreme events. Research is needed on appropriate densities for such networks, including provisions for redundant information. Both the physical and chemical characteristics of the atmosphere need to be considered. Risks associated with exposure (e.g. to air quality, heat, intense precipitation) need to be better understood and taken into consideration in providing climate services. This needs to be explored as part of network design. Given network expansion and operations can be costly, these need to be optimally designed.

Given the potential range of new measurement approaches and the diversity of settings for siting of such instruments, appropriate metadata and protocols must be developed and reported. This will enable the data collected to be used appropriately for wide-ranging applications (e.g. the needs of those interested in wind loading on a building are markedly different to data to force operational weather models). Smart protocols, to address data quality control, siting and metadata, can help to

ensure all users are served well with the potential wealth of urban data. Better information on the urban surface is needed to provide site metadata for observations and as input for urban models. Improved methods are needed to determine key urban surface characteristics; for example, material radiative (e.g. albedo, emissivity), thermal (e.g. heat capacity) and water (uptake and storage) properties. Soil characteristics and ground water conditions need to be known along with vegetation types and their biophysical status. Remote sensing techniques need to be developed so that additional data sets for modelling urban areas are available (e.g. time dependent leaf area index, soil moisture for dense urban areas, Ye et al. 2011). In addition, enhanced spatial resolution and/or improved algorithms to deal with the challenges of the range of urban materials found in small areas, combined with their complex geometries (e.g. creating shadows, mixed pixels) are needed. Given the rapid changes that occur in many urban settings (associated with development and redevelopment), methods to facilitate timely updates also are important. Current activities associated with the WMO Integrated Global Observing System (WIGOS^c) and WMO Information System (WIS^d) could be of assistance in supporting urban-related data needs and management.

Methods need to be developed and evaluated to enhance the suite of variables that are directly modelled and directly observed (e.g. surface “temperatures”, structure function parameters). This requires advances in both modelling and observations. These variables need to be measured over extensive spatial domains (e.g. remotely sensed) and address assumptions to yield the “observed” or ‘modelled’ data, given the challenges and complexity of the urban surface.

The impact of the patchwork of changing densities and heights of buildings (and trees) across the city needs to be much better understood. This requires advances in measurements of the mean and turbulent characteristics of the urban atmosphere in such settings. For example, Doppler LiDAR misses the lowest 90-100 m; SOnic Detection And Ranging (SODAR) is too noisy in urban areas. Attention is also needed to how to model the processes occurring within and above tall urban surfaces. DNS and LES currently require too much computational resources to undertake realistic simulations for extensive areas, i.e. to yield realistic surface temperature forcing, stabilities, and there are minimal data for evaluation of model results (e.g. extensive atmospheric and surface measurements of radiation, temperature, wind, chemical concentrations, horizontally and vertically within tall urban canyons). Moreover, instrumentation needs to be developed and deployed to sample this environment at rates that are compatible with the modelling.

Observations are needed for a larger range of urban land uses (morphologies) to establish universal flow and flux characteristics. Existing long-term measurement stations need to be preserved to enable broader spatial representativeness of frequent, rare and extreme urban phenomena. Simultaneous measurements of flow properties at various sites/levels are needed to better understand coherent structures and intermittent ventilation processes within the RSL.

To improve the understanding of air quality and greenhouse gases, measurements of fluxes of greenhouse and other gases and particles need to be undertaken. These need to be combined with isotopic and chemical fingerprint analysis to determine not only the magnitudes of these fluxes but also to identify emission sources (e.g. background concentration, gasoline combustion, natural gas combustion and respiration).

Anthropogenic gas, heat and moisture emissions need to be better quantified by improved measurement and estimation techniques at a range of scales. The individual building scale permits closure of budgets (e.g. energy) for a control volume and is the scale for much decision-making. For applications and future model development, model evaluation and integration of physical and chemical processes at this scale will need nested observations down to this scale. Given the immense size and variations in tall buildings in cities, there are many challenges that need to be overcome.

^c http://www.wmo.int/pages/prog/www/wigos/index_en.html

^d <http://www.wmo.int/pages/prog/www/WIS/>

Hydrological processes, including precipitation patterns, soil moisture, evaporation rates and runoff are spatially variable across a city. Enhanced knowledge of these patterns, as precursor conditions for intense rainfall events, is needed to enhance the provision of weather and climate services to predict and respond to hydro-meteorological events that can be life threatening (e.g. intense precipitation, flooding). The influence of cities on precipitation patterns has been (e.g. Lowry 1998) and remains an area of intense research need (e.g. Han et al. 2014).

People spend a large amount of their daily lives indoors, yet the interaction of atmospheric conditions indoors and outdoors is poorly understood. Ingested air impacts the comfort, health and operations of the buildings. Greater knowledge of actual in situ conditions can reduce energy usage and CO₂ emissions. Consideration of external emissions with building openings and air-intakes also is important and if better known could reduce resource use and improve the health of those internally and outside. Thus many would benefit from improved predictive capability of well evaluated and routinely run models that capture these interactions.

In addition to physical and chemical processes of the urban atmosphere, are human behaviours (individually and collectively) impact emissions (e.g. atmospheric pollutants, energy, water, heat) and these need to be observed and incorporated into modelling. Many end-users (e.g. street vendor, outdoor sports person, car driver, etc.) would like tailored products. Human response on mass (e.g. mode of transport used) have important feedbacks on urban environmental prediction systems. The more seamless methods to capture these controls and feedbacks, the more effective predictive models will be.

Data assimilation (DA) in the urban environment is another area that needs extensive exploration and should be considered as part of new observational network design. Current DA techniques for atmospheric and chemical models rely on traditional meso-net observations. With the recent availability of large urban observational networks, it may become possible to provide higher resolution analysis that integrates urban climate. Forecasting over urban areas will then benefit from improved initial conditions. The 4-D nature of physical, chemical, and human processes/states is needed for the wide range of models continuously operated to maintain city operations. Consideration initially is required to assess what variables, at what scale and with what error will be beneficial for DA. Data assimilation in coupled models is in its early stages and applications are illustrating the co-benefits to improved forecasts that are possible by assimilation of both meteorological and atmospheric composition observations (Saide et al. 2012, 2013, 2014; Bouquet et al. 2014). Given the elementary nature of the capabilities at the moment, development of the human capacity and observations in focussed areas may be the essential starting point.

18.6 INTEGRATION AND APPLICATIONS

18.6.1 Background

Success in improving predictive capabilities for urban areas depends on a set of issues including: initiation of integrated urban weather, climate, water and related environmental services, databases and data sharing (e.g. socio-demographic data, observations), modelling and prediction, applications, communications and outreach, evaluation, research and capacity development. Seamless prediction of weather and air quality and projection of climate in urban areas necessitates integration of complex elements of the Earth system drawing on advances which historically have been reached almost independently. With increasing computational power in operational and research centres, and increasing amounts of available data, the logical trend is to build comprehensive coupled systems to serve megacities, agglomerations and smaller urban areas.

Applications are, however, becoming wider, and the list of potential end-users increasing (e.g. NRC, 2012). As highlighted above, the main applications concern NWP, air quality (prediction and assessment), flooding and climate (projection and assessment of adaptation measures). Public health agencies also are requesting more and more derived products as the potential for seamless predictions in urban areas increases.

These tools are needed not only for short events but also long-term operations of cities. Urban planners require the scientific background for pertinent strategies to both mitigate and adapt their city to climate change (Lemonsu et al. 2014). Tools needed to be generic, but also capable of taking into account site characteristics and local geographical, historical and social features and impacts (Masson et al. 2014). Cultural and social behaviours, in a governance context, modify people's behaviour. This interacts with, and feedback to, the urban climate increasingly (e.g. the urban heat island). Thus seamless weather prediction in the urban context extends from meteorological and chemical processes to include hydrological, economic and social dimensions. The services need to cross multiple scales, from the individual (e.g. exposure) to the city (e.g. urban planning), supporting decisions at times scales from short term (e.g. fire related, energy use) to those that impact for hundreds to thousands of years (e.g. urban planning). With it the dissemination of raw or derived products has to support the wide range of end-users (e.g. from specialized operational requirements to the public or non-specialists).

18.6.2 Underpinning research

Understanding of the interactions between urban/social processes and heat/pollutant emissions needs to improve and current basic and applied knowledge in these disparate fields needs to be drawn together (Grimmond 2013). The World Meteorological Organization's (WMO) Global Atmosphere Watch (GAW) Urban Research Meteorology and Environment (GURME) project^e has helped enhance capabilities of some national meteorological services to handle meteorological and related aspects of urban pollution and urban extreme weather.

Some operational centres already provide services that use integrated models (e.g. Tan et al. 2015). This is helpful, but will benefit from future research and development of coupled models. As already noted research on basic physical and chemical processes, and the development of numerical models and tools are integral components to reliable and accurate forecast products and services. As operational personnel cannot be fully responsible for all the research and development activities, strong and long-term partnerships need to be established and sustained between researchers and internal and external operational groups. These partnerships should promote the development of methods to measure improvements in forecast skills and benefits.

Cities exist within the context of other globally changes. The impact of this on cities needs to draw upon the understanding of the large-scale and long-term processes (e.g. ocean temperature and currents, sea-level rise, changes in land cover, slow-changing atmospheric variables). These changes can produce climate fluctuations that potentially are predictable at seasonal and inter-annual timescales. Targeted prediction products, of temperature, rainfall and high-impact events (e.g. heat waves (several days), floods (minutes to several days)) can refine regional downscaling of integrated climate-chemistry or Earth system models. Concurrently improvement to global models and bias corrections associated with downscaling also are needed (e.g. Schoetter et al. 2012).

18.6.3 Requirements

In cities there are extensive ranges of specialized end-users, and often there is a mismatch between availability of tools and demands. As new tools are developed to support end-users, it is important that due attention is given to the dynamic changes (e.g. data availability, communications) to benefit research intensive situations and those in operational situations that may be data poor. Thus, for example, emergency response situations with minimal real-time data (e.g. winds from the nearest airport) can benefit from new tool development incorporating the essential urban 3-D urban morphology (GIS) data if gathered. It is critical that new tools are made 'openly' available, to reduce duplication of effort and to focus attention on improvements. In some cases developing web-based interfaces to run the models may greatly enhance usage, as will simple tools to improve provision of data.

^e <http://mce2.org/wmogurme/>

Many policy-makers, in different governance structures, along with community groups are actively engaged in proposals and discussions to enhance urban sustainability and resilience. These may involve changes to the local buildings/infrastructure in terms of urban greening through tree planting; repaving/replacing roads/pavements with high(er) albedo or low-emissivity materials, , Sustainable Urban Drainage Systems (SUDS: see e.g. Butler and Davies, 2010) or investing in multi-function solutions. Tools are needed that allow such stakeholders to consider competing and unintended impacts of suggested changes. For example, green infrastructure introduced with the intent of reducing air temperatures, will increase humidity and change the air quality. Stakeholders need to be able to consider the net benefits to health and comfort in the context of their city. To achieve this goal, limit values for heat and moisture exposure as well as for wind load need to be developed. Different considerations will come into play if the concern is with day-to-day management versus extreme events. Who the stakeholders and end-users are needs to be explored, with the intent of engaging these evolving communities with the applications of interest to them, with attention to the scale of interventions needed. Such needs assessments should inform research developments to address those with greatest demand and potential benefit. The breadth of these stakeholders and end-users, and how they vary between and across cities, also needs to be recognized.

Enhancing two-way communication between the meteorological community and those operating city services is essential in ensuring the tools developed are usable and beneficial to residents/occupants of cities. High profile special events (e.g. Olympics or other sports events, political meetings, etc) have been catalysts in developing collaborations with stakeholders and end-users to develop early warning systems (e.g. Beijing London, Shanghai, Toronto, Glasgow). However, many improvements are needed and learning from these events/settings needs to be generalised.

Knowledge of what information, what form it needs to be presented in, and with what lead times needs to be gathered. For example, a number of public health warnings could be improved by providing more tailored forecasts (e.g. heat waves, cold, air quality, pollen, flooding). Consideration, through collaborations with stakeholders and end-users, is needed as to what improvements of weather products will be of greatest benefit to the end-users. It is critical to develop appropriate and effective ways to communicate data and warnings, both through conventional means and current (and evolving) electronic media.

18.7 CONCLUSIONS

Weather, climate, water and related environmental conditions have profound effects on cities and their residents. The majority of the world's population is now urban and city dwellers. Worldwide cities are growing, particularly in Asia and Africa. Increasing attention is being directed to the predictions of atmospheric conditions and its interaction with other components of the Earth System at the scale of cities, in the context of better understanding the risk and resilience of urban environments. Recognition is also emerging of important variability across large conurbations and the effects of the cities and their residents on atmospheric processes and local conditions. This summary highlights that much remains to be done and the importance of a coordinated and strategic approach to maximize benefits to stakeholders and to best draw on research capacity. The key areas where investment is particularly important, identified also by others, are highlighted in terms of observations and metadata; frameworks for analysis; models; tools; and communication. Specific recommendations are made about: (1) development of high-resolution coupled environmental prediction models that include realistic city specific processes, boundary conditions, and fluxes of energy and physical properties; (2) enhanced urban observational systems to determine unknown processes and to force these models to provide high quality forecasts to be used in new urban climate services; (3) understanding of the critical limit values for meteorological and atmospheric composition variables with respect to human health and environmental protection; (4) new, targeted and customized delivery platforms using an array of modern communication techniques, developed in close consultation with users to ensure that services, advice and

warnings result in appropriate action and in turn inform how best to improve the services; (5) the development of new skill and capacity to make best use of technologies to produce and deliver new services in complex, challenging and evolving city environments.

An overall challenge moving to higher resolution and taking into account the considerations highlighted here, is to ensure that a balanced effort across all aspects occurs, rather than striving for disproportionate accuracy in one part of the model while gross errors remain in other parts.

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