AMBIO 2012, 41:851–864
DOI 10.1007/s13280-012-0288-z

KUNGL.
VETENSKAPS-
AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

REVIEW PAPER

Interactions of Physical, Chemical, and Biological Weather Calling for an Integrated Approach to Assessment, Forecasting, and Communication of Air Quality

Thomas Klein, Jaakko Kukkonen, Åslög Dahl,
Elissavet Bossioli, Alexander Baklanov, Aasmund Fahre Vik,
Paul Agnew, Kostas D. Karatzas, Mikhail Sofiev

Received: 19 September 2011 / Revised: 3 February 2012 / Accepted: 3 April 2012 / Published online: 25 May 2012

Abstract This article reviews interactions and health impacts of physical, chemical, and biological weather. Interactions and synergistic effects between the three types of weather call for integrated assessment, forecasting, and communication of air quality. Today's air quality legislation falls short of addressing air quality degradation by biological weather, despite increasing evidence for the feasibility of both mitigation and adaptation policy options. In comparison with the existing capabilities for physical and chemical weather, the monitoring of biological weather is lacking stable operational agreements and resources. Furthermore, integrated effects of physical, chemical, and biological weather suggest a critical review of air quality management practices. Additional research is required to improve the coupled modeling of physical, chemical, and biological weather as well as the assessment and communication of integrated air quality. Findings from several recent COST Actions underline the importance of an increased dialog between scientists from the fields of meteorology, air quality, aerobiology, health, and policy makers.

Keywords Air quality · Health impacts · Pollen · Bioaerosols · Monitoring · Modeling · Policy

INTRODUCTION

Outline

This article reviews health impacts and interactions of physical, chemical, and biological weather and their implications for the assessment, monitoring, forecasting, and communication of air quality. In this article, the terms physical, chemical, and biological weather are used as in current European and international research communities such as the COST networks ES0602 (COST ES0602 2011), ES0603 (COST ES0603 2011), ES1004 (COST ES1004 2011). Definitions:

- Physical weather is defined as the short-term atmospheric state and variation, characterized by physical atmospheric variables, such as solar radiation, temperature, humidity, pressure, and wind speed and direction.
- The term chemical weather in turn is defined as the short-term (<2 weeks) state and variation of the atmospheric chemical composition (Lawrence et al. 2005; Kukkonen et al. 2012).
- By analogy, the short-term state and variation of concentrations of bioaerosols, such as allergenic pollen and fungal spores, can be defined as the biological weather.

The term "air quality" in this article is defined in a broad sense, including also bioaerosols.

The article starts with a brief introduction to health aspects of physical, chemical, and biological weather. The "Main analysis" section provides a review and a concrete example of interactions among the different types of weather as well as a critical analysis of the existing policy frameworks and infrastructures used to assess, forecast, and communicate air quality. The article concludes with a list of identified gaps and associated recommendations.

Our review is based on the existing scientific literature and findings from five workshops and expert meetings organized by the COST Action ES0602: "Towards a European Network on Chemical Weather Forecasting and Information Systems (ENCWF)" (Kukkonen et al. 2009). Our analysis focuses on Europe with selected references to scientific findings for other regions. For the sake of compendiousness, we exclude issues such as pollution from accidents and natural air pollution from other than biological sources, and air pollution impacts on vegetation or materials. For an overview of physical, chemical, and biological weather in a changing climate the reader is referred to existing reviews (e.g., IPCC 2007a, b).

Health Impacts of Physical, Chemical, and Biological Weather

Physical weather can include a wide variety of hazardous extreme weather events, such as tornados, severe storms, heatwaves, etc. We focus in this brief review solely on temperature effects.

Exposure to high temperatures causes increases in blood viscosity, blood cholesterol levels, and mortality forward displacement (Huynen et al. 2001). Recent European heatwaves include the 2003 heatwave, the less severe heatwaves in 2006 and 2007, and the 2010 Russian heatwave. During the latter heatwave, weeks of unprecedented heat and suffocating smog led to a significant rise in mortality (e.g., Barriopedro et al. 2011).

Detrimental effects of cold weather on health have also been observed. Cold spells may affect cardiovascular and peripheral diseases, cerebrovascular diseases, and respiratory diseases, and may contribute to communicable diseases. Influenza also indirectly contributes to cold-related mortality. Increased risk of injuries and frostbite can be observed. In contrast to heatwaves, extreme cold does not lead to cold-induced mortality forward displacement (Huynen et al. 2001). However, effects on mortality may persist for considerable time periods, beyond 2 weeks (Keatinge and Donaldson 2001; Carder et al. 2005), opposing the initial suggestions for immediate effects (e.g., Alberdi et al. 1998; Pattenden et al. 2003). According to Keatinge and Donaldson (2001), atypical patterns of prolonged cold weather can give false indications of mortality associated with sulfur dioxide (SO_2), carbon monoxide (CO), or smoke episodes.

Chemical weather can affect respiratory, cardiovascular, immunological, hematological, neurological, and reproductive developmental systems. Existing literature (e.g., WHO 2005; Curtis et al. 2006) demonstrates the associations between exposure to atmospheric pollutants and ill-health endpoints. According to an assessment of air pollution in Europe for the period of 1990–2004, the main air pollution human health issues in Europe are impacts of exposure to particulate matter (PM) and ozone (O_3), and to a lesser extent nitrogen dioxide (NO_2), SO_2, lead, benzene, and other heavy metals, and persistent organic pollutants (EEA 2007). In a mapping study for 2005 (EEA 2009), the number of premature deaths per million inhabitants attributable to PM_{10} exposure (the EU27 as a whole) is estimated to range from 510 to 1150 cases per million, with a best estimate of 830 deaths per million (median).

Biological weather can imply health impacts through adverse concentrations of pollen, spores, viruses, bacteria, and microbes. Diseases due to aeroallergens (allergic asthma, hay fever, and atopic dermatitis) are among the major causes of a growing rate of morbidity and demand for healthcare. In a pan-European survey of an unselected population, the prevalence of self-reported allergic rhinitis was 18.7 % across Europe (Bauchau and Durham 2004). In the European Community Respiratory Health Survey (ECRHS), another population-based study, the sensitization rate was 19.3 % for pollen and 4.4 % for molds. Among subjects with rhinitis sensitized to pollen, 16 % also had asthma, and among those with rhinitis sensitized to molds, the asthma prevalence was 22 % (Leynaert et al. 2004). Among asthmatics in general, the prevalence of mold sensitization is around 30 %, and is also associated with asthma severity (Denning et al. 2006).

MAIN ANALYSIS

Interactions

Physical and Chemical Weather

Physical weather is a key driver of chemical weather. It impacts on emissions, transport, chemical processes, and atmospheric removal processes (e.g., Seinfeld and Pandis 2006). There is also increasing evidence of chemical weather impacts on physical weather. Examples of the latter include aerosol feedbacks on meteorology (e.g., Baklanov et al. 2007; Jacobson et al. 2007; Zhang 2008), such as:

- a reduction of downward solar radiation (direct effect);
- changes in surface temperature, wind speed, relative humidity, and atmospheric stability (semi-direct effect);
- a decrease in cloud drop size and an increase in drop number by serving as cloud condensation nuclei (first indirect effect);
- an increase in liquid water content, cloud cover, and lifetime of low level clouds, and suppression or enhancement of precipitation (second indirect effect).

Traditionally, aerosol feedbacks have been neglected in numerical weather prediction (NWP) and air quality modeling mostly due to a historical separation between the meteorological and air quality communities as well as a limited understanding of the underlying interaction mechanisms. Such mechanisms may, however, be important on a wide range of temporal and spatial scales, from days to decades and from global to local. Field experiments and satellite measurements have shown that chemistry-atmosphere feedbacks exist among the Earth systems including the atmosphere (e.g., Grell et al. 2005; Rosenfeld et al. 2007, 2008). The issue of including aerosols in NWP models is currently being addressed (e.g., Grell and Baklanov 2011).

Synergistic health impacts of physical and chemical weather are especially evident at local levels, e.g., in urban heat islands (McMichael 2000). Increasing energy demand increases the energy-related primary emissions, while elevated temperatures increase directly the formation rate of secondary pollutants. In urbanized areas, the spatial distribution is also influenced by enhanced turbulence (e.g., Sarrat et al. 2006; Bossioli et al. 2009). The combined effect of higher air pollution levels, increased daytime temperatures and reduced nighttime cooling, can affect human health directly (McMichael 2000). The spread of vector-borne diseases can also be enhanced. The combined effect of urban heat islands and heatwaves may also increase the risk for potential heat-related illness for the individuals living in the urban zone (Basara et al. 2010). The possibility of interactions between cold temperature and air pollutants in terms of their effect on cardiorespiratory mortality and whether this relation varies according to season has been investigated (Roberts 2004; Carder et al. 2008).

A recent example of a prolonged episode with interactions and joint impacts of physical and chemical weather in Eurasia is illustrated in Fig. 1 (2010 Russian heatwave). The episode was characterized by the simultaneous effect of anomalously high temperatures and severe air pollution from the wild-land fires in Central Russia. It is noteworthy that the meteorological conditions enhanced the fire development and also provoked the concentration build-up due to poor ventilation of the lower troposphere in the anti-cyclonic conditions. Potential contributions of biological weather to health impacts during this episode have not been studied.

Physical and Biological Weather

The primary driver of biological weather is the climate, i.e., the long-term average of the physical weather, but its effects are to a large degree modified by short-term physical weather. Physical weather controls the reproduction of plants and fungi and thus the emissions of pollen and spores as well as their atmospheric transport, diffusion, and deposition. Changes in meteorological factors can affect aeroallergen production, which in turn impacts the prevalence or severity of allergic illness via sensitivity and response pathways. Changes in the timing and length of the pollen season, as presently observed as a result of climate change, lead to changes in human exposure, which can affect sensitization as well as exacerbation of allergic illnesses (Reid and Gamble 2009).

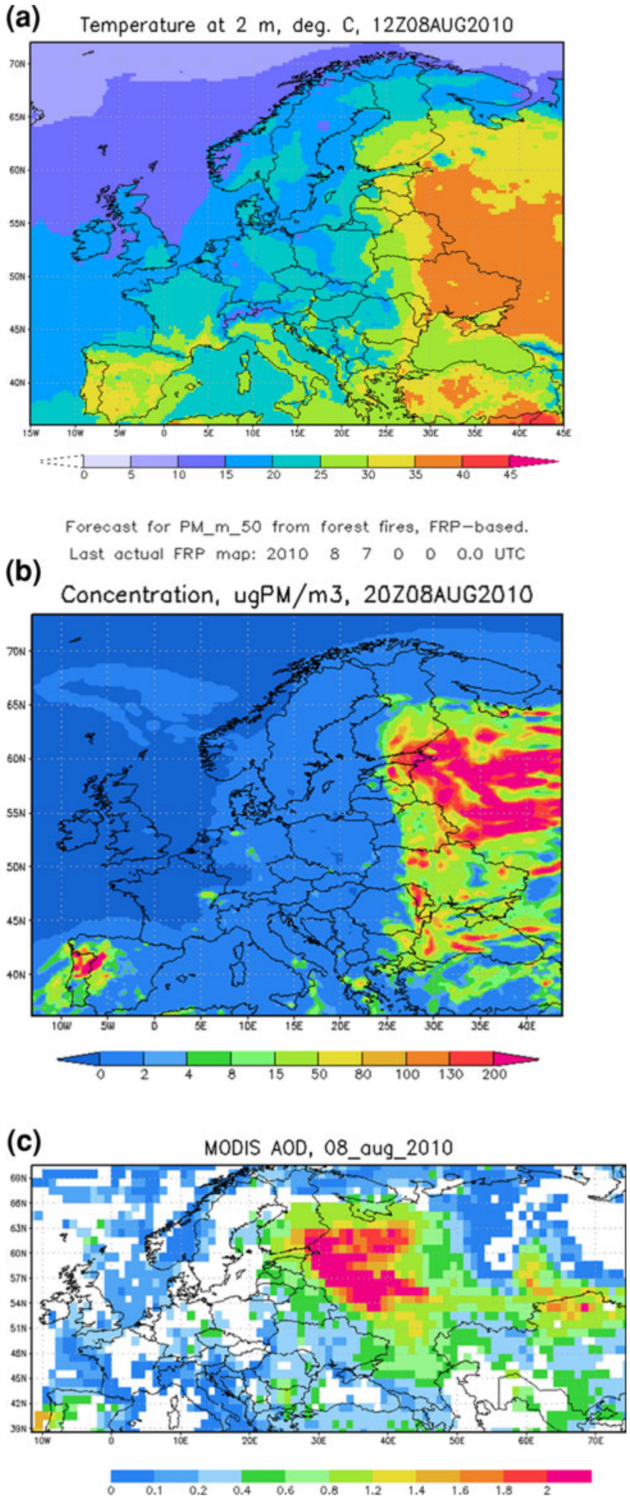


Fig. 1 Example of an episode with severe physical and chemical weather (2010 Russian heatwave): **a** air temperature at 2 m (C), based on 12-h-ECMWF deterministic forecast, valid at 2010-08-08 1200UTC, **b** SILAM-predicted fine PM from wild-land fires (μg $PM_{2.5}\,m^{-3}$), valid at 2010-08-08 2000UTC, **c** MODIS aerosol optical depth at 550-nm wavelength, valid at 2010-08-08

Physical weather can affect the size and nature of the biotic matter in the air. For instance, damaged pollen grains that may have burst from excess water or osmotic shock can expel cytoplasm debris of micronic and submicronic size (subpollen particles, SPP). These minute particles are often associated with cytoplasmic allergens. In ragweed, they have been shown to carry enzymes that cause oxidative stress and allergic airway inflammation. As with other small particles, SPPs are able to penetrate deep into the airways, where they can have direct inflammatory effects and where they may induce a stronger immune response than intact pollen does. Grass pollen grains are sensitive to humidity and can rupture in the anthers during moist conditions (Taylor et al. 2007 and references therein).

Schappi et al. (1997) found that atmospheric birch pollen allergen concentrations are correlated with birch pollen counts, but that light rainfall produced a dramatic increase in birch allergen-loaded respirable particles in the atmosphere. In Derby, UK, pollen levels had an effect on emergency visits for asthma on days of light rainfall, but not on dry days (Lewis et al. 2000). An increased incidence of asthma has been observed in connection with large-scale thunderstorms. It was suggested that during such weather, bioaerosols can be trapped into a cloud base, where they are exposed to electric fields that cause them to rupture and fragment. Cold outflows transport the debris, containing, e.g., fragmented fungal spores, to ground levels, where sensitized people may react to their allergens (Pulimood et al. 2007). Resuspension processes can play a significant role in secondary re-emission of pollen particles during dry weather conditions.

Chemical and Biological Weather

Chemical weather can cause quantitative and qualitative changes of the content of bioaerosols, e.g., of pollen, increase their allergenic load and the bioavailability of their content. The pollen grains contain proteins, including allergens, and an array of non-allergenic and pro-inflammatory lipid mediators and enzymes, that have been suggested may be involved in the pathogenesis of allergic diseases (Gilles et al. 2009). Pollutants may cause collapse and thinning of the outer pollen wall (Shahali et al. 2009), and facilitate the release of the pollen content, including sub-pollen particles (Traidl-Hoffmann et al. 2009). In a contaminated environment, the amount of allergenic proteins or lipid mediators may increase (Aina et al. 2010) and the proteins can easily be nitrated by polluted air which may augment their allergenic potential. Pollen grains absorb heavy metals, nitrate, and sulfur.

The defense system of the human airways can be altered by air pollutants, which induce respiratory inflammation and impact the response to bioaerosols. The response tends to promote allergic reactions in predisposed individuals. The impact involves damage to the mucociliary system and to the epithelium, giving an increase in airway permeability (D'Amato et al. 2000), which is partly caused by oxidative stress. O_3, NO_2, and particulate pollutants oxidize biomolecules. Thereby, they induce the production of reactive oxygen species (ROS) that induce or aggravate allergic inflammation. Vagaggini et al. (2002) suggested that O_3 and NO_2 exposure may "prime" eosinophils for subsequent activation by the allergen. Exposure to O_3 and NO_2 lower the response threshold to bioaerosols (D'Amato et al. 2000; Peden and Reed 2010 and references therein).

Diesel exhaust particles (DEPs) represent the major part of inhaled abiotic particles below 2.5 µm in urban surroundings. Their particulate nature has adverse effects, but they also challenge the airways because of their association with organic compounds. For example, polycyclic aromatic hydrocarbons (PAHs) easily enter the circulation, e.g., through the alveolar epithelium, where they interact with cells involved in the immune response, contribute to enhanced antibody (IgE) and cytokine synthesis, and to an increased release of inflammatory mediators even in the absence of antigen (Lubitz et al. 2010 and references therein). They do so also at low ambient concentrations and at short-term exposure (Li et al. 2003; Schober et al. 2007). In birch pollen-sensitized persons, but not in non-atopics, DEPs synergizing with antigen can significantly enhance the activation of basophils that are key initiators of immediate allergic responses after allergen exposure (Lubitz et al. 2010). Pollen grains can carry DEPs and other particles on their surface (Traidl-Hoffmann et al. 2009 and references therein).

Other evidences of synergistic effects of bioaerosols and chemical weather are from long-term epidemiological studies evaluating the relationship between, e.g., living in an area with a high load of traffic pollutants and the risk of developing allergic disease and asthma (Bråbäck and Forsberg 2009). Indoor air is a complex mixture of bioaerosols and chemical pollutants, of which some enter the building through ventilation and leaky envelopes. In the RIOPA-project, it was found that almost three quarters of indoor $PM_{2.5}$ concentration had an outdoor origin (Meng et al. 2005; RIOPA 2011). Several studies conducted in different countries and under different climatic conditions show that the occupants of damp or moldy buildings are at increased risk of respiratory disease and exacerbation of asthma, even if the causative agents of these have not yet been identified conclusively.

There are few short-term epidemiological studies showing acute, short-term reactions due to such combined effects. In some of the studies that have collected both the aeroallergen data and the pollutants, a potential synergy was not evaluated, but one factor or the other has been regarded as a possible confounder. The results from studies addressing interaction are contradictory. The levels of O_3, SO_2, and PM_{10} were associated with an increased risk of asthma symptoms in pollen-allergic asthmatic patients (Feo Brito et al. 2007). Dales et al. (2004) found a synergistic adverse effect of O_3 and aeroallergens combined. Higgins et al. (2000) found a relationship between symptom severity of asthma and chronic obstructive pulmonary disease (COPD) and the prior O_3 level, indicating a potentiating role of the latter. Hospital admissions have been related to an interaction between airborne pollens and particulates (Lierl and Hornung 2003; Ghosh et al. 2010). A number of authors (references in Fuhrman et al. 2007; Peden and Reed 2010) found significant but independent effects of pollen and air pollution. Low et al. (2006) found independent exacerbating effects of warmer, drier air, grass pollen, SO_2, and particulate air pollution, on upper respiratory infections and stroke incidence. A data-driven analysis conducted with the aid of computational intelligence methods indicated strong correlations between pollen concentrations of particular taxa (*Betula*, *Alnus* and Poaceae) with PM_{10} and O_3 (Voukantsis et al. 2009).

A number of other studies did not find any convincing evidence of interaction (e.g., references in Fuhrman et al. 2007). Possible explanations of the contradictory results are geographical differences in the species mix of aeroallergens and in the prevalence of sensitization in the human population (Heinzerling et al. 2005). The majority of studies have focused on the most severe episodes, although there may be an aggravation of symptoms without needing emergency care. The relationship between effects and aeroallergen levels could be nonlinear (Tobias et al. 2004; Erbas et al. 2007), whereas some authors have looked for linear effects only. The study period was not always limited to the period of pollen or spore dispersal. Then, the subject group sometimes included both the atopics and the non-atopics, although their reactions are likely to be different.

The existing evidence of physical, chemical, and biological weather interactions with regard to atmospheric emissions, transport, deposition, and human health is summarized in Table 1, while Fig. 2 provides a graphical illustration of selected interactions.

An illustration of combined health impacts of physical, chemical, and biological weather is given in Fig. 3. It should be noted that interactions and synergistic effects may lead to an earlier appearance or aggravation of certain impacts/symptoms and to larger parts of the population being affected compared to the isolated health impacts of either type of weather.

An Example of an Integrated Air Pollution Episode

An example episode that contained pollen, pollutants from wild-land fires and anthropogenic air pollution occurred in Europe in April and May 2006 (Sofiev et al. 2011). Examples of predicted concentrations during this episode are presented in Fig. 4. In a comparison to MODIS data, Sofiev et al. (2011) found that the prediction model SILAM correctly captured the main developments of the main fire-induced episode. Verification against in situ pollen measurements showed that pollen arrival dates were within an error range of ±1 day and that the absolute levels of the concentrations were of the same order of magnitude as the observations. The birch pollen mainly originated from forests in Eastern Europe and Western Russia. The measured concentrations of pollen grains were very high over most of Central and Northern Europe during several days in the beginning of May and reached record high levels in some regions.

For a few weeks before the episode, dry and warm weather conditions in Western Russia contributed both to the flowering of birches, and to the formation of widespread wild-land fires. Therefore, the area affected by the fires overlapped with the flowering birch forests. The predictions of this episode are based on forecasts and reanalysis performed using the SILAM modeling system. The pollutants forecast by SILAM included birch pollen, $PM_{2.5}$ originating from wild-land fires, primary anthropogenic $PM_{2.5}$, and PM_{10} and sulfur oxides.

Table 1 Interactions between different weather types

Impact on influencing weather type	Impact on affected weather type							
	Emissions		Atm. transport and deposition			Human health		
	CW	BW	PW	CW	BW	PW	CW	BW
PW	X	X	X	X	X	X	X	X
CW	X	X	X	X	X	X	X	X
BW		X			X	X	X	X

PW physical weather, *CW* chemical weather, *BW* biological weather

An "X" in the table indicates that a particular weather type denoted in the leftmost column influences a weather type denoted in the second row with regard to the impact areas atmospheric "emissions," "atmospheric transport and deposition," and "human health"

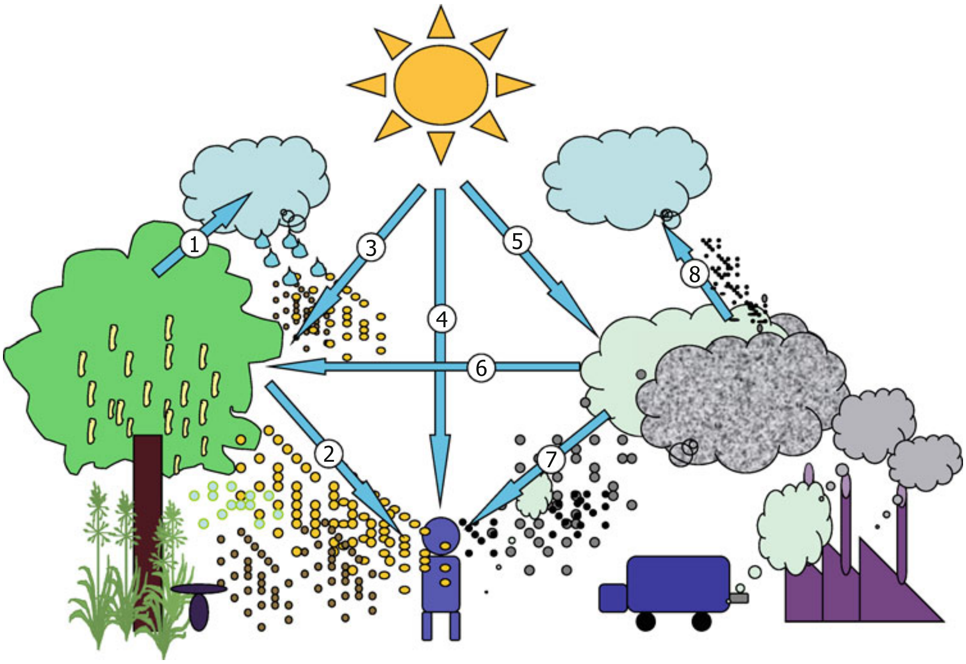
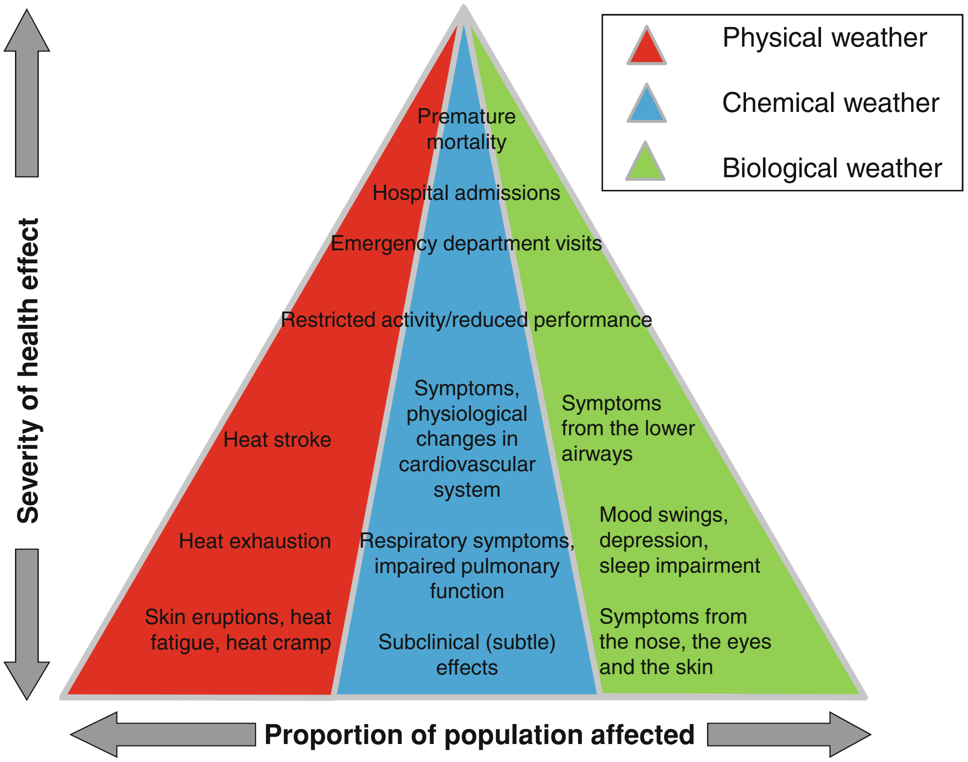


Fig. 2 Selected interactions of physical, chemical, and biological weather. *1* Plants emit gases into the atmosphere that influence air quality and may cause particulate and cloud formation. *2* Plants and fungi produce pollen and spores that may affect the health of human beings. *3* Heat and light from the sun affect the amount of pollen production. Rain and moisture cause the release of subpollen particles. Clearly, physical weather influences the dispersion and transformation of both the chemical and the biological pollutants. *4* Heatwaves or cold spells together with high pollutant concentrations may have synergistic effects on human health. *5* Tropospheric ozone is formed from nitrogen oxides and hydrocarbons, the latter partly from biogenic sources, through photochemical reactions. *6* Gaseous pollutants may affect plants and pollen as to enhance their allergenic effects. *7* Chemical and biological pollutants jointly affect the health of human beings, e.g., chemical pollutants may act as adjuvants and enhance allergic reactions. *8* Particles from chemical pollution and bio-aerosols may cause cloud formation and thus influence physical weather

Fig. 3 Illustration of combined health impacts of physical, chemical, and biological weather. Effects of cold spells are not included in the figure as the concentrations of bioaerosols are generally low during such episodes. Interactions and synergistic effects may lead to an earlier appearance or aggravation of certain impacts/symptoms and to larger parts of the population being affected compared to the isolated health impacts of either type of weather



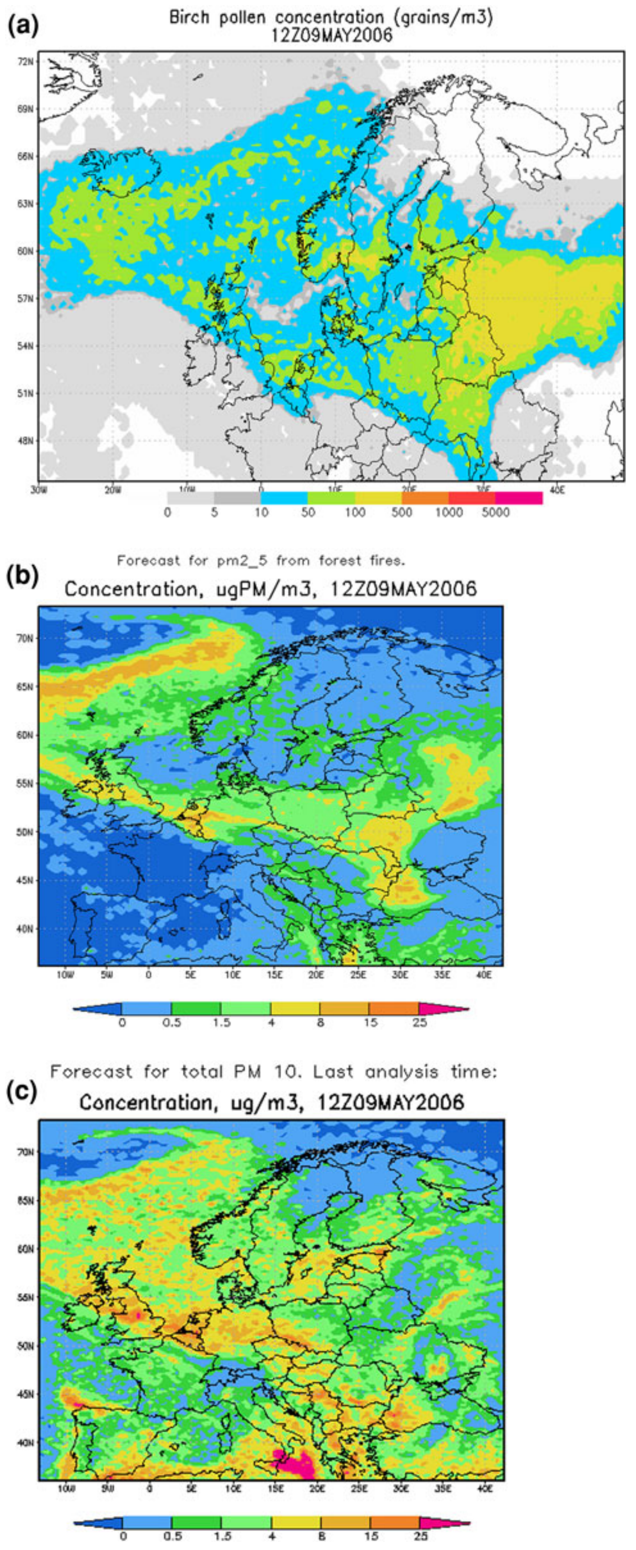


Fig. 4 Example results of a European-scale pollen, wild-land fire, and anthropogenic air pollution episode that occurred in April and May 2006 (Sofiev et al. 2011). The *panels* show the predicted distribution of concentrations on May 9, 2006: **a** birch pollen (grains m^{-3}), **b** $\mathrm{PM}_{2.5}$ originated from biomass burning ($\mu\mathrm{g}\,\mathrm{PM}_{2.5}\,\mathrm{m}^{-3}$), **c** $\mathrm{PM}_{2.5}$ originated from anthropogenic emissions of primary aerosol and sulfur oxides ($\mu\mathrm{g}\,\mathrm{PM}_{2.5}\,\mathrm{m}^{-3}$)

During the episode, primarily warm and dry weather continued for several weeks. These conditions resulted in high concentrations of various air pollutants over Eastern Europe and Russia in the beginning of May 2006. This multi-pollutant plume was transported toward Central and Northern Europe during May 1–7, 2006 and caused severe deterioration of air quality up to Iceland and Spitsbergen and widespread allergenic reactions.

Capabilities and Policy Needs

Monitoring

Physical weather monitoring has a long history and builds on many established networks and mechanisms at different levels. The collective infrastructure of the meteorological community comprises observing systems, telecommunication facilities, and data-processing, forecasting, and dissemination centers. Internationally, operational monitoring and exchange of data in near-real-time (NRT) are coordinated through organizations such as WMO and, at the European level, through the Network of European National Meteorological Services (EUMETNET) and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) for in situ and space-based observations, respectively.

Chemical weather monitoring and its coordination have developed rapidly during the last decades in response to emerging environmental problems (Tørseth and Fahre Vik 2009). The EU-Directive 96/62/EC on ambient air quality assessment and management establishes rules for air quality measurement principles in a pan-European monitoring network. Today, the Co-operative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP, European Monitoring and Evaluation Programme) and the Exchange on Information decision (EoI) on Air (Council Decision 97/101/EC of Jan 27, 1997 establishing a reciprocal exchange of information and data from networks and individual stations measuring ambient air pollution within the Member States) form the basis for all air quality monitoring in Europe. Most European countries have even developed data acquisition systems for NRT collection of data and web-based systems for providing up-to-date information to their citizens. NRT data may also be used to validate chemical weather forecasts or to improve and constrain them through data assimilation techniques (e.g., GAS 2011). A working group of the COST Action ES0602 was tasked to further improve the coordination and to reduce redundancies among the many existing data exchange mechanisms for chemical weather observations. The working group also found that today's monitoring requirements do not always reflect the emerging political priorities: e.g., while there is a need for increased monitoring of $PM_{2.5}$ mass and composition, there is an abundance of sites measuring SO_2 close to instrument detection limits throughout the year. The monitoring systems (monitoring sites, data acquisition, and dissemination systems) are furthermore not designed to take advantage of the modeling and forecasting capabilities that are currently being developed (Tørseth and Fahre Vik 2009).

There are fewer biological weather observations compared to physical and chemical observation networks. The most prominent initiative for the exchange of observations is the European Aeroallergen Network (EAN) Pollen Database, which is used to gather information from more than 600 pollen counting stations all over Europe (EAN 2011). These data are used by European scientists (largely aerobiologists) to create statistics and calculate trends of the pollen distribution, but also for models of phenology and flowering intensity. EAN's webpage is intended for scientists and is accessible to registered users under specific agreements only, although part of the data are made available for the purpose of dispersion modeling and pollen forecasting to other organizations. Measurement techniques are often relatively time consuming which complicates NRT exchange and, e.g., assimilation in operational models (COST ES0602 2009). Key issues such as the positioning of monitoring equipment, geographical representativeness of pollen observations, harmonization needs, and concentration thresholds are under investigation by the COST Action ES0603. The scarcity of today's biological weather observations and the lack of resources to ensure their sustainability were highlighted by the joint COST ES0602, COST ES0603, and WMO workshop on "Chemical and biological weather forecasting" (COST ES0602 2009).

Modeling

Significant efforts have been invested in the documentation and comparison of existing forecast capabilities for chemical weather. The COST Action 728 compiled a model database, and an extensive compilation of model properties, including scientific model evaluation, was performed by COST ES0602 (Kukkonen et al. 2012). Recent reviews of European modeling capacities (Baklanov et al. 2011; Kukkonen et al. 2012) show that chemical weather models have substantially advanced during the last decade, although there are still considerable research challenges compared to traditional NWP models.

Today, the majority of atmospheric chemical transport (ACT) models in operational use in Europe are so-called offline models, which use meteorological physical fields from external NWP models as driver of the chemical transport system. Online models unite ACT and NWP model capabilities in the same model, thus allowing for feedbacks of changes in modeled atmospheric composition on the driving physical meteorological fields. Yet, both types of modeling approaches have specific strengths and weaknesses (Baklanov et al. 2007). The number of on-line coupled ACT and NWP models is quickly growing, but most of them are still in a research and development phase (Baklanov et al. 2011; Kukkonen et al. 2012). The COST Action ES1004 EuMetChem (European framework for online integrated air quality and meteorology modeling) will focus on a new generation of online integrated ACT and meteorology modeling with two-way interactions among atmospheric chemistry (including gas-phase and aerosols), clouds, radiation, boundary layer, and other meteorological and climate processes.

In the list of 18 models compared by Kukkonen et al. (2012), two models (SILAM and Enviro-HIRLAM) included allergenic pollen. Following these examples, several other modeling communities are currently working on the inclusion of biological weather forecasting in their operational models. These three-dimensional transport models can complement the statistical models in use in many countries and provide biological weather forecasters (trained aerobiologists) with information on the ambient flow and large-scale transport patterns.

Communication

The findings from the COST ES0602 workshop in Thessaloniki (Karatzas and Kukkonen 2009) stressed the increasing need to provide society and, in particular, sensitive user communities with tailored and personalized information services on chemical weather.

Coordinated initiatives such as the GMES Atmospheric Service (GAS 2011) or COST ES0602 (Kukkonen et al. 2009; Balk et al. 2011) integrate a large number of standalone (often national or regional) modeling initiatives and systems. The latter facilitates the transition from individual deterministic forecasts of chemical weather to ensemble chemical weather prediction systems with the ability to provide more robust forecasts and to assess and explore forecast uncertainty. The scientific and technical complexity that characterizes the prediction of chemical weather forecasts and the development of ensemble systems poses new challenges in the communication of chemical weather and its related uncertainties. While many user communities of physical weather information (e.g., energy sector, agriculture) have become used to this concept, it is still relatively new to users of chemical weather information (Karatzas and Kukkonen 2009).

According to the findings of the five workshops organized by COST ES0602, there are considerable improvements in the availability of information sources for the individual atmospheric domains, e.g., the Meteoalarm system for physical weather (Meteoalarm 2010), the COST ES0602 Chemical weather portal ENCWP (Balk et al. 2011), and the Polleninfo-site (Polleninfo 2011). These examples reflect a trend for a transition from individual, isolated systems toward internationally integrated services accessible from portals and one-stop shops, in a seamless and transparent way, especially for citizens. Yet, despite progress on harmonization and integration within the individual domains, there is currently no single international portal for physical, chemical, and biological weather, delivering integrated air quality assessments, forecasts, and information. Scientifically robust and agreed indices for the assessment of joint health effects or quality of life in general, for physical, chemical, and biological weather, are also missing.

Overall criteria for integrated weather forecast and information services will include an adequate level of aggregation, integration, and comprehensibility of information content, user friendliness, presentation, and delivery mechanisms (modern ICT tools) as well as timeliness and reliability of service provision (Karatzas 2009). New directions include human-centric, personalized, environmental information provision (e.g., Rose et al. 2004; Karatzas and Lee 2008) and Participatory Environmental Sensing (PES, Karatzas 2011). PES aims at an active involvement of citizens to the environmental information collection, annotation, and communication. A prominent example of the latter for biological weather is the personal “pollen diary,” where sensitive people can report on their symptoms which then can be compared to the registered pollen values or forecasts (Polleninfo 2011). A recent development on personalized information provision is reported in Karatzas et al. (2012) who demonstrate the combined use of data from pollen forecasts and symptoms recordings in the development of health services for pollen allergists.

Policy Frameworks

Physical weather has consequences for national and international safety, economy, environment, and security and health. Physical weather information and warnings thus have a long tradition. In many countries, experiences from recent heatwaves have led to the installation of additional information and warning systems and contingency plans for extreme temperatures (e.g., Fouillet et al. 2008).

Regarding chemical weather, many policy initiatives have been developed in response to increasing scientific evidence for environmental issues such as acidification and nitrification of ecological systems, transboundary air pollution, stratospheric O_3 depletion, and climate change. Examples of international and European policy in the field of air pollution are the protocols under the Convention on Long-range Transboundary Air Pollution (CLRTAP) and the EU National Emissions Ceilings (NEC) Directive. The EU-directives 2002/3/EC and 2008/50/EC explicitly require that up-to-date information on ambient air concentrations of pollutants covered by the directives should be routinely made available to the public. Current EU-legislation for O_3, e.g., defines concentration thresholds for both the short- and long-term effects and requires member state authorities to inform and warn the public about exceedances. As a consequence, significant efforts have been invested in the monitoring, modeling, and communication capabilities for chemical weather at national levels and through European initiatives (e.g., GAS 2011).

For biological weather the situation is different. Allergy toward pollen and spores has physical, emotional, psychological, and social implications, which often affect the daily functioning of the affected persons and their families. Among people with seasonal allergic rhinitis (SAR), disease severity is mild in ∼35 % and moderate to severe in ∼65 %. Asthma occurs in ∼30 % of people suffering from SAR, anxiety occurs in 11 %, and sinusitis occurs in ∼5 % (Canonica et al. 2007). In addition to the impaired quality of life attached to these chronic conditions, economical resources originally intended for basal needs must often be re-allocated for medical care. There is also a considerable cost in health care and medicine to society as a whole, plus absenteeism and decreased productivity at work and school (Bousquet et al. 2008). In the UK, treatments for asthma and other allergic disorders account for 10 % of primary care prescribing costs, and social security costs for managing allergic problems are estimated at over 1200 million Euro per annum (Gupta et al. 2004).

The adverse health effects and economic burden could be reduced if forecasting and information systems for aeroallergens are implemented, in analogy to the capabilities existing for physical and chemical weather. A positive correlation between pollen or spore counts with allergic symptomology has been found in several clinical trials and in epidemiological studies documenting the impact of aeroallergens on symptom scores (Roberts et al. 2005; Takasaki et al. 2009), drug consumption (Fuhrman et al. 2007 and references therein); consultations for allergic rhinitis (Pedersen and Rung Weeke 1984), emergency visits and hospitalizations (Lewis et al. 2000; Lierl and Hornung 2003; Tobias et al. 2004; references in Fuhrman et al. 2007 and in Peden and Reed 2010), and mortality (Targonski et al. 1995).

Allergen avoidance is one of the most important preventative measures to reduce the risk of symptom and disease aggravation and for the development of severe reactions. The World Allergy Organisation stresses that patient education is essential. Guided self-management to prevent, assess, and treat symptom is the key to optimizing control of the condition (Johansson and Haahtela 2004; Scadding et al. 2008). In the long term, help with self-management is likely to reduce large future costs for e.g., asthma treatment, emergencies, and hospitalization. Pollen and spore warnings can give such guidance. They increase awareness about the disease and its connection to ambient aeroallergen levels. In several European countries and in North America, forecasts of the production, release, and atmospheric dispersal of aeroallergens are provided to the public and the health care. Additional research is needed to allow for the provision of public information taking into account combined impacts and interactions of chemical and biological pollutants (COST ES0602 2009).

In addition to fine PM, harmful natural allergens are likely to be the single most important air quality issue. Every fourth or fifth person suffers from pollen allergy, and is according to EU-directives (2003/4/EC) entitled to know about the status of, e.g., the ambient flora and ambient air if there is a risk that it will exert an adverse health impact (Karatzas 2009). Yet, the long-term sustainability of the expertise and infrastructure (databases, networks, modeling frameworks, and services) able to deliver such information is a critical issue. The joint COST ES0602, COST ES0603, and WMO workshop on “Chemical and biological weather forecasting” stressed the need for stable funding arrangements for biological weather forecast and information capabilities, e.g., public funding through national governments and regional authorities (COST ES0602 2009).

Policies for biological weather are not limited to adaptive measures such as the provision of information and warnings. Even mitigation options geared toward a direct reduction of emissions need to be explored. In some countries, legislation is needed to prevent the allergen load to increase due to human activities, as has been the case in the dispersal of the weed *Ambrosia artemisiifolia*. Mandatory abatement strategies have now been introduced in some of the most severely infested countries and in some countries at risk of invasion. Scientific research is needed to find out the most cost-effective strategies and measures to reduce the adverse health effects. It is also necessary to take legislative measures to prevent the large-scale planting for ornamental purposes of plants with a well-known allergenic capacity, such as *Cupressus sempervirens* or *Betula pendula* in South Europe.

Planning measures to reduce adverse health effects of allergens require reliable allergy-related forecasts several days ahead. Such forecasts should include the start time of the pollen season, the timing of the peak concentrations and the duration of the high season, but also daily changes in expected pollen concentration and information about the area where the particular forecast is relevant (COST ES0602 2009).

CONCLUSIONS AND RECOMMENDATIONS

Physical, chemical, and biological weather can have significant impacts on human health and quality of life. In addition to the separate impacts, there is increasing evidence of joint and sometimes synergistic health effects. Interactions among the three weather types can have important implications both for the assessment, the forecasting, and the communication of air quality. The latter in turn suggests an integrated approach to both air quality legislation and the design and management of infrastructure used to monitor, model, and communicate air quality.

The following knowledge, infrastructure, and policy gaps have been identified based on the analysis in this article and associated recommendations are made:

- Monitoring:
  - An integrated assessment and forecasting of air quality will require an improved sustainability and NRT-data exchange of biological weather observations. Resources are needed to ensure stable operational arrangements.
  - The monitoring networks for chemical weather need to be re-evaluated in terms of the current knowledge of the adverse health effects. More measurements are needed especially regarding fine PM and its chemical composition on a fine temporal resolution.
- Modeling:
  - Chemical weather forecasting models need to be extended by biological forecasting capabilities.
  - There is a need to advance models through the improvement of a wide variety of physical, chemical, and biological processes and, in particular, interactions and feedbacks between these areas.
  - The integration of physical, chemical, and biological weather in online modeling systems is recommended as the optimum approach to achieving a unified treatment of these phenomena. Running fully integrated models will consume increased computational resources and require on-going investment in computing infrastructure.
  - Together with modeling developments, further effort is recommended in model verification through comparison with observations. For chemical weather, extending verification from surface observations to satellite retrievals is an active line of research. The challenge with biological weather, as recognized above, is the availability of NRT observations against which models can be evaluated.

- Research:
  - Overall, it is necessary to improve the integration of physical, chemical, and biological weather and associated research.
  - There is a need for increased interdisciplinary research, comprising meteorology, air quality and aerobiology, and health.
  - It is specifically recommended to increase research on integrated health effects, air quality thresholds, and integrated air quality indices.
- Communication:
  - While there has been some progress in the transition from individual, isolated physical, chemical, and biological weather forecasting systems to internationally integrated services, major challenges remain in developing these services to be comprehensive, user-friendly, and versatile.
  - Comprehensive, personalized, and participatory services (e.g., pollen diary) should be explored further.
  - There is a need for a systematic assessment and better communication of uncertainty and the limits of confidence of the model forecasts (e.g., ensemble results).
  - Scientifically sound and agreed integrated air quality indices, taking into account any two of the combined physical, chemical, and biological weather effects, are not yet available.
- Policy requirements:
  - There is a need to design and implement public information and warning levels for biological weather (COST ES0602 2009).
  - There is a need to design and implement public information and warning levels for integrated weather effects.
  - Furthermore, it is necessary to explore options for emission control legislation for biological air pollution.

Finally, several recent COST Actions have led to an improved dialog between scientists from the fields of meteorology, air quality, aerobiology, and health. We recommend that this form of interdisciplinary collaboration, and in particular, the dialog between scientists and policy makers is increased.

Acknowledgments This publication was supported by COST, in particular the COST Action ES0602 "Towards a European Network on Chemical Weather Forecasting and Information Systems".

REFERENCES

Aina, R., R. Asero, A. Ghiani, G. Marconi, E. Albertini, and S. Citterio. 2010. Exposure to cadmium-contaminated soils increases allergenicity of *Poa annua* L. pollen. *Allergy* 65: 1313–1321.

Alberdi, J.C., J. Diaz, J.C. Montero, and I. Miron. 1998. Daily mortality in Madrid community 1986–1992: Relationship with meteorological variables. *European Journal of Epidemiology* 14: 571–578.

Baklanov, A., B. Fay, J. Kaminski, and R. Sokhi. 2007. Overview of existing integrated (off-line and on-line) meso-scale systems in Europe. Joint Report of COST728 and GURME, May 2007. WMO-COST publication, 106. GAW Report No. 177. WMO TD No. 1427.

Baklanov, A., A. Mahura, and R. Sokhi. 2011. *Integrated systems of meso-meteorological and chemical transport models*. New York: Springer, 242. ISBN: 978-3-642-13979-6.

Balk, T., J. Kukkonen, K. Karatzas, T. Bassoukos, and V. Epitropou. 2011. A European open access chemical weather forecasting portal. *Atmospheric Environment* 45: 6917–6922.

Barriopedro, D., E.M. Fischer, J. Luterbacher, R.M. Trigo, and R. Garcia-Herrera. 2011. The hot summer of 2010: Redrawing the temperature record map of Europe. *Science* 332: 220–224. doi: 10.1126/science.1201224.

Basara, J.B., H.G. Basara, B.G. Illston, and K.C. Crawford. 2010. The impact of the urban heat island during an intense heatwave in Oklahoma City. *Advances in Meteorology*, 10. doi:10.1155/2010/230365. Article ID 230365.

Bauchau, V., and S.R. Durham. 2004. Prevalence and rate of diagnosis of allergic rhinitis in Europe. *European Respiratory Journal* 24: 758–764.

Bossioli, E., M. Tombrou, A. Dandou, E. Athanasopoulou, and K.V. Varotsos. 2009. The role of planetary boundary-layer parameterizations in the air quality of an urban area with complex topography. *Boundary-Layer Meteorology* 131: 53–72.

Bousquet, J., N. Khaltaev, A.A. Cruz, J. Denburg, W.J. Fokkens, A. Togias, T. Zuberbier, C. Baena-Cagnani, et al. 2008. Allergic rhinitis and its impact on asthma (ARIA) 2008 update (in collaboration with the World Health Organization, GA2) LEN and AllerGen). *Allergy* 63: 8–160.

Bråbäck, L., and B. Forsberg. 2009. Does traffic exhaust contribute to the development of asthma and allergic sensitization in children: Findings from recent cohort studies. *Environmental Health* 8: 17.

Canonica, G.W., J. Bousquet, J. Mullol, G.K. Scadding, and J.C. Virchow. 2007. A survey of the burden of allergic rhinitis in Europe. *Allergy* 62: 17–25.

Carder, M., R. McNamee, I. Beverland, R. Elton, G.R. Cohen, J. Boyd, and R.M. Agius. 2005. The lagged effect of cold temperature and wind chill on cardiorespiratory mortality in Scotland. *Journal of Occupational and Environmental Medicine* 62: 702–710. doi:10.1136/oem.2004.016394.

Carder, M., R. McNamee, I. Beverland, R. Elton, M. Van Tongeren, G.R. Cohen, J. Boyd, W. MacNee, and R.M. Agius. 2008. Interacting effects of particulate pollution and cold temperature on cardiorespiratory mortality in Scotland. *Journal of Occupational and Environmental Medicine* 65: 197–204. doi:10.1136/oem.2007.032896.

COST ES0602. 2009. Conclusions from the COST ES0602, COST ES0603 and WMO joint workshop chemical and biological weather forecasting: State of the art and future perspectives, Aveiro, Portugal, 13 October 2009. http://www.chemicalweather.eu/material/6th-meeting/workshop_conclusions.pdf. Accessed 19 Aug 2011.

COST ES0602. 2011. Homepage of the COST Action ES0602: Towards a European network on chemical weather forecasting and information systems. http://www.chemicalweather.eu/. Accessed 19 Aug 2011.

COST ES0603. 2011. Homepage of the COST Action ES0603: Assessment of production, release, distribution and health impact of allergenic pollen in Europe (EUPOL). http://www.eupollen.eu/. Accessed 19 Aug 2011.

COST ES1004. 2011. Homepage of the COST Action ES1004: European framework for online integrated air quality and meteorology modelling. http://eumetchem.info/. Accessed 9 Sept 2011.

Curtis, L., W. Rea, P. Smith-Willis, E. Fenyves, and Y. Pan. 2006. Adverse health effects of outdoor air pollutants. *Environment International* 32: 815–830.

Dales, R.E., S. Cakmak, S. Judek, T. Dann, F. Coates, J.R. Brook, and R.T. Burnett. 2004. Influence of outdoor aeroallergens on hospitalization for asthma in Canada. *Journal of Allergy and Clinical Immunology* 113: 303–306.

D'Amato, G., G. Liccardi, and M. D'Amato. 2000. Environmental risk factors (outdoor air pollution and climatic changes) and increased trend of respiratory allergy. *Journal of Investigational Allergology and Clinical Immunology* 10: 123–128.

Denning, D.W., B.R. O'Driscoll, C.M. Hogaboam, P. Bowyer, and R.M. Niven. 2006. The link between fungi and severe asthma: A summary of the evidence. *European Respiratory Journal* 27: 615–626.

EAN. 2011. European aeroallergen network pollen database. https://ean.polleninfo.eu/Ean/. Accessed 19 Aug 2011.

EEA. 2007. Air pollution in Europe 1990-2004. EEA Report No 2/2007. EEA, Copenhagen, Denmark, 79.

EEA. 2009. Spatial assessment of PM_{10} and ozone concentrations in Europe (2005). Technical report No 1/2009. EEA, Copenhagen, Denmark, 54.

Erbas, B., J.H. Chang, S. Dharmage, E.K. Ong, R. Hyndman, E. Newbigin, and M. Abramson. 2007. Do levels of airborne grass pollen influence asthma hospital admissions? *Clinical and Experimental Allergy* 37: 1641–1647.

Feo Brito, F., P. Mur Gimeno, C. Martínez, A. Tobías, L. Suárez, F. Guerra, J.M. Borja, and A.M. Alonso. 2007. Air pollution and seasonal asthma during the pollen season. A cohort study in Puertollano and Ciudad Real (Spain). *Allergy* 62: 1152–1157.

Fouillet, A., G. Rey, V. Wagner, K. Laaidi, P. Empereur-Bissonnet, A. Le Tertre, P. Frayssinet, P. Bessemoulin, et al. 2008. Has the impact of heatwaves on mortality changed in France since the European heatwave of summer 2003? A study of the 2006 heatwave. *International Journal of Epidemiology* 37: 309–317.

Fuhrman, C., H. Sarter, M. Thibaudon, M.C. Delmas, A. Zeghnoun, J. Lecadet, and D. Caillaud. 2007. Short-term effect of pollen exposure on antiallergic drug consumption. *Annals of Allergy, Asthma & Immunology* 99: 225–231.

GAS. 2011. The GMES atmospheric service. http://www.gmes-atmosphere.eu/. Accessed 19 Aug 2011.

Ghosh, D., P. Chakraborty, J. Gupta, A. Biswas, and S. Gupta-Bhttacharya. 2010. Asthma-related hospital admissions in an Indian megacity: Role of ambient aeroallergens and inorganic pollutants. *Allergy* 65: 795–796.

Gilles, S., V. Mariani, M. Bryce, M.J. Mueller, J. Ring, H. Behrendt, T. Jakob, and C. Traidl-Hoffmann. 2009. Pollen allergens do not come alone: Pollen associated lipid mediators (PALMS) shift the human immune systems towards a T(H)2-dominated response. *Allergy, Asthma and Clinical Immunology* 5: 3.

Grell, G., and A. Baklanov. 2011. integrated modeling for forecasting weather and air quality: A call for fully coupled approaches. *Atmospheric Environment* 45: 6845–6851.

Grell, G.A., S.E. Peckham, R. Schmitz, S.A. McKeen, G. Frost, W.C. Skamarock, and B. Eder. 2005. Fully coupled online chemistry within the WRF model. *Atmospheric Environment* 39: 6957–6975.

Gupta, R., A. Sheikh, D.P. Strachan, and H.R. Anderson. 2004. Burden of allergic disease in the UK: Secondary analyses of national databases. *Clinical and Experimental Allergy* 34: 520–526.

Heinzerling, L., A.J. Frew, C. Bindslev-Jensen, S. Bonini, J. Bousquet, M. Bresciani, K.H. Carlsen, P. van Cauwenberge, et al. 2005. Standard skin prick testing and sensitization to inhalant allergens across Europe—a survey from the GALEN network. *Allergy* 60: 1287–1300.

Higgins, B.G., H.C. Francis, C. Yates, C.J. Warburton, A.M. Fletcher, C.A. Pickering, and A.A. Woodcock. 2000. Environmental exposure to air pollution and allergens and peak flow changes. *European Respiratory Journal* 16: 61–66.

Huynen, M.M., P. Martens, D. Schram, M.P. Weijenberg, and A.E. Kunst. 2001. The impact of heatwaves and cold spells on mortality rates in the Dutch population. *Environmental Health Perspectives* 109: 463–470. doi:10.2307/3454704.

IPCC. 2007a. Climate change 2007: The physical science basis. In: *Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change*, ed. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller. Cambridge: Cambridge University Press, 996.

IPCC. 2007b. Climate change 2007: Impacts, adaptation and vulnerability. In: *Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change*, ed. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson. Cambridge: Cambridge University Press, 976.

Jacobson, M.Z., Y.J. Kaufmann, and Y. Rudich. 2007. Examining feedbacks of aerosols to urban climate with a model that treats 3-D clouds with aerosol inclusions. *Journal of Geophysical Research* 112: D24205. doi:10.1029/2007JD008922.

Johansson, S.G., and T. Haahtela. 2004. World allergy organization guidelines for prevention of allergy and allergic asthma. *International Archives of Allergy and Immunology* 135: 83–92.

Karatzas, K. 2009. Informing the public about atmospheric quality: Air pollution and pollen. *Allergo Journal* 18: 212–217.

Karatzas, K. 2011. Participatory environmental sensing for quality of life information services. In *Information technologies in environmental engineering, proceedings of the 5th international symposium on information technologies in environmental engineering, Poznan, 6–8 July 2011*, ed. Golinska, P., M. Fertsch, and J. Marx-Gómez. Springer Series: Environmental Science and Engineering, 123–133. ISBN: 978-3-642-19535-8. doi:10.1007/978-3-642-19536-5_10.

Karatzas, K., and J. Lee. 2008. Developments in urban environmental information perception and communication. In *Proceedings of the iEMSs fourth biennial meeting: International congress on environmental modelling and software (iEMSs 2008). International environmental modelling and software society, Barcelona, Catalonia, July 2008*, ed. Sànchez-Marrè, M., J. Béjar, J. Comas, A. Rizzoli, and G. Guariso, 1133–1139. ISBN: 978-84-7653-074-0.

Karatzas, K. and J. Kukkonen, eds. 2009. *COST Action SE0602: Quality of life information services towards a sustainable society for the atmospheric environment*. Thessaloniki: Sofia Publishers. ISBN: 978-960-6706-20-2.

Karatzas K., M. Sofiev, D. Voukantsis, M. Prank, U. Berger, V. Epitropou, A. Karppinen, J. Kukkonen, and K.C. Bergmann. 2012. Pollen forecasting and allergic symptoms recording as the basis for personalized information services. In Proceedings of the 8th international conference on air quality—science and application, 13–23 March 2012, Athens, Greece (in press).

Keatinge, W.R., and G.C. Donaldson. 2001. Mortality related to cold and air pollution in London after allowance for effects of associated weather patterns. *Environmental Research* 86: 209–216.

Kukkonen, J., T. Klein, K. Karatzas, K. Torseth, A. Fahre Vik, R. San Jose, T. Balk, and M. Sofiev. 2009. COST ES0602: Towards a European network on chemical weather forecasting and information systems. *Advances in Science and Research* 3: 27–33. http://www.adv-sci-res.net/3/27/2009/. Accessed 9 Sept 2011.

Kukkonen, J., T. Olsson, D.M. Schultz, A. Baklanov, T. Klein, A.I. Miranda, A. Monteiro, M. Hirtl, et al. 2012. A review of operational, regional-scale, chemical weather forecasting models in Europe. *Atmospheric Chemistry and Physics* 12: 1–87. doi: 10.5194/acp-12-1-2012.

Lawrence, M.G., Ø. Hov, M. Beekmann, J. Brandt, H. Elbern, H. Eskes, H. Feichter, and M. Takigawa. 2005. The chemical weather. *Environmental Chemistry* 2: 6–8. doi:10.1071/EN05014.

Lewis, S.A., J.M. Corden, G.E. Forster, and M. Newlands. 2000. Combined effects of aerobiological pollutants, chemical pollutants and meteorological conditions on asthma admissions and A & E attendances in Derbyshire UK, 1993-96. *Clinical and Experimental Allergy* 30: 1724–1732.

Leynaert, B., C. Neukirch, S. Kony, A. Guènègou, J. Bousquet, M. Aubier, and F. Neukirch. 2004. Association between asthma and rhinitis according to atopic sensitization in a population-based study. *Journal of Allergy and Clinical Immunology* 113: 86–93.

Li, N., C. Sioutas, A. Cho, D. Schmitz, C. Misra, J. Sempf, M. Wang, T. Oberley, J. Froines, and A. Nel. 2003. Ultrafine particulate pollutants induce oxidative stress and mitochondrial damage. *Environmental Health Perspectives* 111: 455–460.

Lierl, M.B., and R.W. Hornung. 2003. Relationship of outdoor air quality to pediatric asthma exacerbations. *Annals of Allergy, Asthma & Immunology* 90: 28–33.

Low, R.B., L. Bielory, A.I. Qureshi, V. Dunn, D.F. Stuhlmiller, and D.A. Dickey. 2006. The relation of stroke admissions to recent weather, airborne allergens, air pollution, seasons, upper respiratory infections, and asthma incidence, September 11, 2001, and day of the week. *Stroke* 37: 951–957.

Lubitz, S., W. Schober, G. Pusch, R. Effner, N. Klopp, H. Behrendt, and J.T. Buters. 2010. Polycyclic aromatic hydrocarbons from diesel emissions exert proallergic effects in birch pollen allergic individuals through enhanced mediator release from basophils. *Environmental Toxicology* 252: 188–197.

McMichael, A.J. 2000. The urban environment and health in a world of increasing globalization: Issues for developing countries. *Bulletin of the World Health Organization* 78: 1117–1126.

Meng, Q.Y., B.J. Turpin, L. Korn, C.P. Weisel, M. Morandi, S. Colome, J.J. Zhang, T. Stock, et al. 2005. Influence of ambient (outdoor) sources on residential indoor and personal $PM_{2.5}$ concentrations: Analyses of RIOPA data. *Journal of Exposure Analysis and Environmental Epidemiology* 15: 17–28.

Meteoalarm. 2010. http://www.meteoalarm.eu. Accessed 8 Sept 2011.

Pattenden, S., B. Nikiforov, and B.G. Armstrong. 2003. Mortality and temperature in Sofia and London. *Journal of Epidemiology and Community Health* 57: 628–633.

Peden, D., and C.E. Reed. 2010. Environmental and occupational allergies. *Journal of Allergy and Clinical Immunology* 1252: 150–160.

Pedersen, P.A., and E. Rung Weeke. 1984. Seasonal variation of asthma and allergic rhinitis. Consultation pattern in general practice related to pollen and spore counts and to five indicators of air pollution. *Allergy* 39: 165–170.

Polleninfo. 2011. http://www.polleninfo.org. Accessed 8 Sept 2011.

Pulimood, T.B., J.M. Corden, C. Bryden, L. Sharples, and S.M. Nasser. 2007. Epidemic asthma and the role of the fungal mold *Alternaria alternata*. *Journal of Allergy and Clinical Immunology* 120: 610–617.

Reid, C.E., and J.L. Gamble. 2009. Review aeroallergens, allergic disease, and climate change: Impacts and adaptation. *EcoHealth* 6: 458–470. doi:10.1007/s10393-009-0261-x.

RIOPA. 2011. Relationships of indoor, outdoor, and personal air (RIOPA). Part I. Collection methods and descriptive analyses. http://pubs.healtheffects.org/view.php?id=31. Accessed 19 Aug 2011.

Roberts, S. 2004. Interactions between particulate air pollution and temperature in air pollution mortality time series studies. *Environmental Research* 96: 328–337.

Roberts, G., M. Mylonopoulou, C. Hurley, and G. Lack. 2005. Impairment in quality of life is directly related to the level of allergen exposure and allergic airway inflammation. *Clinical and Experimental Allergy* 35: 1295–1300.

Rose, T., G. Peinel, K. Karatzas, P.H. Johansen, and J.E. Lindberg. 2004. Citizen-centred environmental information dissemination via multi-modal information channels. In *Information systems for sustainable development*, ed. L.M. Hilty, E.K. Seifert, and R. Treibert, 378. Hershey: Idea Group Publishing. ISBN: 1-59140-343-X.

Rosenfeld, D., J. Dai, X. Yu, Z. Yao, X. Xu, X. Yang, and C. Du. 2007. Inverse relations between amounts of air pollution and orographic precipitation. *Science* 315: 1396–1398.

Rosenfeld, D., W.L. Woodley, D. Axisa, E. Freud, J.G. Hudson, and A. Givati. 2008. Aircraft measurements of the impacts of pollution aerosols on clouds and precipitation over the Sierra Nevada. *Journal of Geophysical Research* 113: D15203. doi: 10.1029/2007JD009544.

Sarrat, C., A. Lemonsu, V. Masson, and D. Guedalia. 2006. Impact of urban heat island on regional atmospheric pollution. *Atmospheric Environment* 40: 1743–1758.

Scadding, G.K., S.R. Durham, R. Mirakian, N.S. Jones, S.C. Leech, S. Farooque, D. Ryan, S.M. Walker, et al. 2008. BSACI guidelines for the management of allergic and non-allergic rhinitis. *Clinical and Experimental Allergy* 38: 19–42.

Schappi, G.F., C. Suphioglu, P.E. Taylor, and R.B. Knox. 1997. Concentrations of the major birch tree allergen Bet v 1 in pollen and respirable fine particles in the atmosphere. *Journal of Allergy and Clinical Immunology* 100: 656–661.

Schober, W., S. Lubitz, B. Belloni, G. Gebauer, J. Lintelmann, G. Matuschek, I. Weichenmeier, B. Eberlein-Konig, et al. 2007. Environmental polycyclic aromatic hydrocarbons (PAHs) enhance allergic inflammation by acting on human basophils. *Inhalation Toxicology* 19: 151–156.

Seinfeld, J.H., and S.N. Pandis. 2006. *Atmospheric chemistry and physics: From air pollution to climate change*, 2nd ed. New Jersey: Wiley.

Shahali, Y., Z. Pourpak, M. Moin, A. Mari, and A. Majd. 2009. Instability of the structure and allergenic protein content in Arizona cypress pollen. *Allergy* 64: 1773–1779.

Sofiev, M., P. Siljamo, H. Ranta, T. Linkosalo, S. Jaeger, C. Jaeger, A. Rassmussen, E. Severova, et al. 2011. From Russia to Iceland: an evaluation of a large-scale pollen and chemical air pollution episode during April and May, 2006. In *Aerobiological monographs, towards a comprehensive vision*, ed. Clot, B., P. Comtois, and B. Escamilla-Garcia. Montreal: University of Montreal (CA) and MeteoSwiss (CH), 95–114. ISBN: 978-2-8399-0466-7.

Takasaki, K., K. Enatsu, H. Kumagami, and H. Takahashi. 2009. Relationship between airborne pollen count and treatment outcome in Japanese cedar pollinosis patients. *European Archives of Oto-Rhino-Laryngology* 266: 673–676.

Targonski, P.V., V.W. Persky, and V. Ramekrishnan. 1995. Effect of environmental molds on risk of death from asthma during the pollen season. *Journal of Allergy and Clinical Immunology* 95: 955–961.

Taylor, P.E., K.W. Jacobson, J.M. House, and M.M. Glovsky. 2007. Links between pollen, atopy and the asthma epidemic. *International Archives of Allergy and Immunology* 144: 162–170.

Tobias, A., I. Galan, and J.R. Banegas. 2004. Non-linear short-term effects of airborne pollen levels with allergenic capacity on asthma emergency room admissions in Madrid, Spain. *Clinical and Experimental Allergy* 6: 871–878.

Tørseth, K, and A. Fahre Vik. 2009. An overview of WG1: Exchange of AQ forecasts and input data. In *COST Action SE0602: Quality of life information services towards a sustainable society for the atmospheric environment*, ed. Karatzas, K., and Kukkonen, J. Thessaloniki: Sofia Publishers, 118. ISBN: 978-960-6706-20-2.

Traidl-Hoffmann, C., T. Jakob, and H. Behrendt. 2009. Determinants of allergenicity. *Journal of Allergy and Clinical Immunology* 123: 558–566.

Vagaggini, B., M. Taccola, S. Cianchetti, S. Carnevali, M.L. Bartoli, E. Bacci, F.L. Dente, A. Di Franco, D. Giannini, and P.L. Paggiaro. 2002. Ozone exposure increases eosinophilic airway response induced by previous allergen challenge. *American Journal of Respiratory and Critical Care Medicine* 166: 1073–1077.

Voukantsis D., K. Karatzas, A. Rantio-Lehtimaki, and M. Sofiev. 2009. Investigation of relationships and interconnections between pollen and air quality data with the aid of computational intelligence methods. In: *Proceedings of the 23rd conference on environmental informatics and industrial environmental protection: Concepts, methods and tools, September 9–11, 2009, Berlin, Germany*, ed. Wohlgemuth, V., B. Page, and K. Voigt, K. Aachen: Shaker Verlag, 189–198.

WHO. 2005. WHO air quality guidelines global update 2005. WHO Regional Office for Europe, Report EUR/05/5046029, Copenhagen, Denmark, 25.

Zhang, Y. 2008. Online-coupled meteorology and chemistry models: History, current status, and outlook. *Atmospheric Chemistry and Physics* 8: 2895–2932.

AUTHOR BIOGRAPHIES

Thomas Klein (✉) holds a PhD in meteorology. He is currently the director of the Environment Climate Data Sweden initiative of the Swedish Research Council and the Swedish Meteorological and Hydrological Institute. His research interests include air quality and climate.

Address: Swedish Meteorological and Hydrological Institute, Sven Källfeltsgata 15, 42671 Västra Frölunda, Gothenburg, Sweden.
e-mail: Thomas.Klein@smhi.se

Jaakko Kukkonen is the Head of Finnish Meteorological Institute Air Quality Research Unit. He has worked especially on the development, evaluation, and applications of mathematical atmospheric models on scales from local to global. He has been the leader of the COST Action ES0602 "Towards a European Network on Chemical Weather Forecasting and Information Systems".

Address: Finnish Meteorological Institute, Erik Palmenin Aukio 1, P.O. Box 503, 00101 Helsinki, Finland.
e-mail: jaakko.kukkonen@fmi.fi

Åslög Dahl has a PhD in botany and is researcher at Department of Biological and Environmental Sciences, University of Gothenburg. She is a coordinator of the Aerobiology program within Gothenburg Atmospheric Science Centre and responsible for pollen monitoring in South Sweden. Her research interests are aerobiology, plant reproduction, and the interaction between bioaerosols and air pollutants in their health impact.

Address: Department of Biological and Environmental Sciences, University of Gothenburg, P.O. Box 461, 40530 Gothenburg, Sweden.
e-mail: aslog.dahl@bioenv.gu.se

Elissavet Bossioli is an employee at the Laboratory of Meteorology, University of Athens and she holds a PhD in Atmospheric physics. Her scientific and professional directions are based on Atmospheric Physics and Chemistry and application of regional photochemical models.

Address: Laboratory of Meteorology, Department of Physics, National and Kapodestrian University of Athens, Building PHYS-5, Panepistimioupolis, 157 84 Athens, Greece.
e-mail: ebossiol@phys.uoa.gr

Alexander Baklanov is a project leader at the Research department of the Danish Meteorological Institute (DMI) and deputy director of the Danish strategic research centre for Energy, Environment and Health (CEEH). He has 30 years of experience in developing integrated atmospheric dynamics and pollution models and is chair of the COST Action ES1004 EuMetChem.

Address: Danish Meteorological Institute, Lyngbyvej 100, 2100 Copenhagen, Denmark.
e-mail: alb@dmi.dk

Aasmund Fahre Vik is a senior scientist at the Norwegian Institute for Air Research and has a PhD in Inorganic Chemistry. His main activities are related to data management, air quality, and earth observation.

Address: NILU—Norwegian Institute for Air Research, Instituttveien 18, P.O. Box 100, 2027 Kjeller, Norway.
e-mail: afv@nilu.no

Paul Agnew manages the Air Quality and Composition Group at the UK Met Office. His research interests include on-line air quality modeling and atmospheric dispersion.

Address: UK Met Office, FitzRoy Road, Exeter EX1 3PB, UK.
e-mail: paul.agnew@metoffice.gov.uk

Kostas D. Karatzas is an Assistant Professor of Environmental Informatics at the Department of Mechanical Engineering, Aristotle University of Thessaloniki, Greece, and the head of the Informatics Systems and Applications Group. His research interests include Environmental Informatics, Participatory Environmental Sensing, Quality of Life Environmental Information Services, and Computational Intelligence for Industrial, Energy and Environmental applications.

Address: Aristotle University, P.O. Box 483, 54124 Thessaloniki, Greece.
e-mail: kkara@eng.auth.gr

Mikhail Sofiev is a senior scientist in Air Quality Research department at the FMI and an Adjunct Professor at University of Helsinki. His main area of expertise is development and application of air pollution models at various scales—from meso- to hemispheric-wide—and compounds—acidifying, toxic, aerosol, biogenic, radioactive accidental releases—and in related fields: model verification, statistical methodology, data analysis, and computer experiments.

Address: Finnish Meteorological Institute, Erik Palmenin Aukio 1, P.O. Box 503, 00101 Helsinki, Finland.
e-mail: Mikhail.Sofiev@fmi.fi