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Influence of aerosols on atmospheric variables in the HARMONIE model

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ABSTRACT

The mesoscale HARMONIE model is used to investigate the potential influence of aerosols on weather forecasts, and in particular, on precipitation. The study considers three numerical experiments over the Atlantic–Europe–Northern Africa region during 11–16 August 2010 with the following configurations: (a) no aerosols, (b) only the sea aerosols, and (c) the four types of the aerosols: sea, land, organic, and dust aerosols. The spatio-temporal analysis of forecast differences highlights the impact of aerosols on the prediction of main meteorological variables such as air temperature, humidity, precipitation, and cloud cover as well as their vertical profiles. The variations occur through changes in radiation fluxes and microphysics properties. The sensitivity experiments with the inclusion of climatological aerosol concentrations demonstrate the importance of aerosol effects on weather prediction.

1. Introduction

Aerosol particles are the essential part of the atmosphere and as such play an important role in the processes governing the environment. In particular, they are important for human health. Depending on the aerosol origin, chemical composition, lifetime, size, shape and optical properties they can cause many complex effects in the atmosphere on regional and global scales (Kulmala et al., 2009; Lohmann and Feichter, 2005; Calvoa et al., 2012). Owing to the aerosol involvement in a wide range of chemical reactions with subsequent transformation and atmospheric transport, the aerosol presence in the atmosphere may vary from minutes to several years. The complex nature and evolution of various aerosol species in the atmosphere, their physical properties and involvement in cloud formation processes are still a challenge for researchers (Pöschl, 2011). The importance of the aerosol radiative forcing for the climate prediction is well-known (Wang, 2013). It is worth to note that the level of scientific understanding of aerosol effects on atmospheric processes is still low. Many efforts were focused on the improvements of aerosol observations and the assimilation of the observed data into modeling systems of broad range scales (Mangold et al., 2011).

At present, the growing attention to the numerical modeling of microphysical processes and precipitation formation is focused on the role and mechanisms of aerosol evolution (Muhlbauer et al., 2013; Levin and Cotton, 2008; Chen et al., 2011). The progress in weather forecasting inevitably lies in the adequate and detailed description of a broad range of atmospheric processes from small- to mesoscale. Simplified cloud parameterizations are now replaced with more advanced and interactive schemes, which allow for the aerosols as well.

In numerical weather prediction, approaches to the simulation of the full aerosol effect in mesoscale numerical models are quite different from those in global climate models. In the latter, the aerosol parameterizations are based on aerosol information in statistical and climatological senses. The proper representation of aerosol effects in the NWP models requires the detailed description of aerosol properties along with a high-resolution 3D array of aerosol concentration. The assimilation of chemical data including aerosols presents an additional challenge (Sporre et al., 2012).

The air quality and chemical weather forecast (CWF) models use meteorological fields and outer boundary conditions as the drivers for simulating chemical transformations and atmospheric transport (Baklanov et al., 2011). The comprehensive analysis of operational regional-scale CWF models in Europe is given by Kukkonen et al. (2012). That overview highlights 18 models, which were selected due to their wide usage and availability of documentation. Only three of those models, Enviro-HIRLAM, WRF-Chem and SK-IRON/Dust are online integrated with two-way interactions. This allows considering feedbacks between chemical and meteorological processes at each time step of the model integration. Our study focuses on evaluation of the aerosol influence on weather conditions as it is simulated in the HARMONIE model.

2. Materials and methods

The non-hydrostatic spectral high-resolution limited area HARMONIE (Hirlam Aladin Regional/Meso-scale Operational NWP In Europe;

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Driesenaar, 2009) model was used in this retrospective assessment study. It is a collective development of the HIRLAM-B program in the co-operation context of HARMONIE, with major scientific and technical contribution from partners at ECMWF, Meteo-France and members of the ALADIN consortium. The HARMONIE modeling system is based on the convection-permitting AROME physics, 3D-VAR upper air

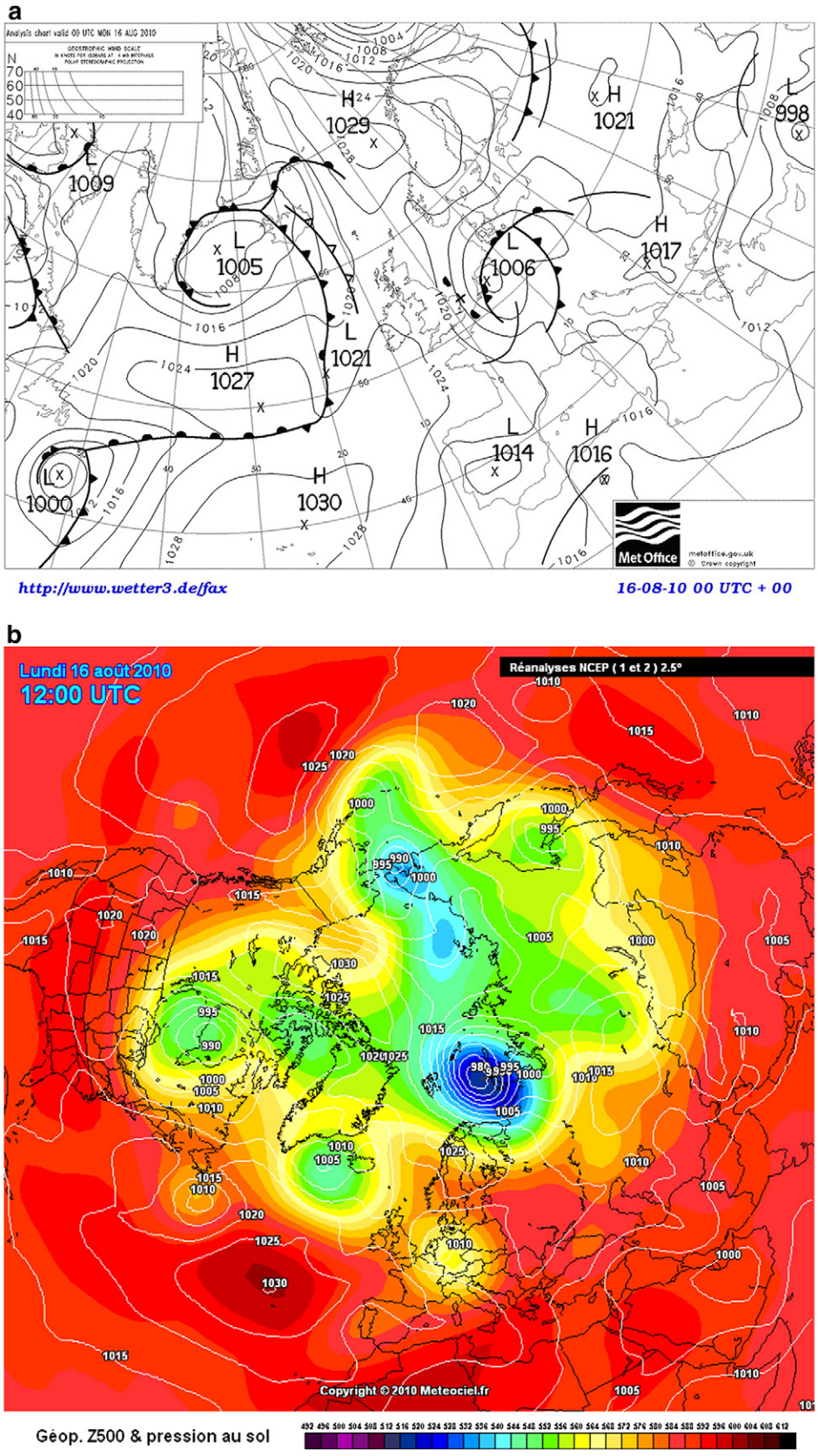

Fig. 1. Weather chart (MetOffice analysis) of the surface pressure on 16 August 2010, 00 UTC (a) and NCEP reanalyzes combined map of geopotential height at 500 hPa with the surface pressure on 16 August 2010, 12 UTC (b). (a)—http://wetter3.de/fax; (b)—http://modeles.meteociel.fr/modeles/reana/2010/archivesnh-2010-8-16.png.

assimilation and the interpolation-based surface optimal analysis on a model grid up to 1-km resolution in horizontal plane and 65 vertical levels.

In all numerical experiments the setup of parameters was identical except the inclusion of aerosol. The model domain covered the Atlantic–Europe–North Africa region with 450 × 360 grid points and horizontal resolution of 25 km. The forecasts were integrated for 120 h with a time step of 120 s. Initial and boundary conditions were supplied by the ECMWF-IFS global model with a time interval of 3 h. The boundary strategy mimicked the behavior of an operational run. Due to the coarse resolution the ALARO physic was applied. Air–surface coupling was described by the SURFEX model implemented as a part of HARMONIE.

The model provided the possibility to consider and modify four aerosol types: sea, land, organic and dust. Aerosol fields were initialized from monthly mean climatologies, and evolved according to the model dynamics and physical processes. The climatologies of each type of aerosol concentrations are initially prescribed as vertically integrated optical thickness at 550 nm. By default, these concentrations were set as follows: marine (sea) aerosol is equal to 0.235×10^{-2} ppm, continental (land) aerosol is 0.151 ppm, soot aerosol is 0.01648 ppm, desert aerosol is 0.02026 ppm, and additional ozone is 0.06369 ppm. The initial aerosol concentrations were interpolated at each model level according to the reference profiles, which are greatly dependent on the aerosol origin.

The first numerical experiment (hereafter referred to as "NO" experiment) was conducted with zero aerosol concentrations. This assumes an idealized case with "clean" (i.e. aerosol-free) atmospheric conditions. In the second experiment, the model took into account only marine (sea) aerosols (hereafter "SEA" experiment), while the third experiment included all aerosols with their predefined climatologies ("YES" experiment). The following analysis of the aerosol influence on

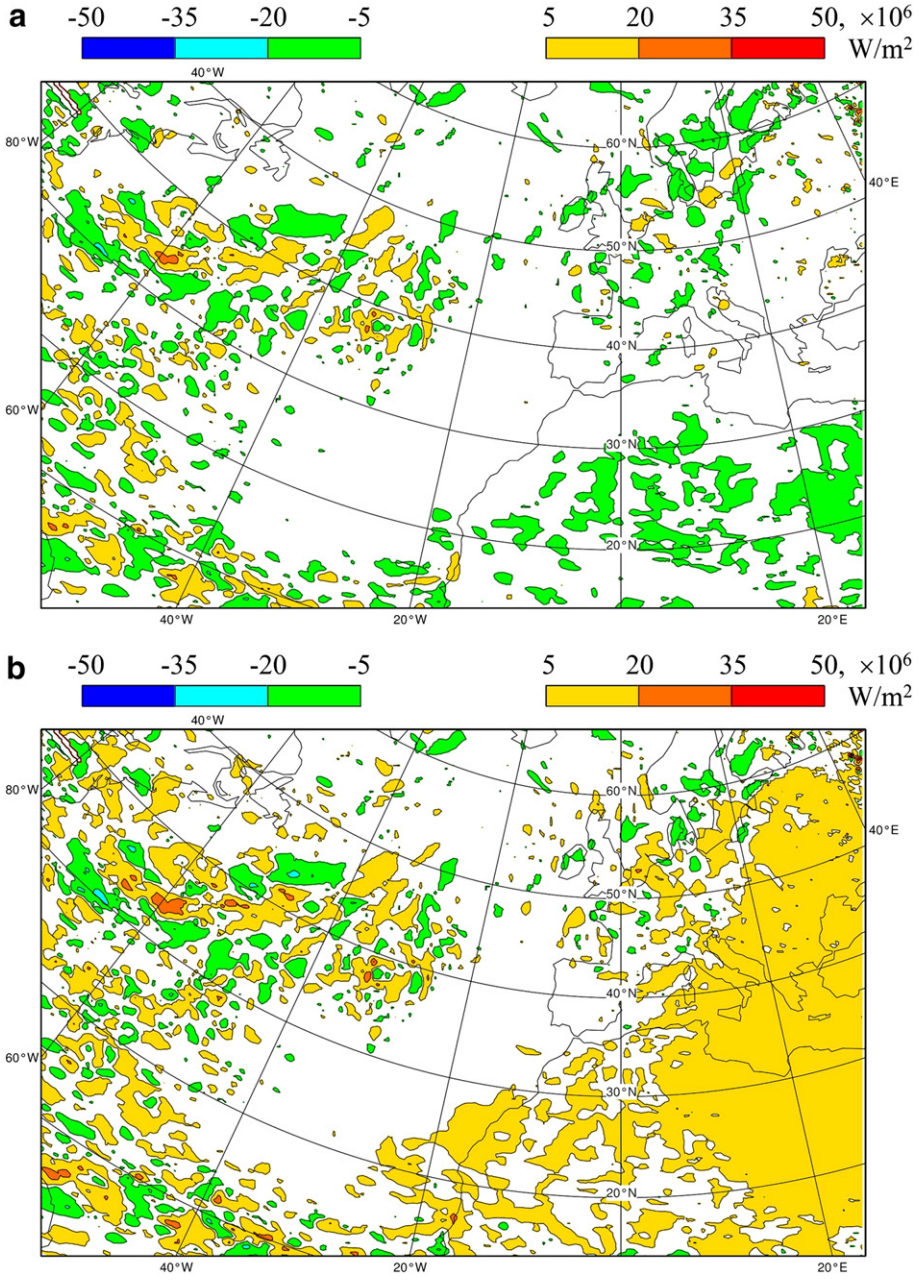

Fig. 2. Difference fields (no aerosols — climate aerosols) of short-wave radiation fluxes simulated by the HARMONIE model (a) at the top of the atmosphere and (b) near the surface on 16 August 2010, 06 UTC.

atmospheric variables is based on the differences between the NO–YES and NO–SEA experiments.

3. Results and discussion

The major uncertainties in understanding of the role of aerosols in the atmosphere are associated with (a) the aerosol radiative forcing; (b) cloud, water vapor content and lapse rate feedbacks; and (c) the development of precipitation processes. In this regard, the chain of interactions between aerosols, clouds and precipitation is the largest contributor to the uncertainties in the estimates and interpretations of the varying energy budget. The reduction of the uncertainties in the aerosol forcing requires a coordinated strategy that is able to successfully consolidate observations and numerical modeling (Kaufman et al., 2002). However, the measurement accuracy required for the adequate description of aerosol composition is currently not well established. The aerosol forcing is estimated mainly from modeled mass concentrations and assumed aerosol properties. Model simulations, in turn, rely on the representation of processes of the aerosol formation and evolution in the atmosphere, which are subject to large uncertainties (Stocker et al., 2013). The other aspect of this problem is the need to treat the aerosol variability in a consistent way. This need creates a requirement to rationalize the differences in spatial and temporal resolutions between observational networks and model grids (Anderson et al., 2003). Otherwise, the representativeness error arises and becomes considerable (Ivanov and Palamarchuk, 2007). Mesoscale variability is a common and universal feature in the lower-tropospheric aerosol distribution. Such variation is below the traditional synoptic or "airmass" scale, where the aerosol is often assumed to be essentially homogeneous except for plumes from point sources, and below the scales that are resolved by chemical transport models (Anderson et al., 2003). Thus, at the moment there is no robust approach for evaluating the contribution from each element of the chain of interactions between physical and chemical components in the atmosphere.

The present study focuses on documenting the role of aerosols in atmospheric processes by comparing fields from a number of experiments during 11–16 August 2010 over the North Atlantic and Europe. The summer atmosphere was characterized by typical synoptic patterns (Fig. 1). An active low dominated in the entire troposphere with a multi-centered depression at the surface. A relatively dry cold arctic air mass was separated from the warm subtropical air by a polar frontal system. Dynamical activity along the frontal line created favorable conditions for cyclogenesis over the Western Atlantic. Deepening and propagation of the low system caused significant increase in wind speed up to 20–25 m/s near the ocean surface and well-developed jet streams in the upper troposphere. Associated precipitation patterns moved along with the frontal systems. Downdraft of cold and dry air intensified the processes on the front lines and sharpened the temperature contrasts near the ocean surface up to ~8–10 °C behind the front. Tropospheric divergence produced favorable dynamic conditions for further deepening of the low and its shift to the northeast. However, a strong anticyclone over Russia blocked that eastward propagation. As a result, the high cyclone with central pressure of 1006 hPa at the surface and corresponding cold core (−20 °C) at the 500 hPa became stationary over France. The regular inflow of cold air into the cyclone rear and warm inflow into its eastern part regenerated the vortex with accompanied heavy rainfall (more 8 mm/h) over Central Europe, especially in the Alpine region. A wide high pressure ridge from the Azores extended to the northeast. This had created favorable conditions for transporting a hot subtropical air mass to southern Europe, which subsequently caused fires in Spain and Portugal. A high-gradient zone developed northeastward from the eastern coast of the North America. Intensive interactions between air masses of essentially different characteristics occurred all the way from the surface to the top of the troposphere.

The model results showed that the inclusion of aerosols has resulted in the changes in most of the atmospheric fields, such as air temperature, humidity, vertical velocity, cloud cover, precipitation, short-wave and long-wave radiation fluxes through the low and middle troposphere. The model results also showed that the inclusion of aerosols has caused prominent changes in precipitation and other physical atmospheric fields. Three-dimensional spatio-temporal analysis of air temperature, humidity, short-wave and long-wave radiation, vertical velocity, cloud cover has revealed the complex cross-chain between those parameters. In a nutshell, aerosols first alter both short- and long-wave radiation fluxes, which in turn affect the vertical profiles of temperature and humidity. Subsequently, these processes cause the modification of vertical velocity profiles and stratification, and finally have a vague effect on cloudiness and precipitation. Also, changes in the water content in the atmosphere affect radiation fluxes, which

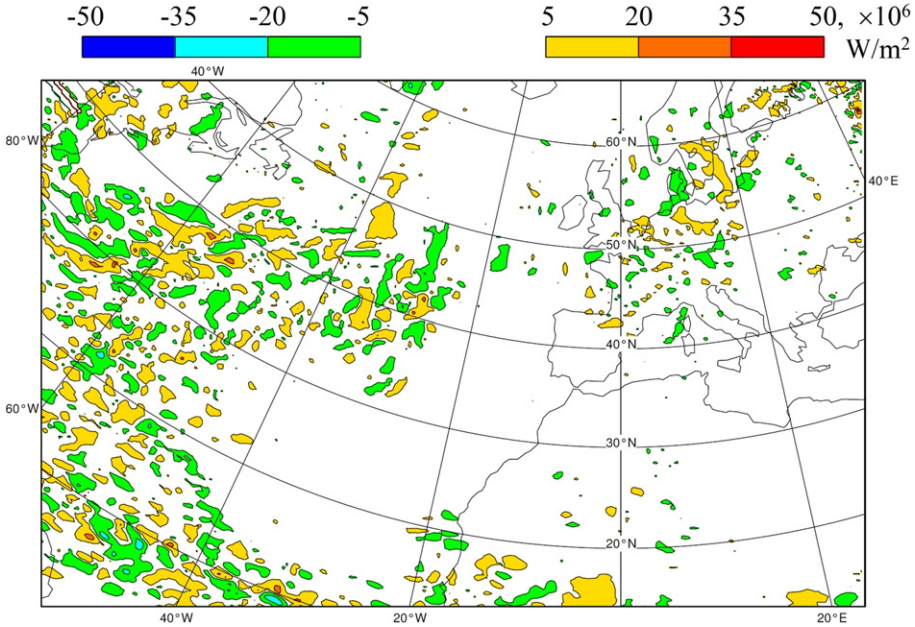

Fig. 3. Difference fields (no aerosols – sea aerosols only) in short-wave radiation fluxes simulated by the HARMONIE model near the surface on 16 August 2010, 06 UTC.

close the chain. So far, the model simulations with and without aerosols have shown their role as a trigger-link, which generates the above chain of interactions between physical atmospheric variables.

As expected, in the "YES" experiment short-wave radiation has increased at the top of the atmosphere by extra ~100 W/m^2, while it has decreased near the surface by extra ~200 W/m^2 (Fig. 2). Long-wave radiation was less sensitive to aerosols at clear sky conditions. However, it became tentative along a front line and at cloudy areas. The changes in radiation fluxes prevailed over the North Africa and were mainly related to the areas, where the interaction between mid-latitude and tropical air masses with different thermal characteristics occurred. A large area of low short-wave radiation at the surface over the Sahara desert exhibited the strong influence of dust particles due to the scattering and absorption of solar radiation. The absence of similar Sahara cooling in the "SEA" experiment indicates the leading role of the solid dust particles over the continental areas (Fig. 3).

The results obtained describe the air temperature vertical distribution under the clear and polluted conditions. The largest differences in the temperature and specific humidity fields are observed within the 500–1500-m layer with the maximum at mid-latitudes just above the planetary boundary layer (PBL) (Figs. 4–5). The other important detail is that the domain-averaged values of atmospheric characteristics did not significantly change during the simulation period. Rather, they oscillated around a mean value (Fig. 6). Thus, after the 5-day simulations the differences between the "NO–YES" experiments for the temperature fields at single cells reached up to ±5–6 K. They were related to particular geographical regions, specific patterns of the atmospheric flow and appeared mainly within PBL. The domain-averaged differences were less pronounced and showed the increase in air temperature only by 0.2 K in the aerosol-polluted troposphere. However, the opposite effect, when the clean atmosphere is warmer than polluted, is revealed in the PBL for the "SEA" experiment (Fig. 6b). This feature can be explained by

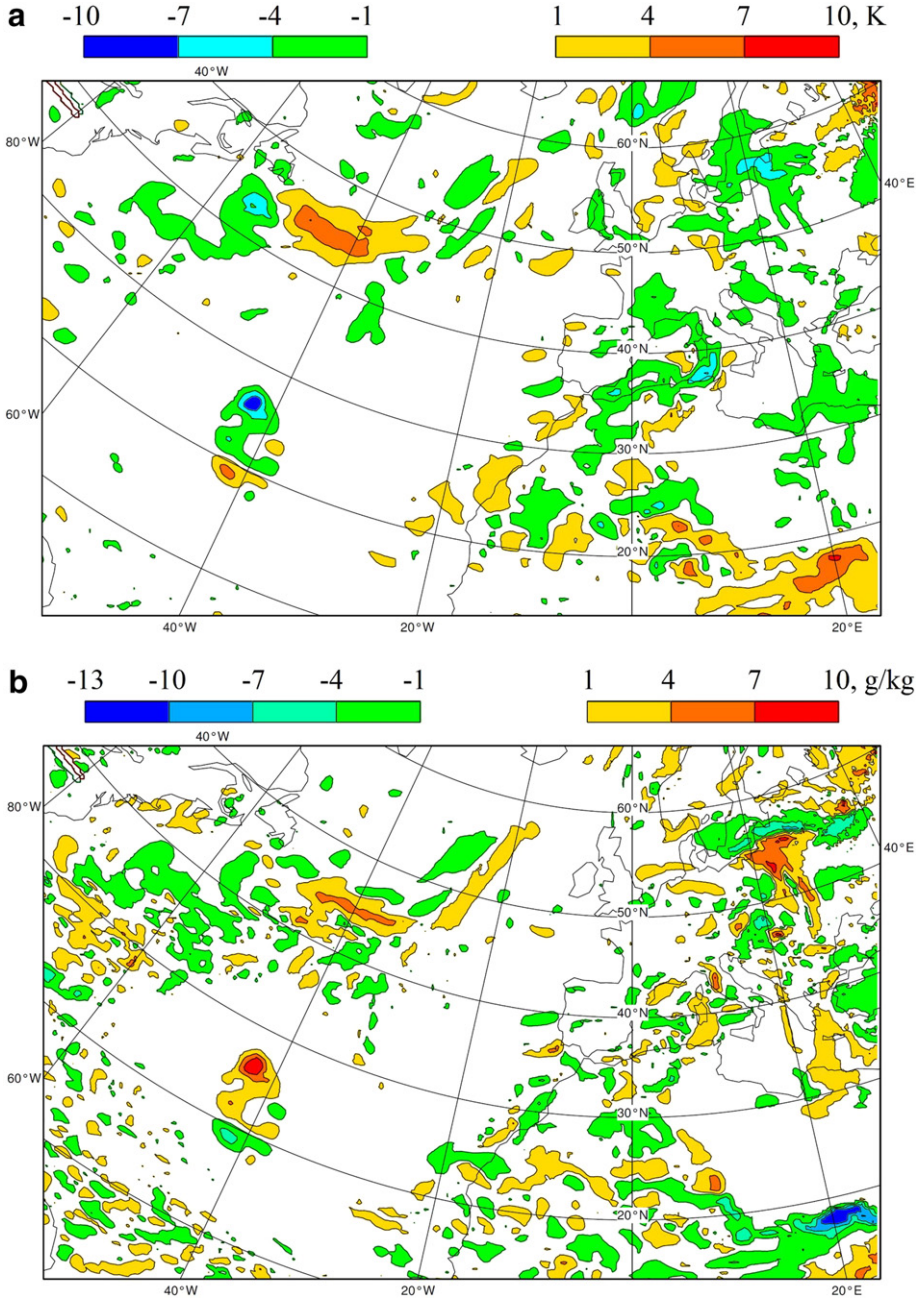

Fig. 4. Difference fields (no aerosols — climate aerosols) in temperature (a) and specific humidity (b) simulated by the HARMONIE model at the level 925 hPa on 16 August 2010, 06 UTC.

the intense reflectivity and scattering of the solar radiation from sea salt sulfate molecules.

The sea aerosol modified the vertical profiles of local heat fluxes with subsequent changes in stratification and suppressed or enforced the convection. Because the model physics is tuned to convection parameters, the relative humidity varies from 10% for the "NO–YES" experiments to 30% for the "NO–SEA" experiments. Accordingly, the specific humidity differences demonstrated the model tendency to simulate higher humidity in the presence of aerosols: at 0.05–0.1 g/kg for domain-averaged values and ±8–10 g/kg for local variations. Such mesoscale patchiness in mass distribution resulted in well-developed local updraft and downdraft motions. The forcing was identified mainly along the frontal zones over the oceanic surface in mesoscale cells, as above, in which the vertical velocity differences peaked at ±2.5 m/s.

Regarding the microphysics, the effect from aerosols was manifested in the increased cloud cover in the lower troposphere, which was accompanied by the drop in precipitation rate (Fig. 6c). This also changed the conditions of the formation, evolution and destruction of single clouds, and their lifetime. Such impact was mainly associated with the frontal zone in the North Atlantic region. The experiments also showed the significant aerosol impact on the medium and high clouds. In the "YES" experiment the stronger high cloudiness developed behind the cold front, while the exclusion of aerosols (the "NO" experiment) led to increased high cloud cover on the warm side of the frontal zone.

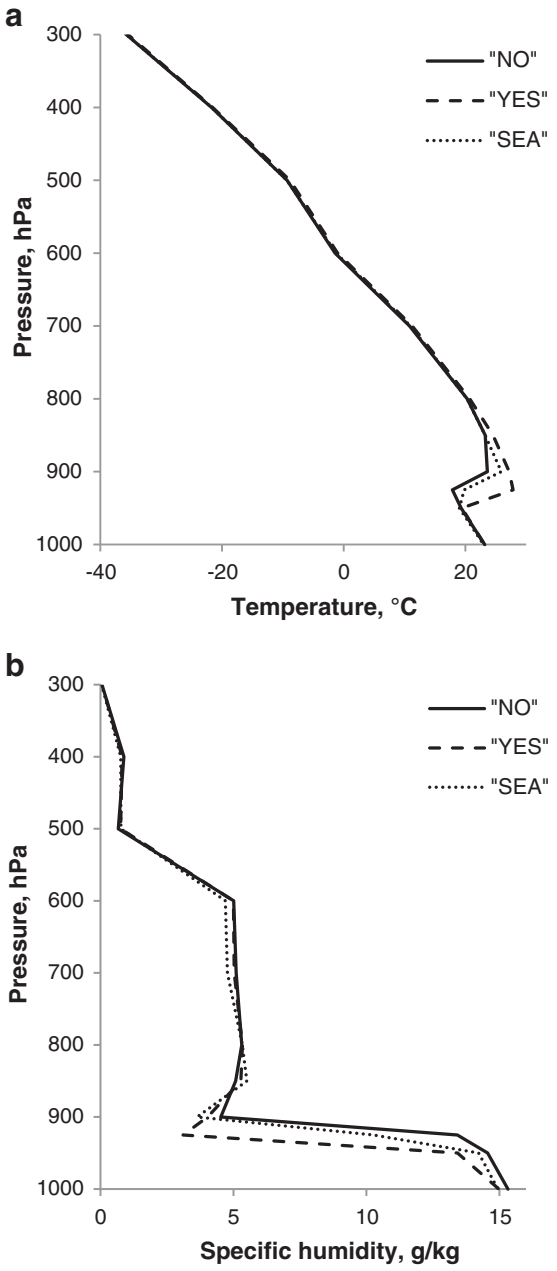

Fig. 5. Vertical profiles of temperature (a) and specific humidity (b) at the point of maximum difference (26,129N/42,264W) on 16 August 2010, 06 UTC. Solid lines—"NO", dashed lines—"YES", dotted lines—"SEA" experiments.

Changes in humidity mainly occurred in the low troposphere and were accompanied by extra rain water formation in the 925–850 hPa layer. The model results demonstrated the evident influence of aerosols in both aerosol scenarios ("YES" and "SEA"). In the cold air mass behind the arctic frontal system extra precipitation of up to 3.5 g/m^2 was simulated in the polluted atmosphere. Domain-averaged difference in rain water has increased in the presence of sea aerosols by up to 0.12×10^{-3} g/m^2 in aforementioned layer. The total impact of all aerosol particles ("YES") was less uniform. The highest differences of opposite signs from -3.6×10^{-3} g/m^2 to 4.5×10^{-3} g/m^2 were associated with mesoscale cells. Those values were compensating each other and have resulted in the domain-averaged value of about of 0.05×10^{-3} g/m^2. Such spatial structure with intermittent cells of opposite signs is similar to the so-called "phase error" for precipitation forecasts, which arises from mistaken locations of precipitation forms while the precipitation amount is properly predicted. In our case, aerosols work as a "sponge", which accumulates water mass and shifts the precipitation phase.

Thus, the common feature of the aerosol impact on major physical fields has been observed in a form of intermittent mesoscale structures, which are similar to the Benard cells. This phenomenon occurred despite of the homogeneous or smooth distribution of the aerosols climatic concentrations used in the experiments. The major cause of this mesoscale variability stems from the inner atmospheric dynamics including the diversity of non-linear interactions between the temperature and humidity profiles, updraft and downdraft, microphysics and radiation processes, which occur on the scales of orders of 10–100 km. Verification of that composition is a complicate task due to the fact that present databases do not properly resolve the spatial distribution of aerosol fields on mesoscales. While only satellites can provide the required global coverage, remote sensing cannot determine the full range of chemical composition. Patchy sources, sinks and the short lifetime of tropospheric aerosols considerably complicate the task of estimation of global or even regional forcing by aerosols, which is usually accomplished by means of space-time integration of extremely variable properties.

4. Conclusions

Numerical experiments with the HARMONIE model have shown the considerable aerosol influence on most atmospheric variables. The impact occurred through a complex chain of interactions between physical variables, where aerosols played the role of a trigger. However, they worked in a different manner depending on a type of aerosols and synoptic pattern. Major changes occurred in the planetary boundary layer and along the frontal zone of high gradients at all levels. The perturbations appeared in a form of mesoscale cells growing with the leading time, while domain averaged deviations were oscillating around zero values.

In particular, the largest differences in air temperature and specific humidity have been observed near the top of PBL. The temperature discrepancies reached up to ±5 K at single cells depending on geographical region and vertical level. The domain's average differences were less pronounced and showed the increase in air temperature by 0.2 K in the aerosol-polluted troposphere. The opposite effect, when the clean atmosphere is warmer than polluted, is revealed in the PBL for the "SEA" experiment. Relative humidity varied from 10% for the

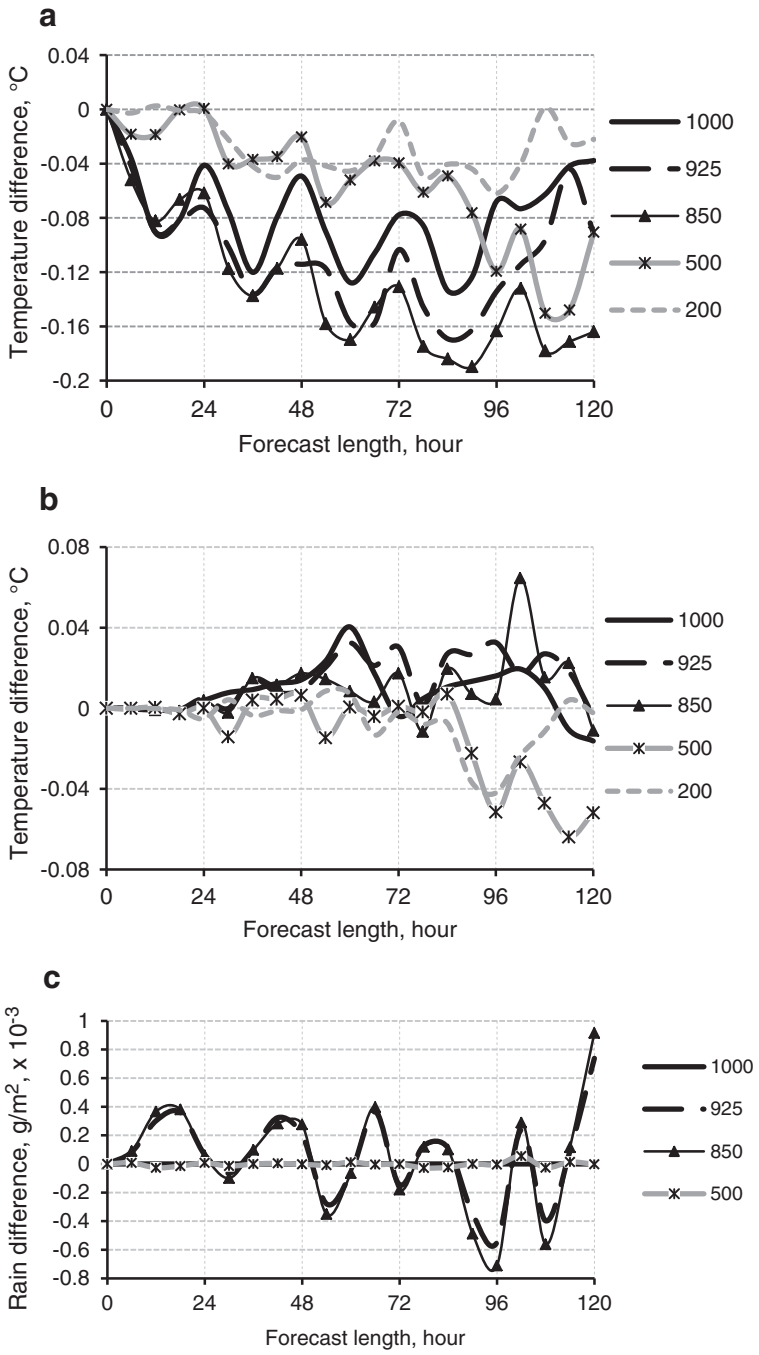

Fig. 6. Temporal evolution of the air temperature differences (no aerosols − climate aerosols)—(a), the air temperature differences (no aerosols − sea aerosols only)—(b), the rain differences (no aerosols − climate aerosols)—(c), averaged over the entire model domain during 11–16 August 2010 as a function of the pressure level.

"NO–YES" experiments to 30% for the "NO–SEA" experiments. Specific humidity differences demonstrated the model tendency to reproduce more humid atmosphere in the presence of aerosols (at 0.05–0.1 g/kg) for the domain-averaged value, while locally they varied at about ±8–10 g/kg. Short-wave radiation increased at the top of the model atmosphere by extra 100 W/m^2, while near the surface it decreased by 200 W/m^2. Long-wave radiation was less sensitive to aerosol, with the exception of frontal zones and cloudy regions. Aerosols have affected mainly weak rates of precipitation by changing their formation and lifetime. In particular, in the aerosol scenario the larger water amount in the atmosphere was accumulated and the precipitation was postponed. The presence of aerosols has increased the cloud cover in the lower troposphere, which was accompanied by the decrease in precipitation rate. The mesoscale patchiness in mass distribution resulted in well-developed local updraft and downdraft motions associated with the mesoscale cells, in which the vertical velocity differences reached up to ±2.5 m/s.

It is worth to note that the proper accounting of aerosols in precipitation forecasts will require the accurate information about their physical properties, concentrations, distribution, and evolution. However, the lack of high-resolution aerosol observation network and dearth of data on aerosol composition still hinders the research of their. This evident problem needs to be addressed. Therefore further studies are needed to assess the contribution of aerosols to separate modules of the HARMONIE model. In particular, the model output with a very short time step will be further used to study the detailed evolution of the life-time of a single precipitation cell.

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