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HARMONIE Case Study: Aerosol Impact on Atmospheric Meso-scale Circulation for Nordic Countries

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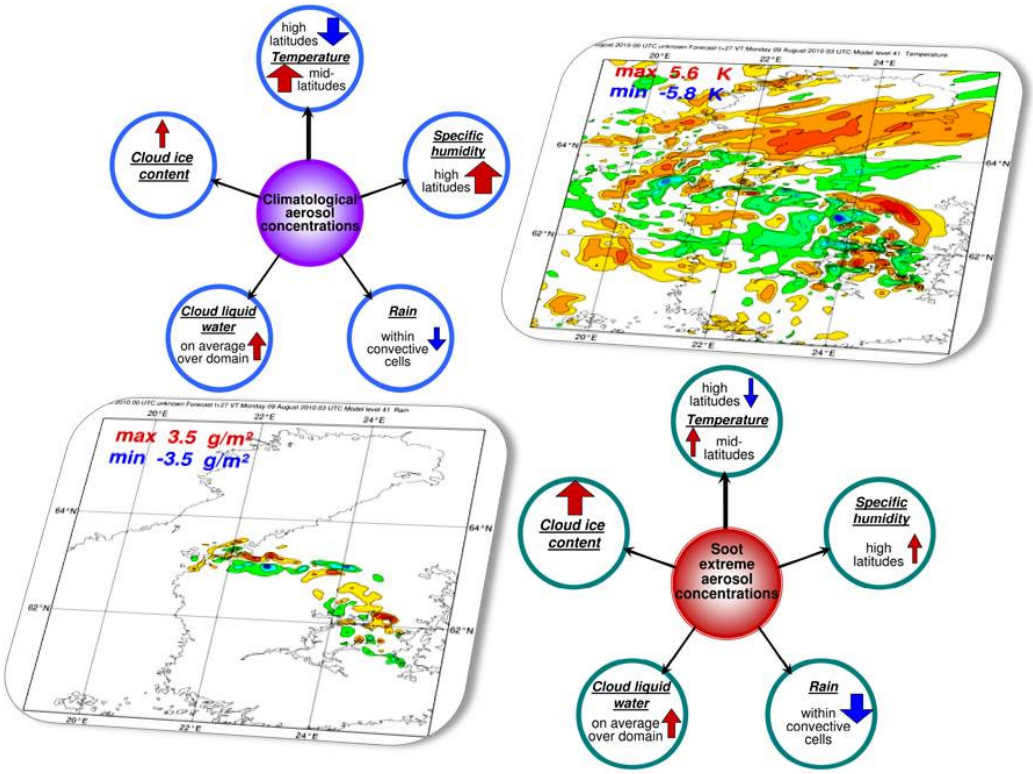

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Abstract

The mesoscale HARMONIE model is used to investigate the potential influence of aerosols on changes in the atmospheric state and quality of weather forecasts. The study considers numerical experiments over the North Atlantic – Europe – Northern Africa region during August 2010 with the following configurations: (a) climatological values for the four types of the aerosols: sea, land, organic, dust aerosols, (b) increased carbon content due to wild forest fires, (c) only the sea aerosols, and (d) in the absence of aerosols. The same initial and boundary conditions are used for all model runs. The spatio-temporal analysis of forecast differences highlights the impact of aerosols on the prediction of main meteorological variables such as radiation fluxes, air temperature, humidity, precipitation, and cloud cover as well as their vertical profiles. The variations occur through changes in radiation fluxes and microphysics properties. It occurs as a chain of interactions, in which aerosols work as a trigger. The main influence is observed within the planetary boundary layer for temperature, humidity, radiation, generation of turbulent kinetic energy. Weaker but still significant impact is visible through the middle troposphere in cloudiness, rain water formation, convective available potential energy and radiation. At the top of the atmosphere, changes in long-wave radiation are mainly considerable. Further increase of aerosol concentrations, as it occurs during wild forest fires, leads to changes in tendencies. The last fact confirms the complexity of positive and negative feedbacks between physical and chemical fields in the atmosphere, which will be track in further investigations.

1. Introduction

Aerosol particles play an important role directly by scattering and absorbing short-wave and long-wave radiation and indirectly by affecting the albedo and lifetime of clouds. The indirect radiative forcing of aerosols shows a high level of uncertainty that needs to be better constrained for improved prediction of weather conditions and climate change (*Baklanov et al., 2011*). Aerosols indirectly affect atmospheric state via changes in cloud properties, which are largely determined by changes in concentration of aerosol particles. That impact is large enough to activate cloud droplets (cloud condensation nuclei, CCN). Particle production in the atmosphere can be classified as either primary or secondary. The earlier includes carbonaceous particles from combustion, sea-salt from bubble-bursting in the ocean and uplift of mineral dust, while the latter are nucleation of sulfuric acid and water. Recent results have shown the large contribution to CCN from secondary particles.

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.

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 on-line integrated with two-way interactions. This allows considering feedbacks between chemical and meteorological processes at each time step of the model integration.

The today's complexity of numerical atmospheric models gives a certain confidence in being very close to real conditions. The extensive developments of different model parts such as improvement of parameterizations of physical processes often appear promising on the way to get better accuracy of atmosphere representation. Nevertheless, the incomplete understanding of natural processes in combination with nonlinear interaction between different model parts sometimes results in deteriorating of the forecast predictability. In other words, improvements in fine simulating particular process may change to worse the overall model performance.

In mesoscale numerical weather prediction, approaches to the simulation of the full aerosol effect 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 HARMONIE model is one of the most powerful tools for numerical predictions of the atmospheric state. This is a non-hydrostatic spectral convection-permitting model, in which default horizontal resolution is less than 2.5 km. The dynamical core, developed by the ALADIN community, is based on a two-time level semi-implicit semi-Lagrangian discretization of the fully elastic equations, using a hybrid coordinate with 65 vertical levels. A variety of sub-grid scale physical processes are taken into account by different parameterization schemes. Additionally, the

model contents the aerosol and chemistry package with several aerosol schemes as well as background climatological aerosol concentrations (*Driesenaar, 2009*). The model directly uses information on cloud formation and removal from the IFS system to account for the complex interactions between cloud processes, heterogeneous chemistry and wet removal. The model is able to represent the high temporal and spatial variability of the aerosol particle mass distribution but must assume a size distribution for the aerosol to calculate their radiative effects.

The latter is in a special focus of a join group of the HIRLAM community. Further, the number and size of primary aerosols depend on the initial size distribution attributed to their source profiles together with the main growth and removal process. The model represents the concentration number parameter developed for mineral dust and for sea salt aerosols. Representation of aerosol number is far more difficult for sulphate and secondary organics because the size distributions of condensing species depend on the size distribution of aerosols, which are present before condensation and on cloud processes. This allows to study the role of aerosols in the atmosphere and to estimate the impact of aerosols on physical processes including radiations and precipitation.

2. Methodology

2.1. General Approach

To investigate the aerosol impact on changes in the atmospheric mesoscale circulation and to investigate main physical mechanisms of the aerosols' influence on the development of 3D meteorological patterns by employing the HARMONIE (Hirlam Aladin Regional/Meso-scale Operational NWP In Europe) model the series of practical steps are performed: (i) to setup, configure and initialize the model over a domain covering Nordic countries; (ii) to select period(s) representing the active precipitation formation and intense release events; (iii) to prepare boundary conditions for meteorological and aerosol fields; (iv) to prepare observations for the inter-comparison with model results; (v) to perform HARMONIE runs at ECMWF HPC system with two aerosol modes: aerosols excluded and aerosols modified; (vi) to visualize, analyze, and evaluate model results vs. observations for physical atmospheric (air temperature, vertical component of wind speed, accumulated precipitation, turbulent kinetic energy, specific humidity) and aerosol (sea salt, organic carbon) fields, and (vi) to study a convective cell life-time with the focus on feedback mechanisms from aerosol toward physical variables, and physical and dynamical mechanisms responsible for direct and indirect aerosol effects.

2.2. Numerical Experiments

The HARMONIE model (version 38h1.1) initialization includes the creation of a domain covering Nordic countries centered over Denmark with the horizontal resolution of 2.5 km, 65 vertical levels, time step of 60 sec. The forecast length varied from 24 to 72 hours with output interval provided at every 1 or 3 hour(s). Boundaries and initial conditions are based on ECMWF-IFS 3D fields updated every 3 hour. To avoid possible additional disturbances from the observations towards prognostic fields, the data assimilation is switched off. The non-hydrostatic forecast option for dynamics and AROME package to calculate model physics are chosen. The SURFEX provides the interface to and modelling of surface processes. The basic set of model parameters allows us to resolve the mesoscale convective atmospheric processes with a high resolution. The AROME physics package (*Seity et al., 2011)* explicitly treats inside the scheme more than 25 microphysical processes. The representation of turbulence is based on a prognostic turbulent kinetic energy (TKE) equation developed by *Cuxart et al. (2000).* The TKE equation is combined with a diagnostic mixing length. The scheme representing physics call tree in AROME is shown in Figure 1.

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 x 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 HARMONIE runs were performed at ECMWF HPC supercomputer for three domains in several modes. The runs over the Finland and Denmark domains included two modes: 1) idealized "clean" atmospheric conditions (aerosols' free atmosphere) and 2) climatological aerosols (or prescribed aerosol concentrations from the MACC dataset). The model results are visualized and analyzed for major meteorological parameters (air temperature, turbulent kinetic energy and specific humidity at different altitudes, CAPE, short- and long-wave radiation fluxes at the top of

the atmosphere and at the surface; accumulated precipitation at the surface) for selected dates in August 2010.

The other series of numerical experiments is run for a case of the increased aerosol optical depth. This happens due to black carbon and organic matter from wild forest fires. Such event has occurred, in particular, over the western Russia during the period from 26 July to 11 August 2010 (https://www.gmes-atmosphere.eu/).

The model domain covered the Atlantic – Europe – North Africa region was used in three types of experiments. The domain size is 450 x 360 grid points and horizontal resolution of 25 km. The forecasts were integrated for 120 hours with a time step of 120 seconds. Initial and boundary conditions were supplied by the ECMWF-IFS global model with a time interval of 3 hours. 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 first numerical experiment (hereafter referred to as the ”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, the ”SEA” experiment), while the third experiment included all aerosols with their predefined climatologies (”YES” experiment). The following analysis of the aerosol influence on atmospheric variables is based on the differences between the NO-YES and NO-SEA experiments.

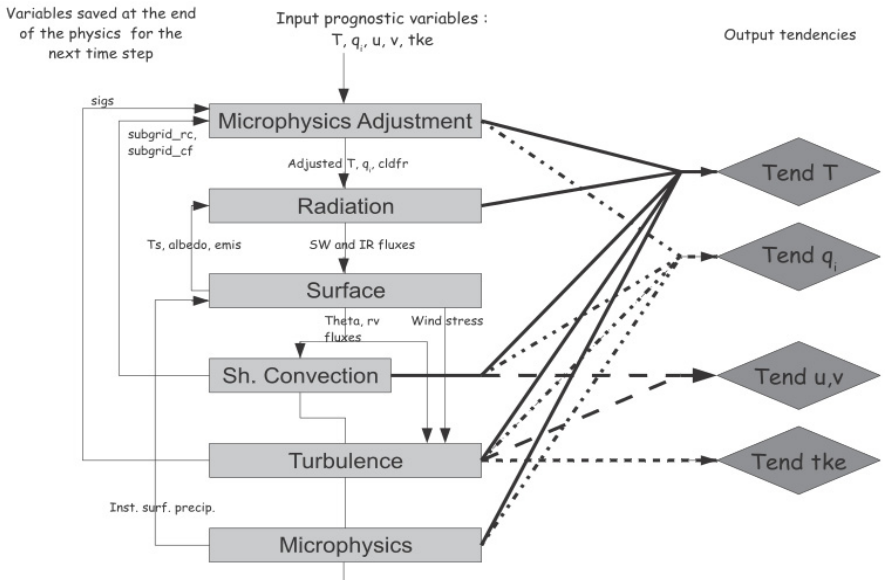


Figure 1. *AROME physics scheme, as a part of HARMONIE model (Seity et al., 2011).*

2.3. Case Studies

The specific case of 8 August 2010 with active precipitation formation over the Nordic area including Denmark was selected for the HARMONIE model numerical experiments and analysis of the aerosols influence. The synoptical pattern of that day is characterized by fast moving frontal system that approached toward north-east (Figure 2a,b). The extended aloft active trough of the low-pressure system prevailed within the entire troposphere. A wide high-pressure ridge from the Azores High extended north-eastward to Europe at the lower levels. Intensive interactions between pressure systems evolved from the surface to the top of the troposphere.

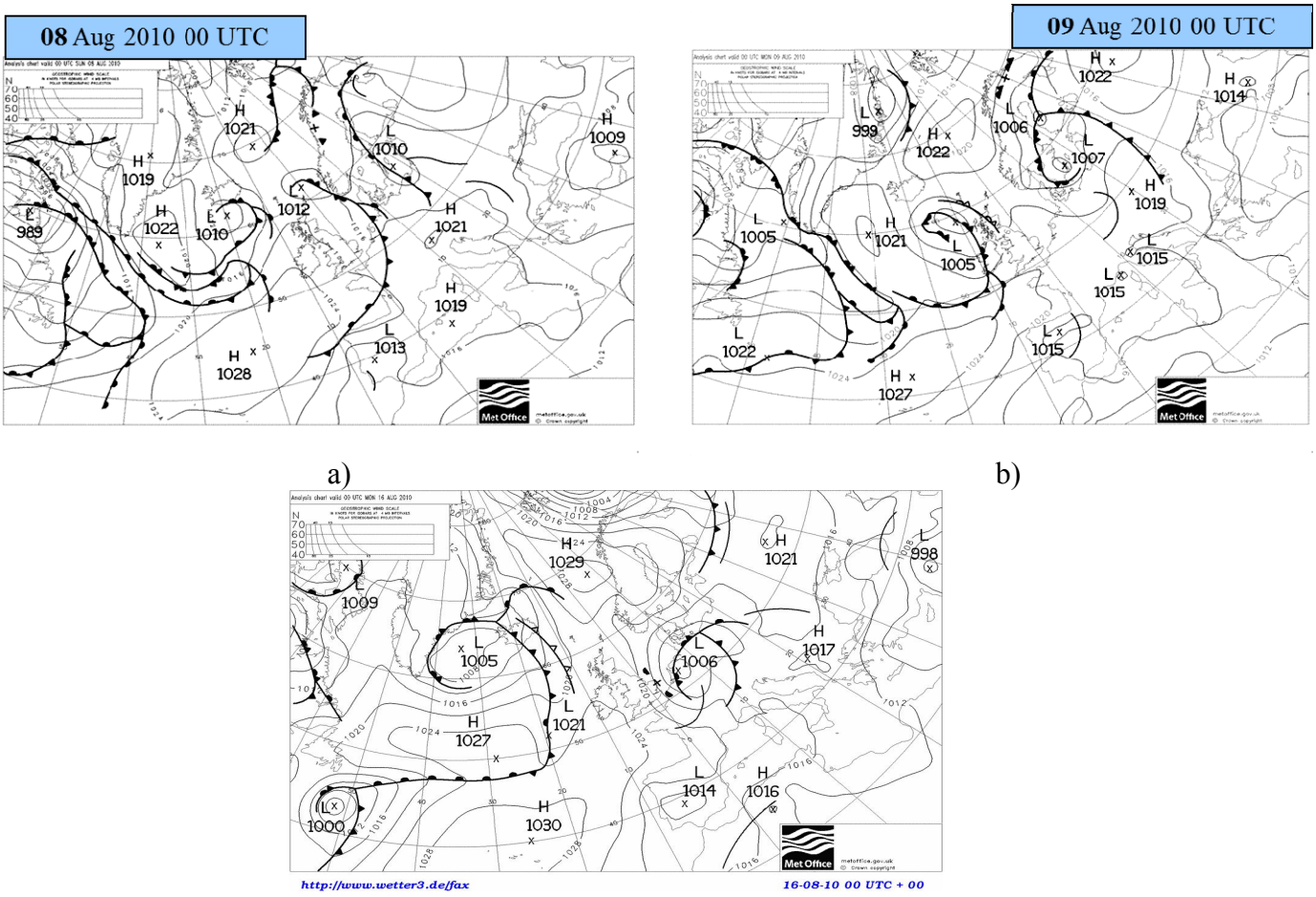


Figure 2. *Surface pressure for the meteorological pattern on 8-9 Aug (a, b) and 16 Aug (c) 2010, 00 UTC (source: http://www.wetterzentrale.de/topkarten/fsfaxsem.html).*

The second series of runs regarding carbon aerosol – atmospheric physics interactions during Russian forest fires of the 2010 year was performed with the HARMONIE model for the period from 8 to 10 August 2010 over the Finland domain. That area has been chosen due to several reasons. First, the domain is regularly used in full operational runs with already prepared background statistics necessary (*Lindskog et al., 2000*) for data assimilation. Then, the BaltRad experiment (https://baltrad.eu) with intensive radar sounding covers the Baltic area including Finland. High resolution radar data gathered during the experiment and containing reflectivity measurements allow verifying model outputs and specifying systematic model errors in further researches. As synoptic charts show (see Fig. 2abc), the smoke from the wild fire tends to be advected eastward, but anticyclonic circulation and transport over the Baltic and Nordic countries can also be seen. Finally, a series of synoptic patterns accompanied by precipitation with different rain rates were passing over the region during that period. This provides a proper basis for numerical experiments to study a life cycle of precipitation forms under various environmental conditions and to tune parameters of aerosol-physics interactions in the model.

Numerical experiments have been carried out with the same initial and boundary conditions, but different aerosol concentrations. They include climatological and zero values as well as increased black carbon and organic matter content. Additionally, the development of a part of the code and associated scripts for successive assimilation of aerosols from the MACC (Monitoring Atmospheric Composition and Climate; https://www.gmes-atmosphere.eu) monitoring system was started.

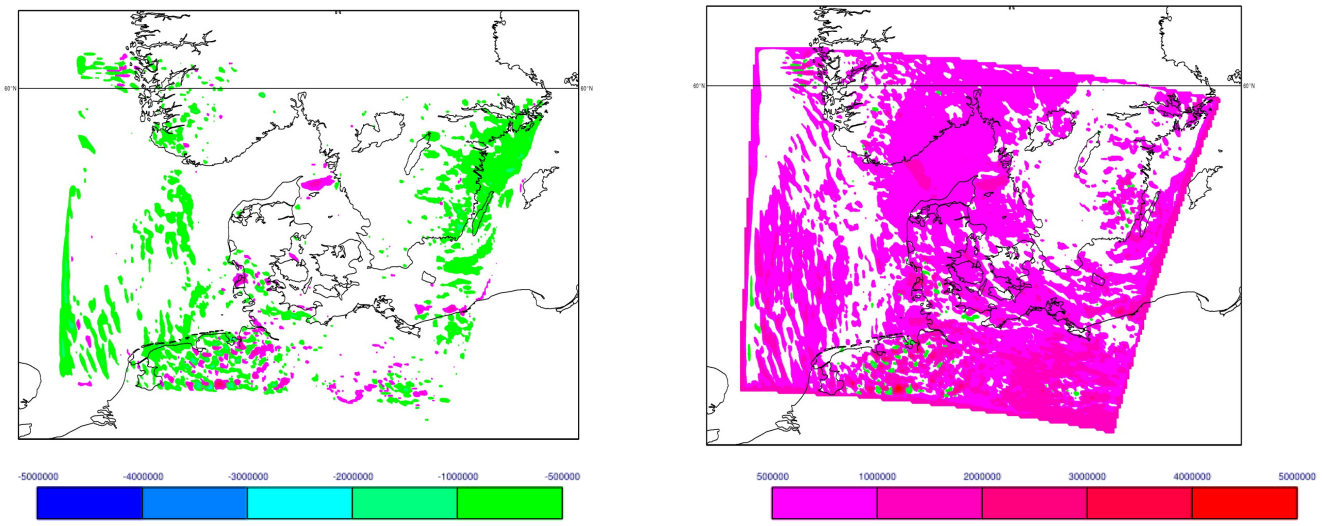
The “sea aerosol” study focuses on documenting the role of aerosols in atmospheric processes by comparing fields from a number of experiments during 11-16 August 2010 over the North Atlantic and Europe. The summer atmosphere was characterized by typical synoptic patterns (Figure 2c). An active low dominated 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.

According to analysis of isobaric surfaces maps (not included here), the 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. Divergence in the troposphere had 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/hour) over Central Europe, especially in the Alpine region. A wide high pressure ridge from the Azores extended to the north-east. 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.

3. Results and Discussions

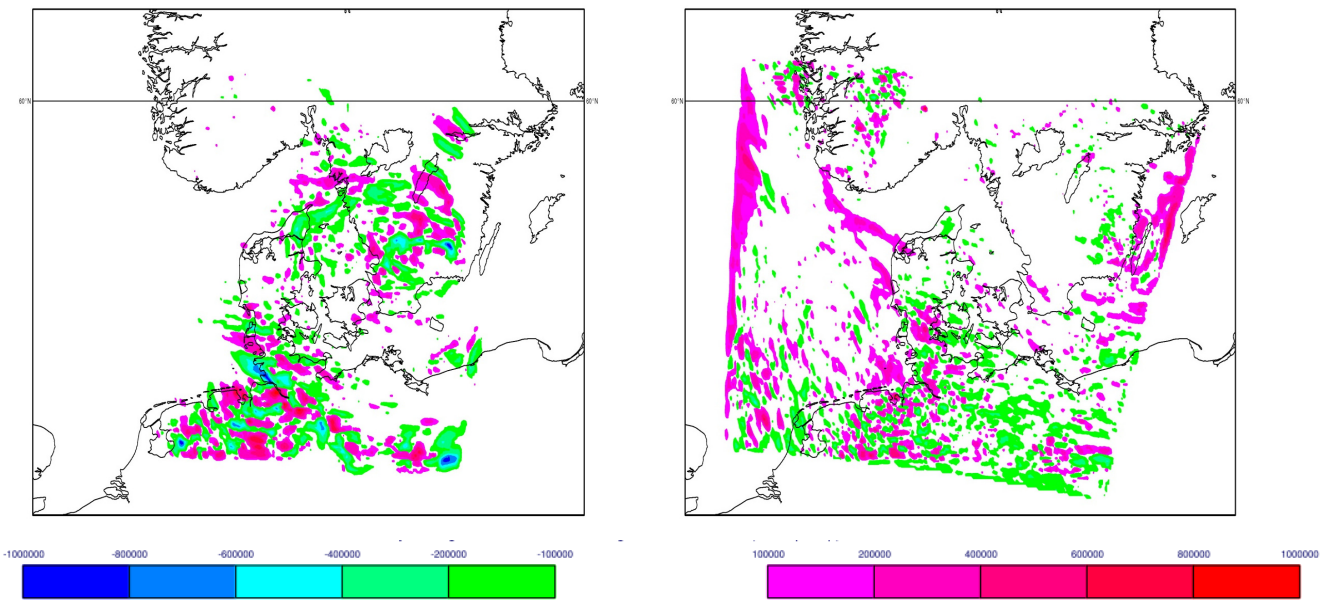
3.1. Short- and Long-Wave Radiation

Model simulations showed the evident influence of aerosols on numerical results for all meteorological parameters. The analysis is based on differences between prognostic fields for two model runs, i.e., "reference" ("clean" atmosphere) minus "aerosol" (climatological aerosol concentrations).



a) *b)*

Figure 3. *Differences (aerosols: reference - climate) in the HARMONIE simulated net short-wave radiation fluxes (in W/m^2) at the (a) top of the atmosphere and (b) surface on 8 Aug 2010, 21 UTC.*



a) *b)*

Figure 4. *The same as in Fig.3, but for net long-wave radiation fluxes (in W/m2) at the (a) top of the atmosphere and (b) surface.*

The net short-wave (SW) radiation fluxes on the top of the atmosphere (TOA) after 24 hour forecast are larger in the polluted atmosphere. The negative differences as large as of about $1x10^6$ W/m^2 and dominate over the whole domain (Figure 3a; note, the white color background on figures shows areas where there are no differences between the reference and modified runs). Near the surface the opposite effect is observed (see Figure 3b), when values vary from 0.5 to $1x10^6$ W/m^2 with a maximum up to $3x10^6$ W/m^2.

The differences in the net long-wave (LW) radiation show more complex behavior. It is less uniform to the aerosol inclusion. In particular, at TOA and near the surface the differences appear in a form of small-scale cells with the opposite signs. For the TOA, on average it varies at $\pm 4x10^5$ W/m^2 (Figure 4) and mostly appears over the continental areas. For the surface, it is distributed over the entire modelling domain and differences varied at the same level of magnitude.

3.2. Air Temperature and Specific Humidity

The significant influence of aerosols on air temperature fields appears in the upper troposphere (Figure 5a), where the average differences vary from -2 K to +2 K and mainly locate over continental areas. The largest positive values are observed behind a frontal zone in cold air masses moving from the Arctic. The air temperature at that layer is warmer in presence of aerosol. On the other hand, this effect is opposite and weaker in the planetary boundary layer (PBL), where temperature differences vary from -1 K to +1 K, and negative values dominate, in particular over southern Sweden (Figure 5c). The area of deviations in PBL covers only about 15% of the total area of temperature deviations in upper troposphere. Towards the surface the aerosol impact on temperature becomes negligible: minor negative values locate in the southern part of the model domain at a continental area (Figure 5b-5d).

The simulated specific humidity fields are sensitive to atmospheric aerosols as well. The spatial distribution of the specific humidity differences over the land and sea areas is similar to the behavior in temperature differences for the lower troposphere (Figure 6). The magnitude of the humidity differences varies from -1 g/kg to +1 g/kg and meso-scale cells of the opposite signs follow by each other. The neighboring areas of maximum and minimum values (reaching ±4 g/kg) are located over the southern Sweden and coincide with the temperature differences.

Figure 7a shows differences between runs for accumulated precipitation. As it seen, the average difference is about 20 mm, while along the frontal zone they increase up to +60 mm. Such large discrepancies can be explained by the fact, that aerosols create conditions for a longer period of precipitation formation by acting as additional cloud condensation nuclei, and change a life-time of precipitation cells. As result, the so-called ”phase error” appears and grows up during simulation.

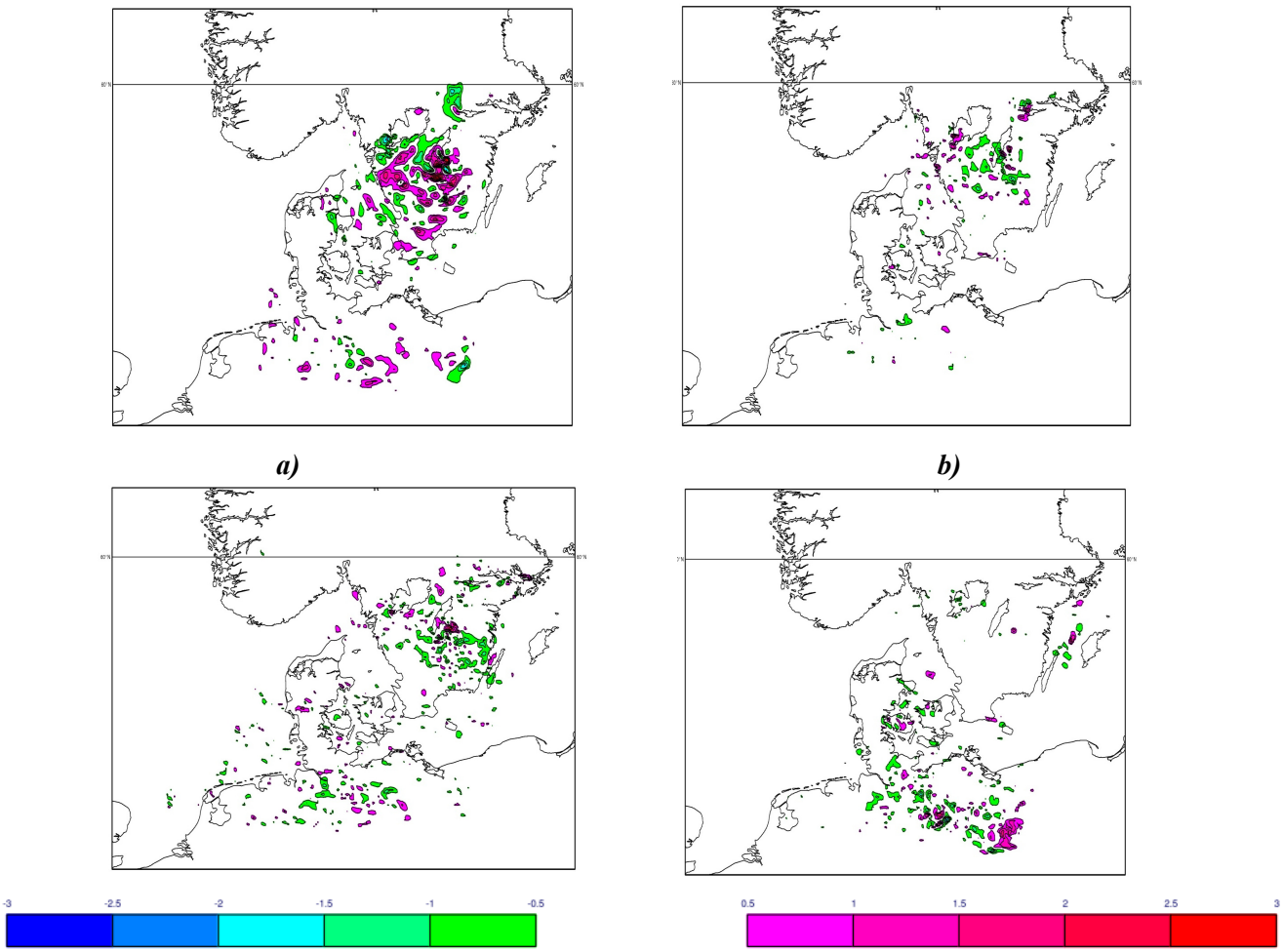


Figure 5. *The same as in Fig.3, but for air temperature (in K) at the altitudes of (a) 10 km, (b) 5.5 km, (c) 1.5 km, and (d) 100 m*

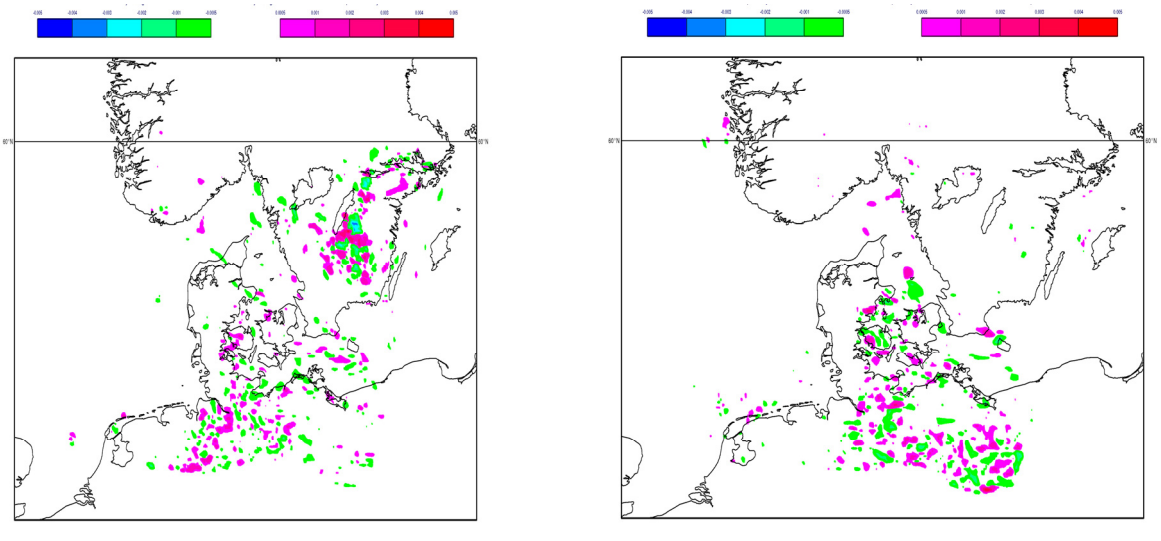
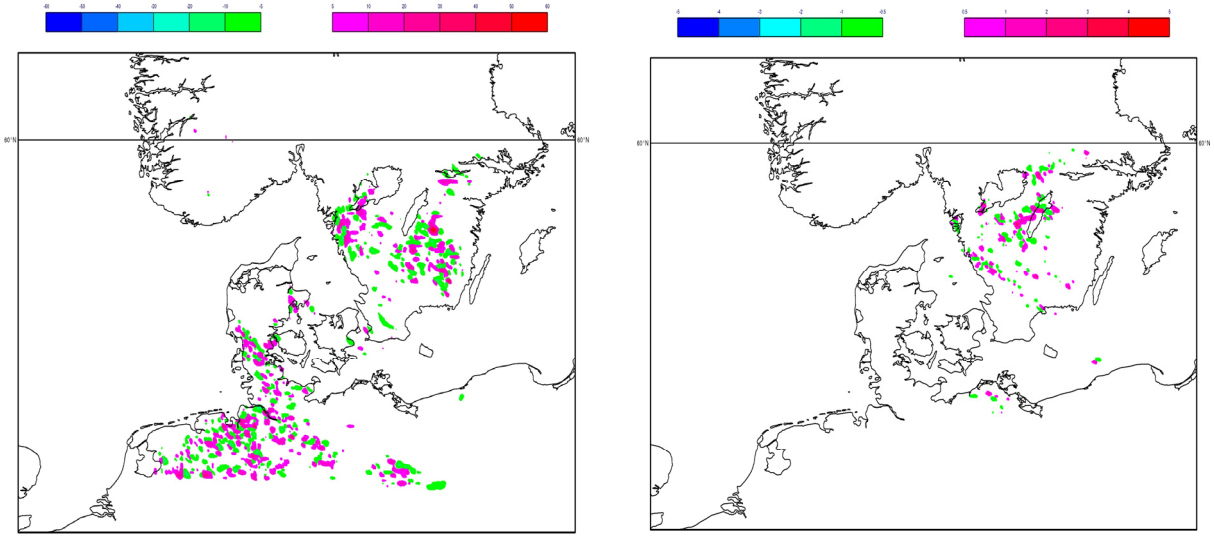


Figure 6: *The same as in Fig.3, but for specific humidity (in g/kg) at altitudes of (a) 1.5 km and (b)100 m.*

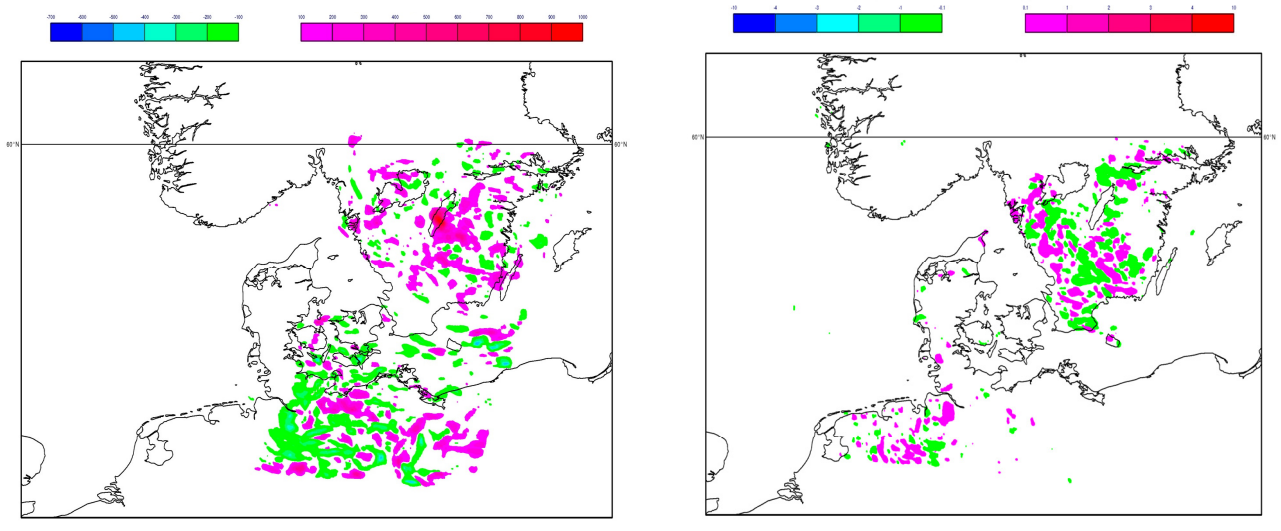


a) *b)*

Figure 7. *The same as in Fig.3, but for (a) accumulated precipitation and (b) vertical velocity (in m/s) at the altitudes of 3 km.*

3.3. Vertical Velocity, Turbulent Kinetic Energy and Convective Available Potential Energy

The aerosol influence on vertical velocity is negligible near the surface, but becomes sensitive and grows up with an altitude above 300 m. From that level updraft at single cells achieves positive values around 1 m/s (Figure 7b). In the middle troposphere the positive differences increase up to +3 m/s and cover larger areas. Negative differences appear within the same layer, are smaller at about three times, but cover extensive areas. Worth to note, the largest influence of aerosols is observed over the southern Sweden, where active interaction between cold arctic, and warm and humid subtropical air masses occurs. Above the middle troposphere vertical velocity is not sensitive to aerosols.



a) *b)*

Figure 8. *The same as in Fig.3, but for (a) CAPE (in J/kg) and (b) turbulent kinetic energy (in m^2/s^2) at the altitudes of 100 m*

One may expect that derivative characteristic of the atmosphere, such as the convective available potential energy (CAPE), could be related to vertical velocity and humidity. However, a link is not so obvious. In particular, the differences for CAPE (Figure 8a) are significantly larger and cover extensive area comparing in vertical velocity. The average values vary from -200 to +400 J/kg, and reaches up to +900 J/kg at the intensive frontal zone.

As for turbulent kinetic energy (TKE), differences between two runs are of about ± 1 m^2/s^2 near the surface. With altitude within PBL they grow up to + 3 m^2/s^2 in value, but decrease in spatial size (Figure 8b). This shows the importance of aerosols in the physical and dynamical mechanisms of TKE generation through PBL. However, it is necessary to keep in mind that TKE simulation is very sensitive to a parameterization scheme used in a corresponding physical package. So far, the conclusion reflects both the physical and numerical components.

3.4. Impact of Carbon Aerosols

Results of this case study (8-10 Aug 2010) with the wild forest fire provide a basis for further analysis, which can be separated at two parts. First, they show the influence of aerosols on most of atmospheric variables. The comparison of results obtained with zero aerosol concentrations versus climatological values in the presence of the whole aerosol set shows changes in main physical atmospheric fields, such as the temperature, humidity, cloud cover, precipitation, short-wave and long-wave radiation fluxes through the low and middle atmosphere (Figures 9, 10, 11).

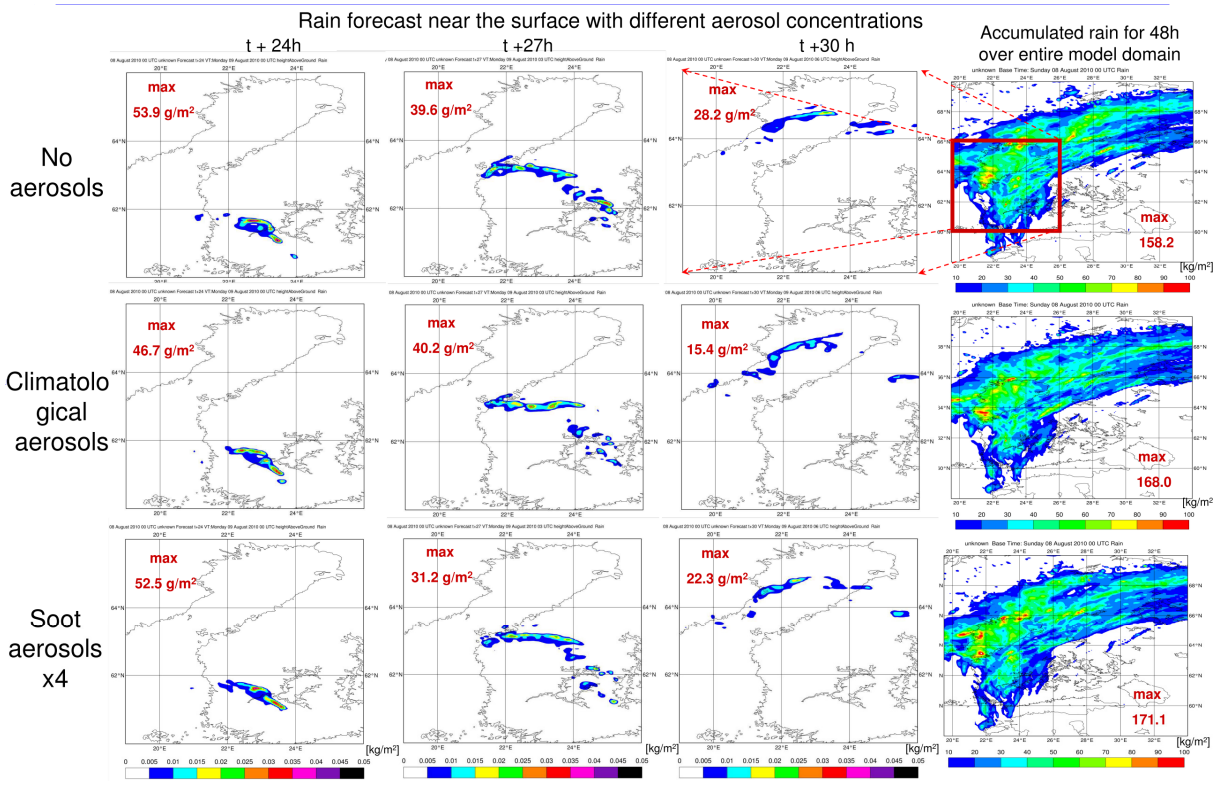


Figure 9. *Rain forecast near the surface with different aerosol concentration simulated in the HARMONIE model on 8 Aug 2010, 21 UTC.*

The most visible effect appears in increasing the cloud cover in the lower part of the troposphere accompanied by decreasing precipitation rate. This confirms the well-known fact that aerosols serve as sponge accumulating water mass, with the following changes in radiation processes. Worth to note, the impact is observed in a form of meso-scale cells inhomogeneously covering the domain and associated with specific areas of synoptic patterns. Such a non-linear and multi-steps response

in physical values occurs due to a chain of interactions. The database of the model outputs with the hourly temporal resolution allows to track the evolution and life-cycle as well as to account changes in heat and mass fluxes due to the aerosol impact.

Second part of the HARMONIE model numerical experiments shows the response in atmospheric fields after emissions of carbon from the Russian forest fires occurred during summer of 2010. The synoptic pattern during 8-10 August 2010 has brought smoke to the Scandinavia region. Increasing of carbon concentration in the atmosphere leads to similar changes in meteorological fields in a form of meso-scale structures with opposite signs (Figures 12, 13abc). At this step of numerical experiments the distribution of the aerosol has been initialized as shown in Figure 13d. Those changes, which actually continue increasing the aerosol concentration, do not follow by previous results. Rather, they often show opposite behavior. It assumes the aerosol impact on the atmospheric physics occurs in a complex way with numerous positive and negative feedbacks, which will be investigated in further studies.

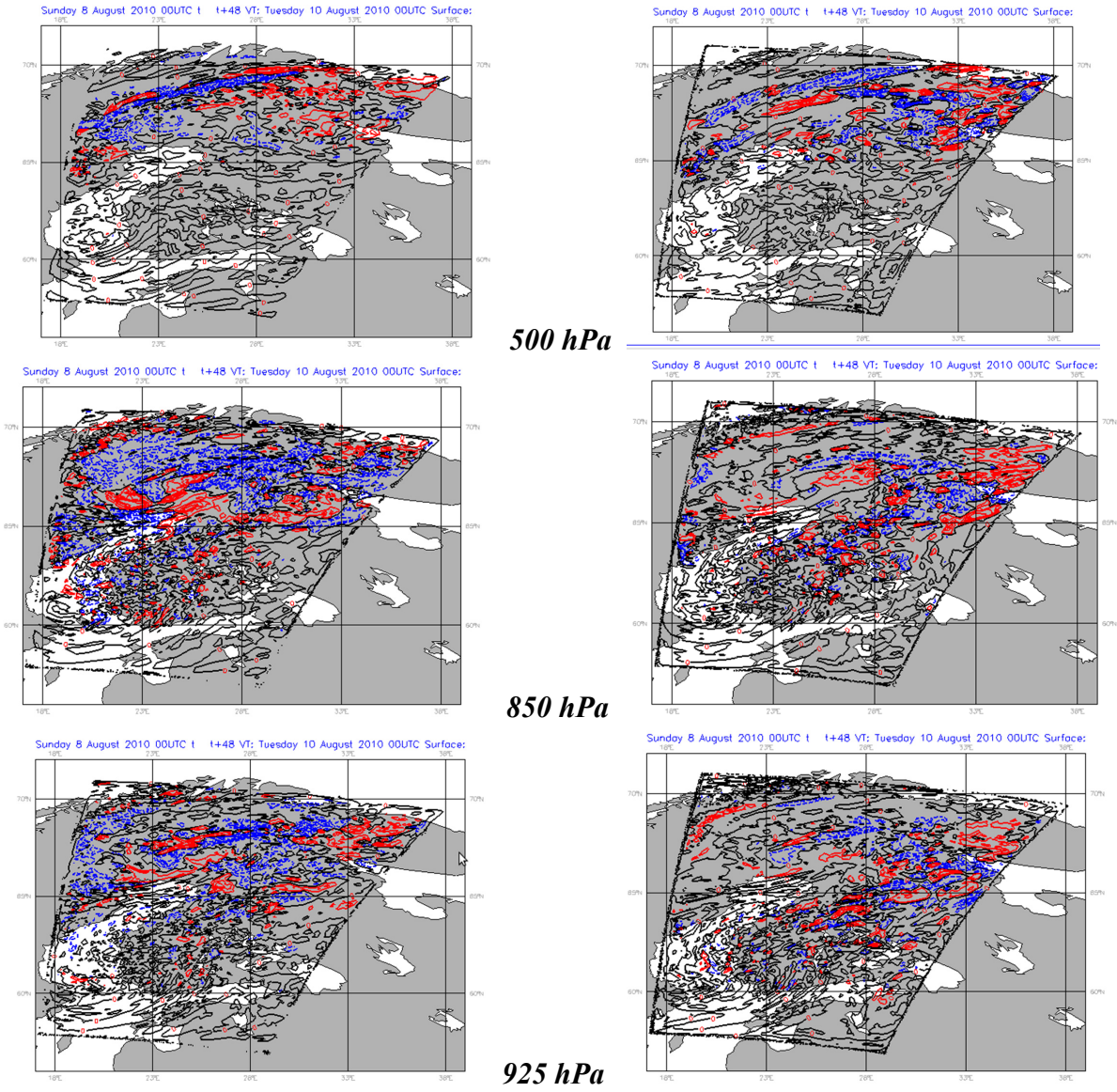


Figure 10. *The same as in Fig.3, but for (a) temperature and (b) specific humidity through the low and middle troposphere over the Finland domain. Blue and red colors correspond to negative and positive values correspondingly.*

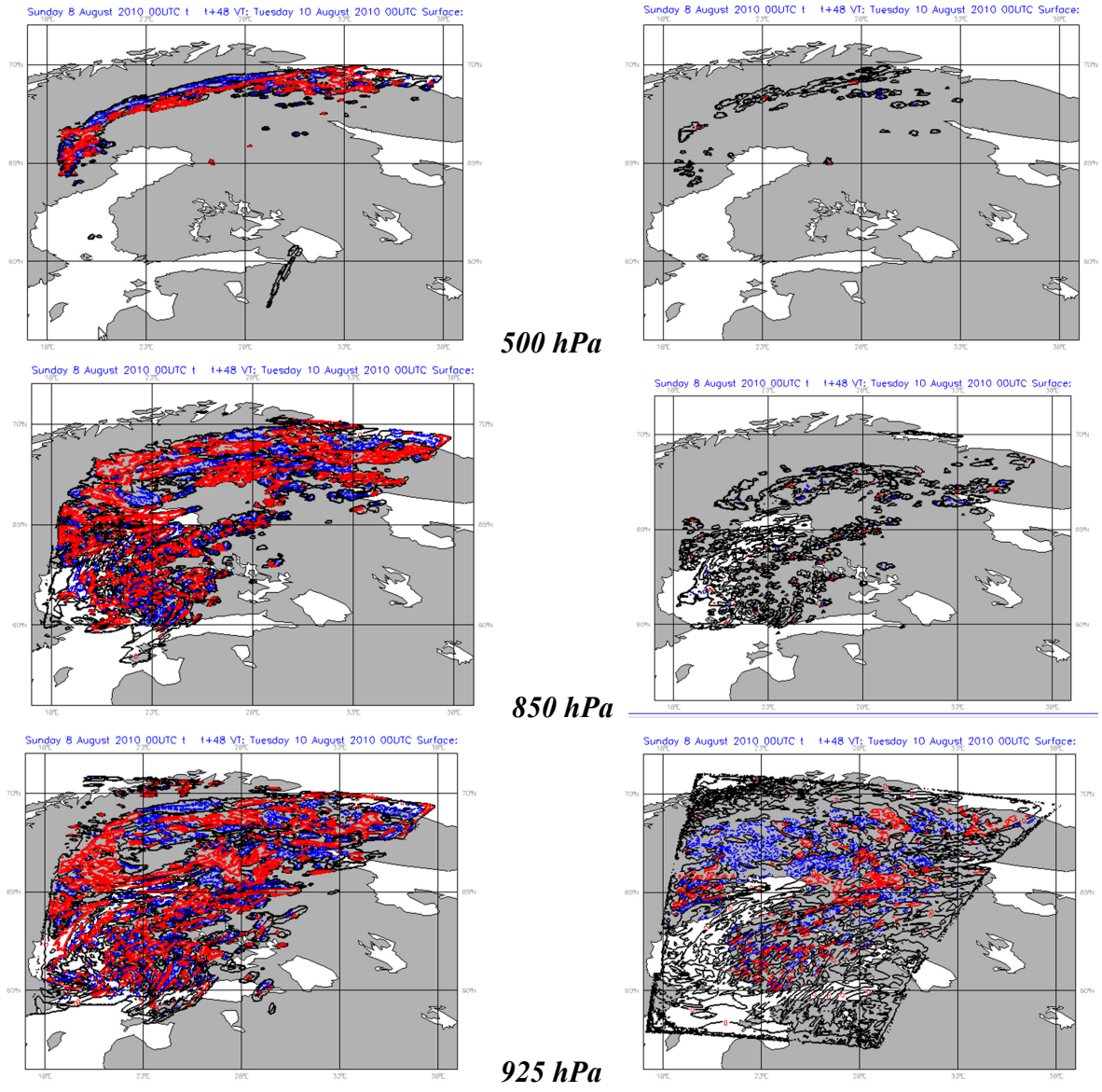


Figure 11. *The same as in Fig.9, but for (a) cloud cover and (b) rain water in the atmosphere.*

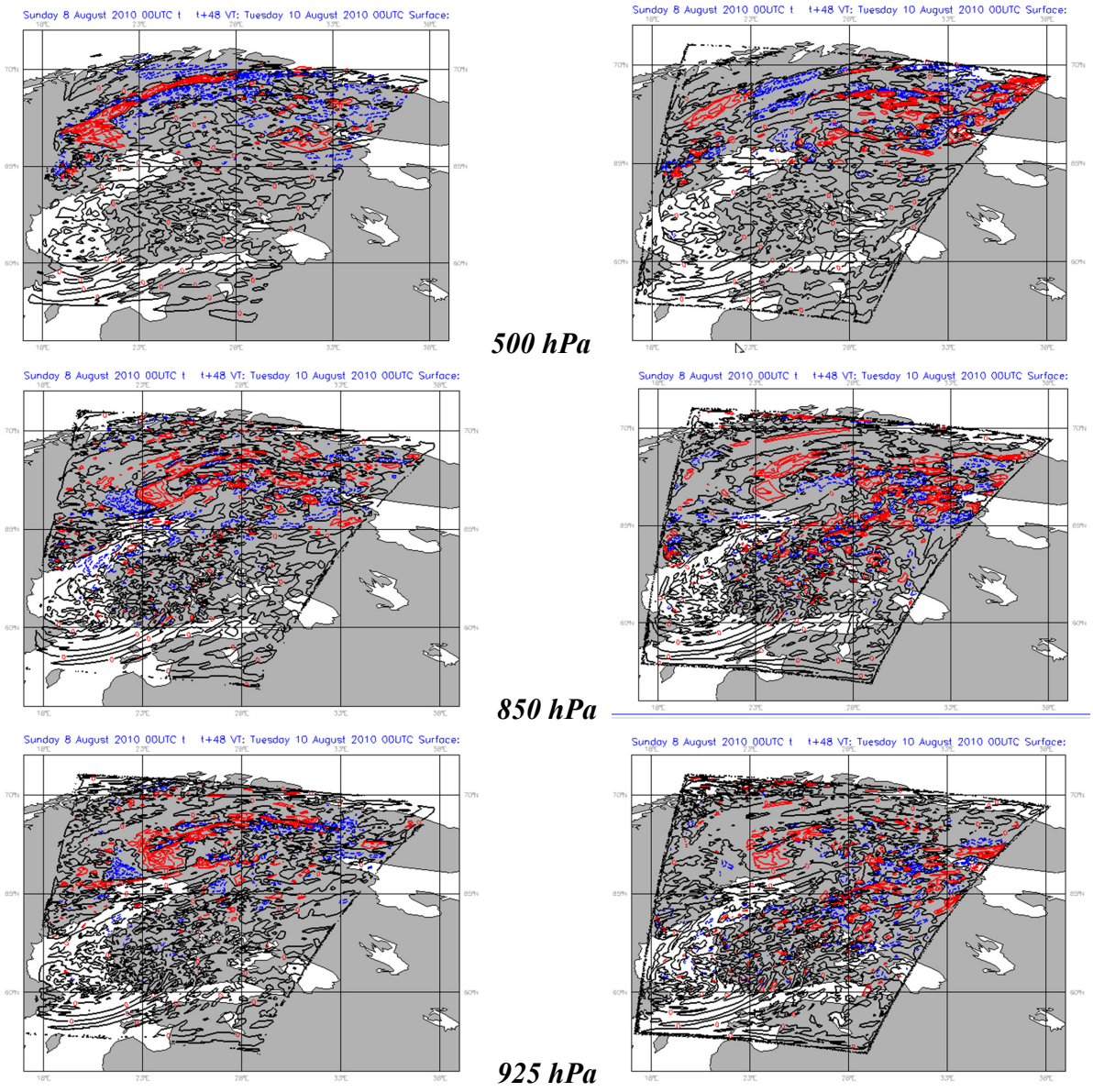


Figure 12. *The same as in Fig.9, but for runs with climatological and increased after Russian fires aerosol concentrations for (a) temperature and (b) specific humidity.*

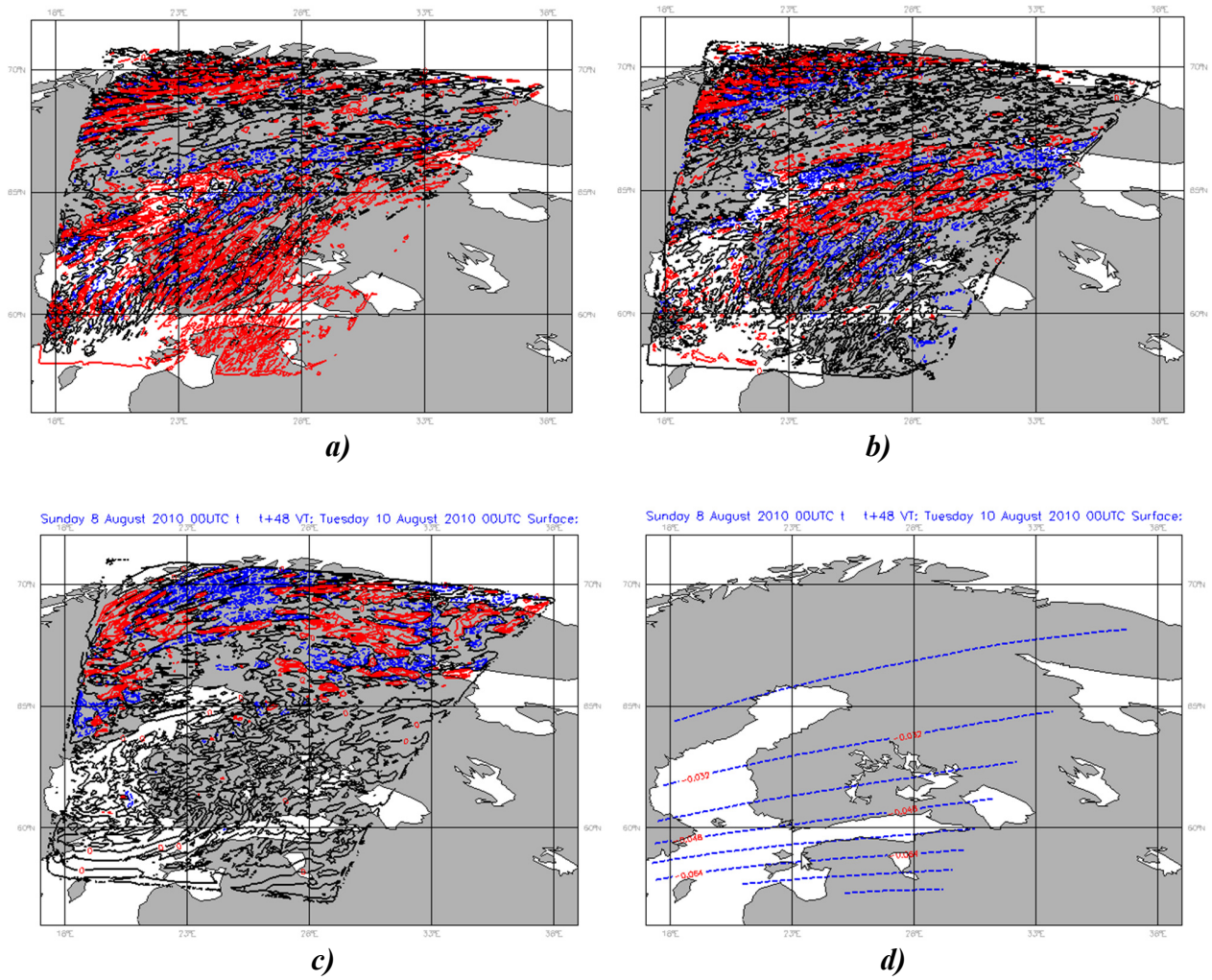


Figure 13. *The same as in Fig.11, but for (a) short-wave at the surface, (b) long-wave at the surface, and (c) long-wave on the top of the atmosphere radiation fluxes; and c) The distribution of aerosol in the run simulating the Russian fire episode 2010.*

3.5. Impact of Sea Aerosols

The role of sea aerosols in atmospheric processes is shown and discussed here by comparing fields from a number of experiments during 11-16 August 2010 over the North Atlantic and Europe. The sea salt aerosol influence on the instantaneous short-wave radiation fluxes on the top of atmosphere as well as near the surface appears very similar in both numerical experiments. On particular, fields of the differences show large areas covered by small scale cells of opposite signs with average values of about ± 20 W/m^2. The increasing or decreasing of SW radiation within a particulate cell on the atmosphere top corresponds to the same changing near the surface. The maximum value of SW radiation provoked by aerosol particles reaches up to 114,5 W/m^2 at the top of the atmosphere and 143 W/m^2 near the surface. The mean LW radiation differences on the top of the atmosphere and near the surface are as much as -0,078 W/m^2 and -0,083 W/m^2 correspondingly, whereas for the SW radiation they are of about 0,12 W/m^2 and 0,17 W/m^2.

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).

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 (Figure 14). The differences in the temperature fields between two experiments after the 5-day model integration are as large as ± 3÷5 K and reach extreme values up to ± 10 K at single cells, which are related to particular geographical regions.

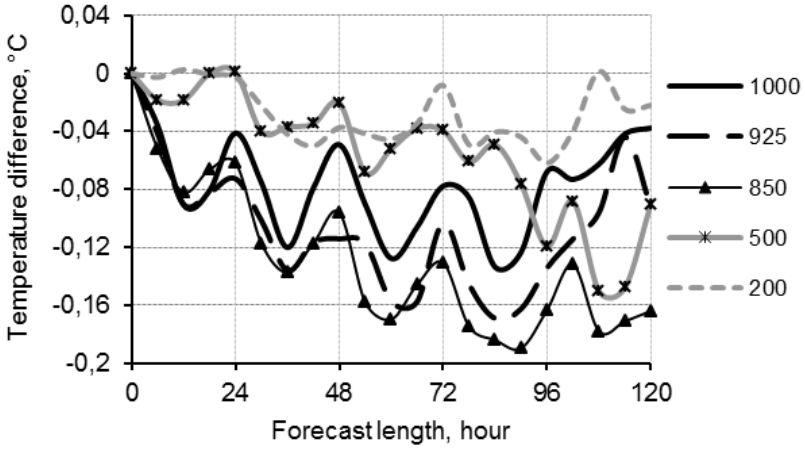


Figure 14. *Temporal evolution of the air temperature differences (no aerosols – sea aerosols only) averaged over the entire model domain during 11-16 August 2010 as a function of the pressure level.*

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, while the differences in rain amount to ±2,5 g/m^2. 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 ± 1 m/s.

The vertical cross-sections clearly show the slopped multi-centered deviations (Figure 15). They are associated with the first direct effect of aerosols; however non-linear dynamical processes developing on atmospheric fronts should be taken into account as well. The spatial distribution of differences in the humidity, precipitation and vertical velocity fields sufficiently depends on the geographical location and atmospheric flow regime.

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. 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 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.

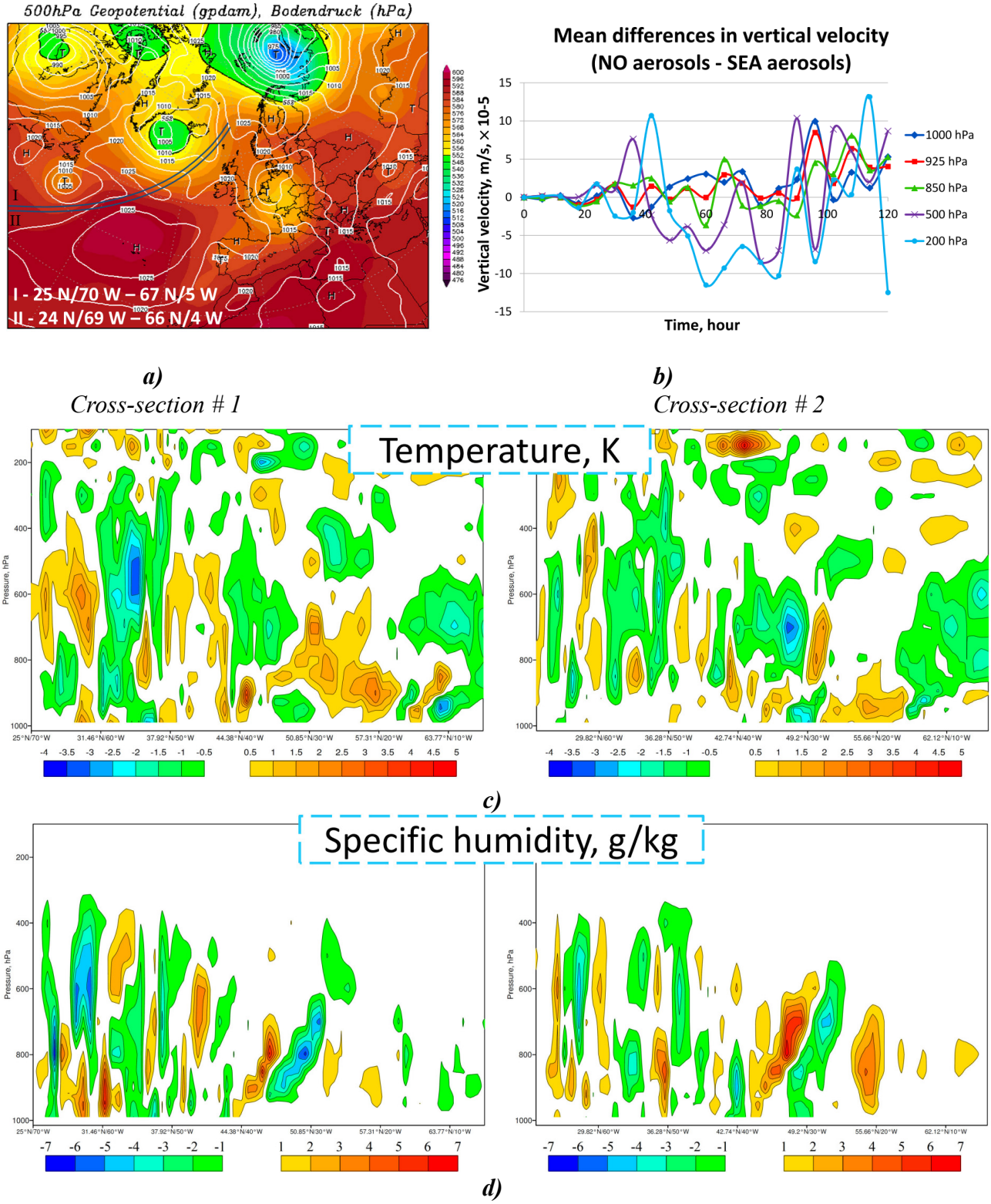


Figure 15. *Differences (aerosols: reference - sea) in the HARMONIE simulated vertical velocity (b), temperature (c) specific humidity (d) along two cross-sections (a) on 8 Aug 2010, 21 UTC.*

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. Discussion and Conclusions

The better understanding of the role of aerosols in the atmosphere are associated with the deepened knowledge of the aerosol radiative forcing; cloud, water vapor content and lapse rate feedbacks; and 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 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*). 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.

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. 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. The proper accounting of aerosols in precipitation forecasts will require the accurate information about their physical properties, concentrations, distribution, and evolution.

The obtained results are important for better representation of aerosol related atmospheric processes leading to improvement of NWP forecasts as well as for a better physical understanding of aerosol effects in the atmosphere. Future plans include additional experiments for the same domain and investigation the evolution of the life-time of a single precipitation cell for a higher spatial and temporal resolution.

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