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VELLE TOLL

Direct radiative impacts of atmospheric aerosols on meteorological conditions over Europe

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Press

This study was carried out at the Institute of Physics, University of Tartu, Estonia. The dissertation was admitted on May 23, 2016, in partial fulfilment of the requirements for the degree of Doctor of Philosophy in physics (environmental physics), and was allowed for defense by the Council of the Institute of Physics, University of Tartu.

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Contents

List of original publications

This thesis is based on the following publications, which are referred to in the text by their Roman numerals. The full texts are included at the end of the thesis.

I **Toll, V.**, Gleeson, E., Nielsen, K.P., Männik, A., Mašek, J., Rontu, L., Post, P., 2016. Impacts of the direct radiative effect of aerosols in numerical weather prediction over Europe using the ALADIN-HIRLAM NWP system. Atmospheric Research 172-173, 163–173.

II **Toll, V.**, Reis, K., Ots, R., Kaasik, M., Männik, A., Prank, M., Sofiev, M., 2015. SILAM and MACC reanalysis aerosol data used for simulating the aerosol direct radiative effect with the NWP model HARMONIE for summer 2010 wildfire case in Russia. Atmospheric Environment 121, 75–85.

III **Toll, V.**, Männik, A., 2015. The direct radiative effect of wildfire smoke on a severe thunderstorm event in the Baltic Sea region. Atmospheric Research 155, 87–101.

IV **Toll, V.**, Männik, A., Luhamaa, A., Rõõm, R., 2015. Hindcast experiments of the derecho in Estonia on 08 August, 2010: Modelling derecho with NWP model HARMONIE. Atmospheric Research 158, 179–191.

V Gleeson, E., **Toll, V.**, Nielsen, K.P., Rontu, L., Mašek, J., 2016. Effects of aerosols on clear-sky solar radiation in the ALADIN-HIRLAM NWP system. Atmospheric Chemistry and Physics 16, 5933–5948.

Author's contribution

The articles on which this thesis is based are the result of collective work. The author's contribution to the publications referred to by their Roman numerals is indicated below.

I Concept and design of the study. Running part of the numerical simulations and carrying out most of the analysis. Preparing most of the manuscript.

II Part of the concept and design of the study. Running HARMONIE meteorological model simulations and carrying out most of the analysis. Preparing most of the manuscript.

III Part of the concept and design of the study. Running all of the numerical simulations and carrying out all the analysis. Preparing most of the manuscript.

IV Part of the concept and design of the study. Running all of the numerical simulations and carrying out most of the analysis. Preparing most of the manuscript.

V Part of the concept and design of the study. Running part of the numerical simulations and carrying out part of the analysis. Part of the manuscript preparation.

Abstract

In this thesis aerosol impacts on weather conditions over Europe were studied using the limited area numerical weather prediction model HARMONIE. Atmospheric aerosols have significant impacts on the global radiation budget and on the Earth's climate. These impacts have previously been extensively studied. Research on the influence of aerosols on the meteorological conditions in the framework of numerical weather prediction characterized by the time scales of a few days has emerged more recently.

Numerical weather prediction models are continuously being developed to improve weather forecasts. In this thesis improving weather forecasts over Europe by including more accurate representation of the direct radiative influence of aerosols was investigated. It was shown that the accuracy of numerical weather forecasts can be significantly increased for cases with high aerosol concentrations in the atmosphere by including a realistic representation of the aerosol influence instead of the commonly assumed climatological average influence of aerosols. During severe wildfires in summer 2010 in Russia, the direct radiative effect of aerosols had a strong impact on meteorological conditions. The forecasts for the shortwave radiation budget at the surface, vertical temperature profile and near surface temperature were substantially improved by considering the influence of wildfire smoke in the meteorological simulations. More accurate forecasts of shortwave radiation are also of great interest to the solar energy industry.

In addition to research on aerosol impacts during a period with high aerosol concentrations in the atmosphere, the influence of aerosols was also studied during a period with aerosol concentrations close to the long-term average. In this case, the most pronounced influences of the aerosols are the modification of the vertical profile of atmospheric temperature and the influence on the energy fluxes at the surface. Including the direct radiative effect of aerosols also significantly improves the accuracy of numerical weather forecasts over Europe for conditions where near average aerosol amounts are present in the atmosphere. When aerosol amounts are close to the climatological average, including either the climatological average or real-time aerosol distributions gives comparable results. This is in contrast to when there are high aerosol amounts in the atmosphere.

Using high resolution models with horizontal grid spacing of the order of a couple of kilometres, such as the HARMONIE model, often enables accurate forecasting of convective storms. Aerosols can have a considerable influence on convection over Europe through the direct radiative effect during conditions when aerosol amounts are high. The direct radiative effect of aerosols influences the convective environment by changing the stability of the atmosphere and surface energy fluxes. This was demonstrated for a case-study involving severe convective storm over northern Europe.

Abbreviations

AERONET	Aerosol Robotic Network
ALADIN	*Aire Limitee Adaptation dynamique Developpement INternational*
AOD	Aerosol optical depth
AROME	Applications of Research to Operations at Mesoscale
BSRN	Baseline Surface Radiation Network
CAPE	Convective available potential energy
ECMWF	European Centre for Medium-Range Weather Forecasts
HARMONIE	Hirlam Aladin Research for Mesoscale Operational NWP in Euromed
HIRLAM	High Resolution Limited Area Model
IFS	Integrated Forecast System
IPCC	Intergovernmental Panel on Climate Change
LW	Longwave
MACC	Monitoring Atmospheric Composition and Climate
MACv1	Max-Planck-Institute Aerosol Climatology version 1
MODIS	Moderate-resolution Imaging Spectroradiometer
MUSC	*Model Unifie Simple Colonne*
MSLP	Mean sea level pressure
NWP	Numerical weather prediction
RMSE	Root mean square error
SILAM	System for Integrated modeLling of Atmospheric coMposition
SW	Shortwave
TEG97	Aerosol climatology following Tegen et al. (1997)

1 Introduction

1.1 Background

Atmospheric aerosols, solid and liquid particles suspended in the air, influence meteorological conditions both directly and indirectly. The direct radiative effect of aerosols results from the absorption and scattering of solar (shortwave, SW) radiation and from the absorption, scattering and emission of terrestrial (longwave, LW) radiation. The interaction of aerosol particles with SW and LW radiation leads to changes in the radiation budget of the Earth determined by the incoming SW radiation and outgoing SW and LW radiation at the top of the atmosphere. When the radiative budget of the Earth is altered by aerosols, the Earth's climate is affected. A great deal of research has been conducted on the direct radiative effect of aerosols to date (e.g. Bellouin et al., 2005; Haywood and Boucher, 2000; Jacobson, 2001; Myhre et al., 2013a) and global estimates of the magnitude of this effect have improved in time. According to Yu et al. (2006), the global average SW direct radiative effect of aerosols over ocean is -5.5 ($\pm$0.2) W/m^2 at the top of the atmosphere and -8.8 ($\pm$0.7) W/m^2 at the surface and over land -4.9 ($\pm$0.7) W/m^2 and -11.8 ($\pm$1.9) W/m^2, respectively.

The direct radiative effect of aerosols is dependent on their physical properties (size distribution, shape, complex refractive index, mixing state) and on the properties of the surrounding environment. The typical radius of an aerosol particle is between 1 nm and 10 μm (Haywood and Boucher, 2000). The direct radiative effect of aerosols is dominated by the SW effect, but the LW effect is important for large particles, such as the particles of mineral dust (Haywood et al., 2005; Liao and Seinfeld, 1998; Pérez et al., 2006). Hygroscopic growth changes the radiative effect of aerosols, e.g. Pilinis et al. (1995) explain that an increase in humidity from 40% to 80% would double the global radiative forcing by aerosols (here radiative forcing refers to the change in the net radiative flux at the top of the atmosphere). The main types of aerosols are mineral dust, sulphate, sea salt, organic matter, black carbon and nitrates, which all have different properties and consequently lead to different direct radiative effects (Myhre et al., 2013a). SW absorption by anthropogenic black carbon leads to positive radiative forcing, but the overall anthropogenic radiative forcing by aerosols is negative, dominated by the forcing by sulphates (Skeie et al., 2011). Absorbing aerosols can induce significant radiative heating in the aerosol layer (Ramanathan et al., 2007), but the net cooling or warming effect caused by absorbing aerosols depends on the presence of clouds below the aerosol layer and on the surface albedo (Chand et al., 2009). In addition, aerosols modify the properties of clouds themselves through microphysical effects referred to as indirect effects.

Aerosols have indirect effects on meteorological conditions since they serve as cloud condensation and ice nuclei and consequently affect cloud albedo (Twomey,

1977) and lifetime (Albrecht, 1989; Lohmann and Feichter, 2005). Clouds are the strongest modulators of SW and LW fluxes and Loeb et al. (2009) have estimated the global average cloud radiative effect at the top of the atmosphere to be -46.6 W/m^2 for SW and +29.5 W/m^2 for LW, giving -17.1 W/m^2 for the net effect. In the research presented in this thesis only the direct radiative effect of aerosols is considered because of the high confidence level associated with the estimates of the magnitude of this mechanism (Myhre et al., 2013b), whereas low confidence level is associated with the estimations of the magnitude of the indirect effects of aerosols (Myhre et al., 2013b). The scientific understanding of the indirect effects of aerosols is still very incomplete (Lohmann and Feichter, 2005; Myhre et al., 2013b).

Radiative forcing induced by anthropogenic aerosols significantly influences Earth's climate, whereas aerosols offset part of the warming induced by the greenhouse gases (Skeie et al., 2011). Estimates for the effective radiative forcing by aerosols given in the 5^{th} IPCC assessment report (Myhre et al., 2013b) is as large as -0.45 (-0.95 to +0.05) W/m^2 for the direct effect and -0.45 (-1.2 to 0.0) W/m^2 for the indirect effect for the industrial period (1750–2011). Here the effective radiative forcing refers to the change in the net radiative flux (SW and LW combined) at the top of the atmosphere after allowing adjustments in atmospheric temperatures, water vapour and clouds (Myhre et al., 2013b). In addition, the uncertainty associated with the aerosol forcing is the main contributor to the total uncertainty associated with the anthropogenic radiative forcing of the climate (Myhre et al., 2013b).

The regional influences of aerosols through the direct radiative effect can be very different from the global average influence of aerosols depending on the emission areas of aerosols and their precursors as the atmospheric lifetime of aerosols is rather short (from a few days to weeks) (Haywood and Boucher, 2000). Aerosols are either directly emitted to the atmosphere (primary particles) or formed through gas to particle conversion (secondary particles). On average, aerosol amounts over Europe are much lower than over southern Asia, eastern Asia or Sahara desert region (e.g. Kinne et al., 2013). Direct radiative effect leads to negative radiative forcing at the top of the atmosphere in the industrial areas of Europe, northern America and Asia (Myhre et al., 2013a). The regional direct radiative effect can lead to modified regional atmospheric circulation, e.g. Lau et al. (2006) and Lau and Kim (2006) explain that the direct radiative effect of aerosols influences the monsoon in Asia.

There is considerable daily and seasonal variability in the regional distributions of aerosols (Sarkar et al., 2006; Smirnov et al., 2002) and the regional influence of aerosols can be very strong. Dust storms can have very large impact on the regional radiation budget (Prasad et al., 2007; Slingo et al., 2006). Slingo et al. (2006) showed that during a particular dust storm over Sahara the downwelling

SW flux at midday decreased by about 250 W/m^2 and the surface temperature decreased by 13 °C, while there were also considerable changes in the LW fluxes. Similarly, smoke from wildfires can have strong regional direct radiative influence on meteorological conditions, e.g. Robock (1991) and Stone et al. (2011) estimated that during particular wildfire events the decrease in the downwelling SW flux at the surface led to surface cooling of about 5 °C. High concentrations of aerosols over Europe can occur e.g. due to dust events, wildfires and volcanic eruptions (Ansmann et al., 2003, 2010; Hodzic et al., 2007; Schwikowski et al., 1995; Stohl et al., 2007).

Changes in the amount of aerosols over Europe modify the radiation climate in the region (Philipona et al., 2009; Wild et al., 2005). There was a decrease in the downwelling SW flux at the surface over Europe from year 1960 to year 1990 followed by an increase in the downwelling SW flux reaching the surface (Wild et al., 2005). A similar change has been found to be characteristic to the clear-sky SW flux over Europe, which is related to the change in aerosol concentrations in the atmosphere affected by the control of anthropogenic emissions (Wild et al., 2005). Also, volcanic aerosol released into the atmosphere from large volcanic eruptions have caused decreases in the downwelling SW flux at the surface in Europe (Ohvril et al., 2009). Philipona et al. (2009) explain how decreased amount of aerosols and increase in downwelling SW flux at the surface contributed to the warming over Europe since the 1980s. It is important to accurately include the direct radiative effect of aerosols in regional climate simulations over Europe as a considerable dependency of the European climate on aerosols has been shown by e.g. Hohenegger and Vidale (2005) and Zubler et al. (2011).

In addition to aerosol modulation of SW fluxes over Europe, meteorological conditions over Europe may be influenced by aerosols through the large scale atmospheric dynamics. Aerosols may influence large scale atmospheric circulation over the North Atlantic and Europe, e.g. Booth et al. (2012) suggest that aerosols may be an important driver of the multidecadal variability in the North Atlantic sea surface temperatures, which influence atmospheric dynamics. However, this hypothesis has been debated by e.g. Zhang et al. (2013). Pausata et al. (2015) and Fischer-Bruns et al. (2009) suggest that a change in the radiative effect of aerosols in the North Atlantic region has an impact on atmospheric circulation and on the North Atlantic Oscillation.

1.2 Motivation and objectives of this work

This thesis is devoted to the direct radiative impacts of natural and anthropogenic aerosols on the atmospheric conditions on short time scales (of a few days) characteristic for the limited area NWP. Local changes in meteorological conditions resulting from the influence of aerosols over Europe are studied. Influence of aerosols in numerical weather forecasts has been much less studied compared to aerosol impacts in global and regional climate simulations (Mulcahy et al., 2014). The fact that the aerosol impacts in NWP are not yet very well understood (Mulcahy et al., 2014) motivates the research presented in this thesis. Mulcahy et al. (2014) explain that the main reasons for having so far only a simple representation of average influence of aerosols in most of the NWP models have been the constraints on the available computational resources together with the incomplete scientific understanding of the indirect aerosol effects. The configurations of operational NWP models are always a compromise between accuracy and computational cost. With larger amount of computational resources becoming available, the more complex models can be used for operational purposes.

The availability of more and more accurate forecasts of aerosol distributions also motivates the research on the influence of aerosols in the NWP framework. Kukkonen et al. (2012) and Baklanov et al. (2014) provide an overview of a large number of different model systems used in Europe that can provide forecasts of atmospheric chemical composition and weather. Global aerosol data, including near real-time forecasts, are available for example from the MACC project (Eskes et al., 2015) under the Copernicus Atmosphere Monitoring Service. An atmospheric chemistry component has recently been integrated into the IFS model for building the Composition-IFS model (Flemming et al., 2014). Recently, the fully coupled modelling of air quality and weather has been suggested as an advanced method to simulate both air quality and weather as this provides an opportunity to interactively account for the complex feedbacks between atmospheric composition and meteorology (Baklanov et al., 2014; Grell and Baklanov, 2011; Zhang, 2008). However, the added value in the numerical weather forecast has to be weighed by the increase in the computational cost resulting from using such coupled model system. In the research presented in this thesis external aerosol data has been used in the HARMONIE NWP model. Using external aerosol data does not noticeably increase the demand for the computational resources used by the NWP model.

Up to now it has been a common approach to consider the climatological average direct radiative effect of aerosols in numerical weather forecasts. However, inaccurate representation of the direct radiative effect of aerosols in the NWP model can lead to considerable errors in the meteorological forecast (Carmona et al., 2008; Milton et al., 2008). Mulcahy et al. (2014), Morcrette et al. (2011) and Reale et al. (2011) present impacts resulting from the consideration of the influence of prognostic aerosols in experimental setups of different global NWP models: simulation of the radiation budget and near surface conditions is improved. Pérez et al. (2006) demonstrated a more accurate forecast of atmospheric temperature and MSLP when interactively accounting for the radiative effects of mineral dust from the Sahara desert. Rémy et al. (2015) presented an improved forecast of LW and SW fluxes and temperature at the surface together with increased atmospheric stability during a dust storm in the eastern Mediterranean, when the direct radiative effect of aerosols is included in the atmospheric model. The aerosol impacts on the large-scale atmospheric circulation are generally weak (Mulcahy et al., 2014; Reale et al., 2011). However, Reale et al. (2011) and Tompkins et al. (2005) showed that when accounting for the influence of aerosols, then, for example, the representation of the African easterly jet is improved in global NWP models.

The mesoscale atmospheric processes can be modified through the direct radiative effect of aerosols. Aerosols can modify the meteorological conditions in such a way that the evolution of the deep convection is affected, e.g. Mallet et al. (2009) and Fan et al. (2008) describe how the direct radiative effect of aerosols can lead to a weakened deep convection by stabilizing the atmosphere and decreasing the amount of CAPE. Increasing resolutions of NWP models lead to improvements in the representation of local weather conditions in numerical weather forecasts. High resolution non-hydrostatic NWP models with explicit treatment of deep convection are capable to simulate organized convection and mesoscale convective systems (Done et al., 2004). Regarding the resolution needed, Weisman et al. (1997) explain that the horizontal resolution of 4-km is often sufficient for resolving deep convection. Thus, including of the more complete representation of the influence of aerosols on the meteorological conditions in high resolution NWP models is becoming more important as these models are getting better in resolving local weather details.

Another reason for improving the representation of the direct radiative effect of aerosols in NWP over Europe, in addition to the potentially improved accuracy of weather forecasts, is that it helps to provide more accurate forecast of the SW flux at the surface for solar energy applications (e.g. Breitkreuz et al., 2009; Qu et al., 2014; Ruiz-Arias et al., 2014). NWP models are the best tools to provide forecasts of SW fluxes several days ahead (Mathiesen and Kleissl, 2011). In addition, there is a growing need for accurate simulation of solar radiation in the solar energy community due to the increasing usage of solar energy and renewable energy in general. Errors in the simulated SW fluxes on the order of 100 W/m^2 may occur in NWP models, when AOD exceeds 0.1 (Zamora et al., 2005); considering the direct radiative effect of aerosols based on the near real-time aerosol data helps to reduce such errors (Ruiz-Arias et al., 2014).

The main goal of this thesis is to study the influences of the direct radiative effect of aerosols on meteorological conditions over Europe using the NWP model HARMONIE, which is used for NWP in many European countries. It is investigated how numerical weather forecasts can be improved by including a realistic representation of the direct radiative effect of aerosols in the meteorological model. In papers **[I-V]**, which form the basis of this thesis, different aspects of the aerosol impacts were studied.

The specific objectives of this thesis are as follows:

1. To study the influence of the direct radiative effect of aerosols on meteorological conditions over Europe during conditions with near average aerosol concentrations (study **[I]**).
2. To investigate aerosol impacts during a wildfire period in summer 2010 with very high aerosol amounts present in the atmosphere (study **[II]**).
3. To analyse aerosol impacts on a convective storm (study **[III, IV]**).
4. To study the sensitivities and accuracy of the simulated direct radiative effect of aerosols (study **[V]**).

The rest of this thesis is organized as follows. In section 2, the NWP model HARMONIE together with the numerical experiment designs, the radiation parameterizations and the optical properties of aerosols and used aerosol datasets are described. In subsection 3.1, the distributions of aerosols over Europe based on different aerosol datasets that are utilized for radiative transfer calculations are presented. An overview of the modelling results from papers **[I-V]** is presented in subsection 3.2. Section 4 provides an outlook for including a better representation of the aerosol effects in numerical weather forecasts over Europe. In section 5, the main conclusions are summarized.

2 Model and methods

2.1 HARMONIE model and experimental designs

HARMONIE model is used for research and for operational NWP in many countries in the European-Mediterranean region with joint efforts to develop the model. In NWP models in general and also in the HARMONIE model, numerical integration of hydrodynamic equations is performed, whereas subgrid physical processes are parameterized. In addition, assimilation of meteorological observations is performed to derive the initial atmospheric state from which the forecast is started. The HARMONIE model combines a non-hydrostatic dynamical core, following Bénard et al. (2010) and Bubnová et al. (1995), with different physical parameterization systems. The surface scheme (SURFEX) (Masson et al., 2013) is included in the HARMONIE model for simulating surface and soil processes. AROME physical parameterizations (Mascart and Bougeault, 2011; Seity et al., 2011) and ALARO physical parameterizations (Gerard et al., 2009) can be used.

In this subsection, the utilized configurations of the NWP model HARMONIE are described; an overview of the used radiation parameterizations and aerosol optical properties is given in subsection 2.2. For simulating a severe convective storm in studies **[III]** and **[IV]**, the default convection allowing setup of the HARMONIE model with the 2.5 km horizontal grid spacing and non-hydrostatic dynamics was used. AROME physical parameterizations described by Seity et al. (2011) and Mascart and Bougeault (2011) were used in combination with the explicit treatment of deep convection. In this model setup, a single-moment mixed phase cloud microphysics scheme is used following Pinty and Jabouille (1998), which is described in more detail by Lascaux et al. (2006). Prognostic variables of water condensates are rain, snow, graupel, ice crystals and cloud droplets. Prognostic turbulent kinetic energy equation in combination with diagnostic mixing length (Cuxart et al., 2000; Seity et al., 2011) is used to calculate turbulence in the boundary layer.

The HARMONIE model at 10 to 15 km horizontal grid spacing was utilized in studies **[I]** and **[II]**. At these horizontal resolutions, hydrostatic dynamics and ALARO physical parameterizations were used, except for the radiation parameterizations. Lindstedt et al. (2015) describe the usage of the HARMONIE model for regional climate simulations using ALARO physical parameterizations. Flux-conservative governing equations of Catry et al. (2007) are used. For turbulence, pseudo-prognostic turbulent kinetic energy scheme following Geleyn et al. (2006) is used. Deep convection is parameterized using the 3MT (Modular Multi-scale Microphysics and Transport) scheme described by Gerard et al. (2009). A single moment microphysical scheme with a statistical sedimentation of precipitation following Geleyn et al. (2008) is used.

In study **[V]**, the MUSC model (Malardel et al., 2006), the single column version of the HARMONIE system, was utilized for the sensitivity experiments of the direct radiative effect of aerosols. AROME physical parameterizations (Mascart and Bougeault, 2011; Seity et al., 2011) were used, except for radiation schemes, which were varied. Using MUSC, the physical parameterizations of the HARMONIE model can be tested in the simplified framework, where large-scale dynamics, horizontal advection, pressure gradient force and large-scale vertical motion are excluded. Although such single column model is not suitable for operational weather forecasting, it is highly efficient for the development of different physical parameterizations. For simulating the direct radiative effect of aerosols with MUSC for one atmospheric column at certain time, it is sufficient to run the model for only one time step.

In HARMONIE simulations, the output from the ECMWF global model IFS and the HIRLAM model (Unden et al., 2002) were used as initial and boundary conditions. In the case of MUSC experiments, 3D HARMONIE output was used to get the initial profiles of different meteorological parameters together with the surface conditions at the specific location. Lambert Conformal Conic projection was used in all the presented 3D simulations. The model setups are summarized in Table 1 and a more detailed description of the domains, boundary conditions, and model setups used is given in the research papers **[I-V]** included in this thesis.

Table 1: HARMONIE model setups in papers **[I-V]**. Here, h refers to hydrostatic and nh to non-hydrostatic dynamics.

Study	**[I]**	**[II]**	**[III]**	**[IV]**	**[V]**
Dynamics	h	h	nh	nh	-
Physical parameterizations	ALARO	ALARO	AROME	AROME	AROME
Horizontal grid spacing	15 km	10 km	2.5 km	2.5 km	single column
Aerosol data	TEG97 MACC MACv1	TEG97 MACC SILAM	TEG97 MACC	TEG97	TEG97 AERONET

Simulated meteorological conditions have been compared to in-situ synoptic measurements and sounding data in Europe. The simulated downwelling SW fluxes at the surface were compared to BSRN measurements described by Ohmura et al. (1998). RMSE and bias (compared to observations in meteorological forecasts with different treatment of the direct radiative effect of aerosols) were computed for a range of meteorological parameters. This enables to evaluate improvements in the meteorological forecasts resulting from accounting for the direct radiative effect of aerosols. *RMSE* is given by

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(f_n - o_n)^2} \quad (1)$$

and *bias* is given by

$$bias = \frac{1}{N}\sum_{n=1}^{N}(f_n - o_n), \quad (2)$$

where N is the total number of observations, f_n is n^{th} forecast value and o_n is n^{th} observed value of a meteorological parameter.

2.2 Radiation parameterizations and aerosol optical properties

For calculating the direct radiative effect of aerosols their optical properties are needed. The optical properties used for calculating the direct radiative effect of aerosols in the HARMONIE model are the single scattering albedo ω, the asymmetry parameter g, the aerosol optical depth at 550 nm (τ_{550}) and the scaling coefficients to calculate τ at all the wavelength intervals from τ_{550}. τ_λ is given by

$$\tau_\lambda = \int_z k_\lambda dz \quad [unitless], \quad (3)$$

where k_λ is the aerosol extinction coefficient, λ is the wavelength and z is the height from the ground level. k_λ is the sum of the absorption coefficient α_λ and the scattering coefficient d_λ

$$k_\lambda = \alpha_\lambda + d_\lambda \quad [m^{-1}] \quad (4)$$

and ω_λ is defined as the ratio of d_λ to k_λ

$$\omega_\lambda = \frac{d_\lambda}{\alpha_\lambda + d_\lambda} \quad [unitless]. \quad (5)$$

g_λ is defined by

$$g_\lambda = \frac{1}{2}\int_{-1}^{1} P(\cos\Gamma_\lambda)\cos\Gamma_\lambda d\cos\Gamma_\lambda \quad [unitless], \quad (6)$$

where Γ_λ is the scattering angle and $P(\cos\Gamma_\lambda)$ is the scattering phase function representing the angular distribution of scattered energy (e.g. Liou, 2002).

By default, τ_{550} of different aerosol species from the TEG97 aerosol climatology is used and ω_λ, g_λ and wavelength dependence of τ for different aerosol species are parametrized following Hess et al. (1998). The Hess et al. (1998) dataset includes water insoluble aerosol, water soluble aerosol, soot, sea salt (accumulation and coarse modes), minerals (nucleation, accumulation, coarse and transported modes) and sulphate droplets. The different aerosol components are characterized with particle size distribution and spectral refractive index and their optical properties are calculated using Mie theory (Hess et al., 1998). In the default setup of the HARMONIE model the aerosol species from TEG97 are mapped to the species of Hess et al. (1998) to parameterize their optical properties (White, 2004). Constant relative humidities have been assumed by default to calculate the aerosol optical properties based on Hess et al. (1998). Climatological vertical profile of different aerosol species is assumed similarly to Tanre et al. (1984) and there is an exponential decrease in the aerosol extinction coefficient with height.

The goal of radiation parameterizations in an atmospheric model is to account for the radiative energy transfer. Radiance L_λ is defined by

$$L_\lambda = \frac{d^4 E_\lambda}{cos\delta dAdtd\Omega d\lambda} \quad [Wm^{-2}sr^{-1}nm^{-1}], \tag{7}$$

where dE is the energy, dA is the area, dt is the time, $d\Omega$ is the solid angle, $d\lambda$ is the wavelength interval and δ is the angle between surface normal and incident direction (e.g. Liou, 2002). Flux (flux density or irradiance is referred to as flux throughout this thesis) F is defined by

$$F = \int_\lambda \int_\Omega L_\lambda cos\delta d\Omega d\lambda \quad [Wm^{-2}]. \tag{8}$$

The radiative transfer equation (e.g. Liou, 2002)

$$\begin{aligned} \mu \frac{dL_\lambda(\tau,\mu,\phi)}{d\tau} &= -L_\lambda(\tau,\mu,\phi) + (1-\omega_\lambda(\tau))B_\lambda(T(\tau)) + \\ &+ \frac{\omega_\lambda(\tau)}{4\pi} \int_0^{2\pi} \int_{-1}^{+1} P_\lambda(\tau,\mu,\phi,\mu',\phi')L_\lambda(\tau,\mu',\phi')d\mu' d\phi' \end{aligned} \tag{9}$$

describes the modification of radiances L_λ through different physical processes that radiation undergoes in the atmosphere: scattering, absorption and emission of radiation. In Eq. 9 ϕ and ϕ' are the azimuth angles, μ and μ' are the cosines of zenith angle, $B_\lambda(T)$ is the Planck function at the temperature T, $P_\lambda(\tau,\mu,\phi,\mu',\phi')$ is the phase function of scattering giving the probability that radiance coming from the direction determined by μ' and ϕ' is scattered in the direction determined by μ and ϕ. In Eq. 9 on the right hand side the different terms represent basic extinction due to scattering and absorption, gain due to emission and gain due to scattering from all the other directions. For SW radiation emission is neglected and for LW radiation scattering is commonly neglected in atmospheric models and also in the HARMONIE model.

For calculating radiative transfer in the atmospheric models, the two stream approximation where radiation is represented with the downwelling and upwelling fluxes (Räisänen, 2002; Ritter and Geleyn, 1992) is commonly used (also in the HARMONIE model). The atmosphere is divided into one-dimensional columns (as it is also done for other physical parameterizations) with plane-parallel homogeneous layers. The radiative heating rates $\frac{\partial T}{\partial t}$ can be computed according to

$$\frac{\partial T}{\partial t} = -\frac{1}{c_p \rho} \frac{\partial F_{net}}{\partial z}, \quad (10)$$

where F_{net} is the net radiation flux (net of the upwelling and downwelling SW and LW fluxes), z is the height from ground, ρ is the density of air and c_p is the specific heat of air at constant pressure. In addition to modulating the vertical temperature profile, the radiative fluxes drive the energy budget at the surface.

In the HARMONIE model, the radiation parameterizations from the ECMWF global model IFS cy25 (Mascart and Bougeault, 2011; White, 2004) are used in the default setup of the model. SW radiation scheme following Fouquart and Bonnel (1980) includes six spectral bands (0.185–0.25–0.44–0.69–1.19–2.38–4.00 μm). The delta-Eddington approximation (Fouquart and Bonnel, 1980; Joseph et al., 1976) is utilized. In the default SW scheme, Rayleigh scattering, absorption and scattering by droplets, scattering and absorption by aerosols and absorption by gases (water vapor, oxygen, carbon dioxide, methane, nitrous oxide and ozone) is accounted for (Mascart and Bougeault, 2011). The clear-sky SW radiative transfer is calculated in a simpler manner following Coakley Jr and Chylek (1975). Rapid Radiative Transfer Model (Mlawer et al., 1997) is utilized for the LW radiative transfer, whereas the LW scattering is neglected. Absorbers in the atmosphere, considered in the LW scheme are clouds, aerosols and atmospheric gases (water vapour, carbon dioxide, ozone, methane, nitrous oxide and chlorofluorocarbons) (Mascart and Bougeault, 2011; Mlawer et al., 1997). These radiation parameterizations have been used in papers **[I-IV]**.

In study **[V]**, the SW direct radiative effect of aerosols, calculated with the default SW scheme following Fouquart and Bonnel (1980), was compared to the calculations performed with the acraneb2 radiation scheme (Mašek et al., 2015) and the hlradia radiation scheme (Savijärvi, 1990). Both acraneb2 and hlradia are broadband schemes using a single SW spectral interval. In addition, in paper **[V]**, the direct SW effect of aerosols calculated with the three SW radiation schemes available in HARMONIE was compared to the radiative effect calculated using the more accurate DISORT radiative transfer scheme (Stamnes et al., 1988) run using 30 streams.

2.3 Aerosol datasets

External aerosol data was used in the HARMONIE model to simulate the direct radiative effect of aerosols. In this subsection different utilized aerosol datasets are described. Aerosol datasets used in papers **[I-V]** are listed in Table 1. By default, the TEG97 monthly aerosol climatology, following Tegen et al. (1997), is used in the HARMONIE model to calculate the direct radiative effect of aerosols. From the TEG97 climatology, AOD of dust, sulphates, sea salt, black carbon and organic matter are available at the quite coarse horizontal resolution of 4° by 5°. This data is based on different modelling results from aerosol transport models for dust, sulphates, sea salt and carbonaceous aerosols (Tegen et al., 1997). Nabat et al. (2013) explain that aerosol distribution in some regions (e.g. dust over northern Africa) is poorly represented in this dataset because of the coarse resolution of the data.

The effect of using the more up-to-date MACv1 (Kinne et al., 2013) monthly aerosol climatology instead of the default aerosol climatology in HARMONIE to calculate the direct radiative effect of aerosols was studied in paper **[I]**. The MACv1 data is based on a combination of the AERONET (Holben et al., 1998) and the Aerosol Comparisons between Observations and Models (AeroCom) aerosol data (Kinne et al., 2013) and is available at the horizontal resolution of 1° by 1°. Kinne et al. (2013) merged the AERONET station data and the AeroCom data of 14 different models by assigning quality and range scores for each AERONET site. The optical properties of aerosols can be derived from the AERONET sun/sky radiometer measurements (Holben et al., 1998).

Aerosol data from the MACC reanalysis (Inness et al., 2013) was used in studies **[I-II]**. The MACC reanalysis data has been computed using the ECMWF global model IFS coupled to chemistry transport model (Flemming et al., 2009). On top of using the prognostic model described by Morcrette et al. (2009), the AOD from MODIS has been assimilated in the reanalysis (Benedetti et al., 2009). The concentrations of sea salt, dust, organic matter, black carbon and sulphates are available at the horizontal resolution of about 80 km from this dataset. The dataset covers the time period 2003-2012. In study **[III]**, the aerosol data originates from the simulations described by Huijnen et al. (2011), where the same model as for the MACC reanalysis was used to calculate the distribution of aerosols. It is important to note that for wildfires, the assimilation of the fire emission estimates was performed using fire radiative power observations from MODIS (Kaiser et al., 2012), as aerosol data for wildfire event is used. The MACC reanalysis provides time series of aerosol data which allowed to account for the time variations in aerosol optical properties in the atmospheric simulations. Near real-time forecasts of aerosol distributions are available in addition to reanalysis from the MACC project (Eskes et al., 2015).

SILAM (Sofiev et al., 2015) aerosol data was used to complement the MACC reanalysis data in paper **[II]** in order to study the direct radiative effect of aerosols during wildfires in Russia in summer 2010. Based on the SILAM simulations, the time series of aerosol optical properties were computed similarly to the MACC reanalysis data. The chemistry transport model SILAM is developed at the Finnish Meteorological Institute. Emission data from the IS4FIRES system (Sofiev et al., 2009) are used as a source for deriving the wildfire primary particulate matter emissions. IS4FIRES emissions were calibrated using the MODIS column-integrated particulate matter product following Sofiev et al. (2009). The MACC reanalysis aerosol data was used as the boundary data in SILAM following Im et al. (2015). The horizontal resolution of the used SILAM data is 0.25° by 0.25°.

3 Results

3.1 Distribution of aerosols over Europe

3.1.1 Climatological distribution of aerosols over Europe

In study **[I]**, the climatological distributions of aerosols over Europe are compared using aerosol data from three different datasets. In general, AOD increases towards the south-eastern part of Europe. Annual average AODs from the MACC reanalysis, the MACv1 aerosol climatology and from the default aerosol climatology in HARMONIE TEG97 agree quite well (Figure 1). Annual average AOD at 550 nm is between 0.05 and 0.25 in most areas. Close to the coast of the Atlantic Ocean, the values of AOD are lower in the TEG97 climatology compared to the other datasets. In the default setup of the HARMONIE model, aerosols are assumed to be more absorbing over Europe (having lower single scattering albedo) compared to the more recent MACv1 aerosol climatology. Over a large part of Europe, the annual average single scattering albedo for aerosols at 550 nm is below 0.9 in the default setup of the HARMONIE model, and above 0.94 based on the MACv1 climatology (**[I]**).

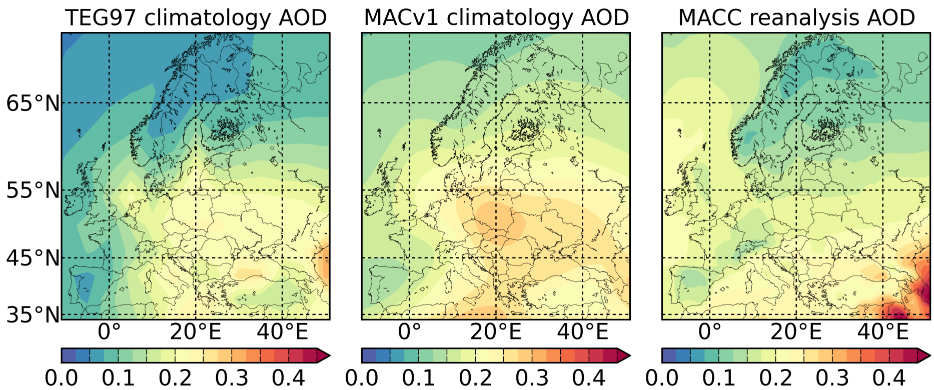

Figure 1: Annual average AOD at 550 nm over Europe from different aerosol datasets **[I]**.

Clear annual cycle is visible in all the aerosol datasets with the highest AOD over Europe (here defined as the area from 10 °W to 50 °E and from 35 °N to 70 °N) in summer and the lowest in winter (Figure 2). The AOD values are the highest in the MACC reanalysis dataset and the lowest in the TEG97 climatology. The monthly average AOD at 550 nm is below 0.3 and 0.2 in the MACv1 and TEG97 climatologies respectively. According to the MACC reanalysis, the monthly average AOD at 550 nm over Europe exceeds 0.35 in summer. The standard deviation for AOD over Europe is also considerable according to the MACC reanalysis (Figure 2). To estimate the frequency of conditions with high AOD over Europe, the number of days with the daily average AOD at 550 nm more than 0.5 and 1.0 were counted based on the MACC reanalysis data. In the western and northern parts of Europe, there were less than 10 days with AOD at 550 nm $\geq$ 1 and less than 100 days with AOD at 550 nm $\geq$ 0.5 during 2003-2012 (Figure 3). In the south-eastern part of Europe, there were many days with high AOD values during this period (more than 15 days with AOD at 550 nm $\geq$ 1.0 and more than 150 days with AOD at 550 nm $\geq$ 0.5).

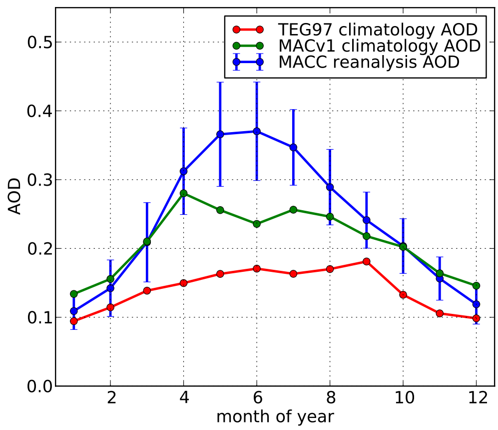

Figure 2: Monthly mean AOD at 550 nm over Europe from different aerosol datasets. Standard deviation of AOD from the MACC reanalysis is given with blue bars **[I]**.

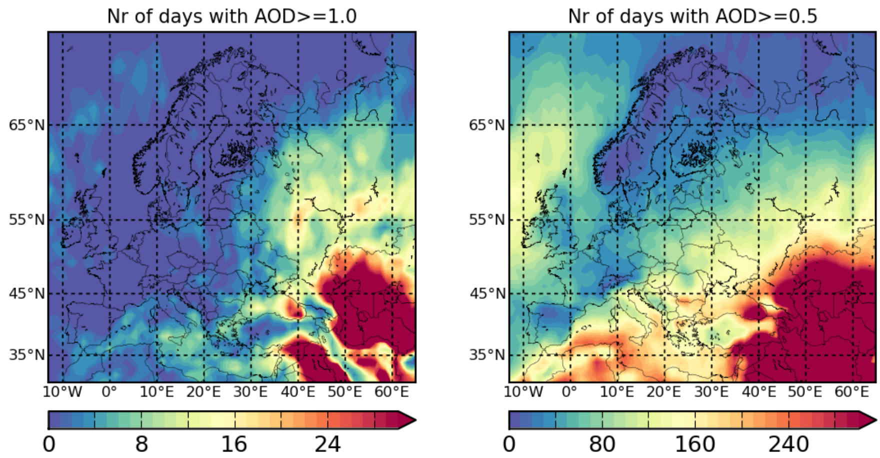

Figure 3: Number of days with the daily average AOD at 550 nm $\geq$ 1.0 in the left panel and AOD at 550 nm $\geq$ 0.5 in the right panel (from the MACC reanalysis for years 2003-2012).

3.1.2 Distribution of aerosols during wildfires in Russia in summer 2010

In paper **[II]** the MACC reanalysis and SILAM aerosol data were used to study the direct radiative effect of wildfire smoke during summer 2010. The AOD based on simulations of Huijnen et al. (2011), having a setup similar to the MACC reanalysis, was used in paper **[III]** for August 8, 2010. There were persistent high pressure conditions in the European part of Russia in summer 2010, resulting in hot and dry weather and causing an outbreak of wildfires (Witte et al., 2011). Because of these wildfires, the pollution levels were high during July and August, 2010 (Huijnen et al., 2011; Kong et al., 2014; Van Donkelaar et al., 2011). In paper **[II]**, the meteorological impacts of smoke over the period of intense fires from 5 to 12 August 2010 were investigated.

Extremely high AOD values were characteristic for the eastern Europe during this wildfire event, with AOD at 550 nm more than 4 during August 8, 2010 (Figure 4). Figure 4 shows that in SILAM, AOD was underestimated compared to the MACC reanalysis and the MODIS data. In the SILAM data, AOD is much lower further away from the centre of the aerosol plume (this was characteristic for SILAM data for the full length of the studied period). This highlights the importance of data assimilation for calculating the distribution of aerosols, as MODIS AOD sensitive radiances have been assimilated in the MACC reanalysis and no data assimilation has been performed in SILAM. In paper **[II]**, it was shown that during the studied period AOD from the MACC reanalysis and SILAM was lower over Moscow compared to the AERONET measurements (AOD at 550 nm exceeded the value of 4 on August 7 based on the data from the Moscow AERONET station) and AOD in SILAM had the lowest values. The wildfire smoke was highly scattering as in the SW wavelength interval, the single scattering albedo of smoke aerosols exceeded 0.95; in addition AOD had strong dependence on wavelength (**[V]**).

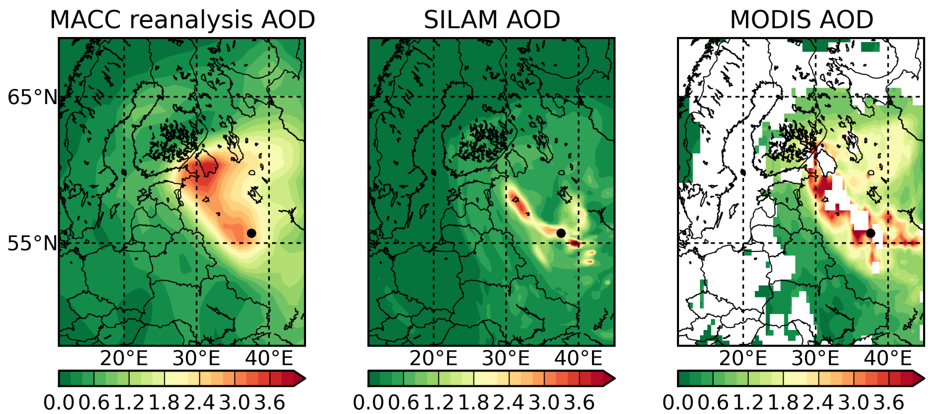

Figure 4: AOD at 550 nm from the MACC reanalysis, SILAM model and MODIS data on August 8, 2010. Black dots mark the location of Moscow **[II]**.

3.2 Modelling results

3.2.1 Evaluation of the accuracy and sensitivities of the simulated direct radiative effect of aerosols

It is important that the aerosol radiative transfer is accurately calculated when investigating the resulting meteorological effects. The default SW radiation scheme in HARMONIE following Fouquart and Bonnel (1980) has been shown to be highly accurate in general by Nielsen et al. (2014). In paper **[V]** the default SW radiation scheme in HARMONIE following Fouquart and Bonnel (1980), hlradia and acraneb2 radiation schemes were tested against DISORT model (Stamnes et al., 1988) and the simulated SW transmittances agreed between different schemes within $\pm 12\%$ for the AOD up to 5. In paper **[V]**, the sensitivities of the direct radiative effect of aerosols, simulated with the HARMONIE model, to relative humidity and the vertical profile of aerosols were studied as well. Assumption of constant relative humidity for parameterizing aerosol optical properties in the default radiation scheme in HARMONIE following Fouquart and Bonnel (1980) was found to be acceptable approximation, but there were relative differences more than 100% for the SW radiative heating rates in the atmospheric boundary layer when the vertical distribution of aerosol was altered, but the AOD was kept constant (**[V]**).

The direct radiative effect of aerosols is very accurately simulated, using different SW radiation schemes available in HARMONIE, when the optical properties of aerosols are well known. The downwelling SW radiation flux calculated with the default SW scheme in HARMONIE following Fouquart and Bonnel (1980) utilizing different treatment of aerosols is compared to the BSRN measurements in Figure 5 during wildfire event on August 8, 2010 over Tõravere (58.3 °N; 26.5 °E). When not accounting for the direct radiative effect of aerosols or assuming the climatological distribution of aerosols, the downwelling SW radiation flux is overestimated by about 150 W/m^2 and about 100 W/m^2 at midday respectively (Figure 5). When the AOD data at 550 nm from the AERONET measurements are used, but other aerosol optical properties are assumed to have their default climatological values, then the downwelling SW flux is underestimated by 100 W/m^2. A very good agreement between the simulated and observed SW flux is found when all the aerosol optical properties (AOD at 550 nm, wavelength dependence of AOD, asymmetry parameters, single scattering albedos) are defined based on the AERONET data. This highlights that other aerosol optical properties besides AOD at 550 nm also need to be accurately known for simulating the direct SW effect of aerosols. The simulated SW fluxes in experiments with different treatment of aerosols were very similar to those presented in Figure 5 when using hlradia and acraneb2 SW radiation schemes (**[V]**).

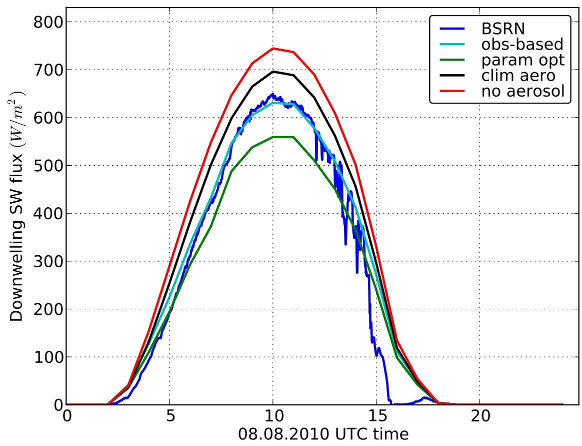

Figure 5: Simulated downwelling SW radiation flux (W/m^2) at the surface for Tõravere on August 8, 2010, compared to the BSRN measurements. obs-based = AOD at 550 nm and other optical properties (AOD scaling coefficients, single scattering albedos, asymmetry parameters) are based on the AERONET data; param opt = AOD at 550 nm is based on the AERONET data but other optical properties are climatological; clim aero = climatological AOD at 550 nm and other optical properties; no aerosol = zero aerosols **[V]**.

3.2.2 Influence of aerosols during conditions with near average concentrations of aerosols

In paper **[I]**, the influence of aerosols on meteorological conditions over Europe was studied based on 3 different aerosol datasets during a period with aerosol concentrations close to the long-term average. In this subsection, different HARMONIE experiments include 1) CNTRLEXP excluding aerosols, 2) TEGEXP using default TEG97 climatology, 3) MACv1EXP using MACv1 climatology and 4) MACCEXP using time-varying aerosol data from the MACC reanalysis to calculate the direct radiative effect of aerosols. Impacts of aerosols were investigated in the 96 hour long HARMONIE forecasts in the domain covering Europe in April 2011.

The direct radiative effect of aerosols leads to a decrease in the downwelling SW radiation flux at the surface which results in a decrease in the sensible and latent heat fluxes over land in the HARMONIE experiments. Figure 6 shows that in TEGEXP, MACv1EXP and MACCEXP, the downwelling SW radiation flux at the surface is decreased compared to CNTRLEXP by 8%, 12% and 10% respectively. Figure 7 shows that in TEGEXP, MACv1EXP and MACCEXP, the daily average SW absorption rate of the atmosphere (W/m^2) is increased compared to

CNTRLEXP by up to 25%, 27.5% and 30% respectively, leading to changes in the SW heating rates.

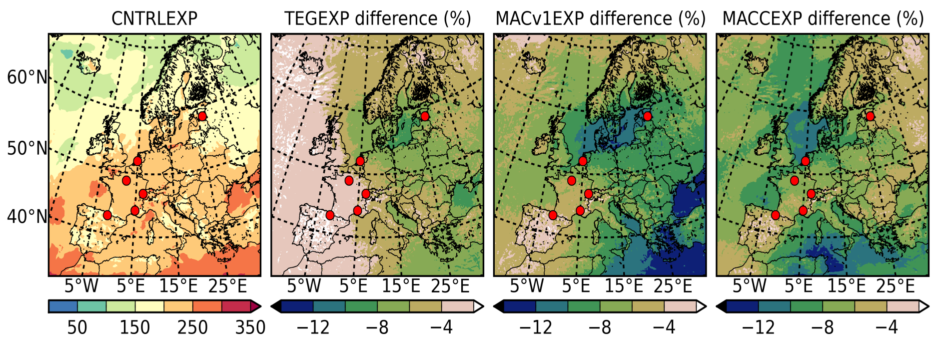

Figure 6: Daily average downwelling SW radiation flux (W/m^2) at the surface in CNTRLEXP and difference (%) relative to CNTRLEXP for TEGEXP, MACv1EXP and MACCEXP **[I]**. Here CNTRLEXP is without any aerosol. Locations of the BSRN stations where the simulated downwelling SW radiation fluxes are compared to measurements are marked with red dots.

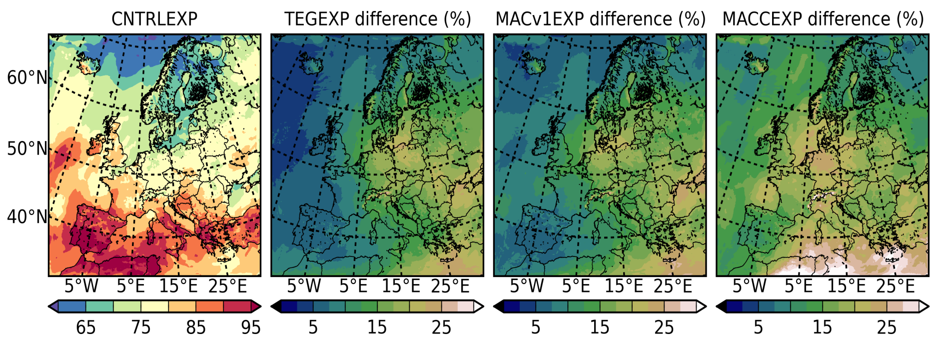

Figure 7: Daily average SW absorption rate of the atmosphere (W/m^2) in CNTRLEXP and difference (%) relative to CNTRLEXP for TEGEXP, MACv1EXP and MACCEXP **[I]**. Here CNTRLEXP is without any aerosol.

Reduction in the downwelling SW radiation flux leads to decreased near surface temperatures and humidity over land due to weakened turbulent fluxes. The daily average 2 m temperatures over land decreased up to 0.125 °C, 0.2 °C and 0.15 °C compared to CNTRLEXP in TEGEXP, MACv1EXP and MACCEXP respectively (**[I]**). The daily average 2 m specific humidity over land decreased up to 0.1 g/kg, 0.2 g/kg and 0.15 g/kg compared to CNTRLEXP in TEGEXP, MACv1EXP and MACCEXP respectively (Figure 8). The absorption of SW radiation in the aerosol layer leads to a temperature increase in 1000 to 700 hPa pressure level and a decrease in MSLP. In the 96 hour long forecasts, the domain average temperature in 950 to 800 hPa pressure level increases by 0.15 °C in TEGEXP and MACv1EXP and by 0.25 °C in MACCEXP compared to CNTRLEXP excluding aerosols (**[I]**).

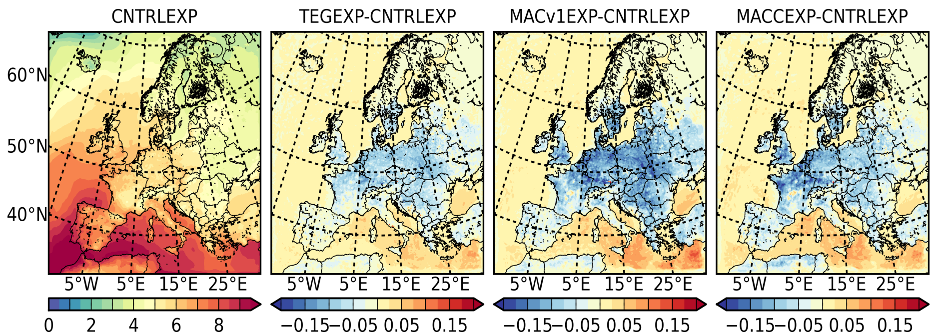

Figure 8: Daily average 2 m specific humidity (g/kg) in CNTRLEXP and differences (g/kg) from CNTRLEXP for TEGEXP, MACv1EXP and MACCEXP **[I]**. Here CNTRLEXP is without any aerosol.

Accuracies of the numerical weather forecasts are improved in all aerosol-containing experiments compared to CNTRLEXP which excludes the influence of aerosols. There are no big differences between TEGEXP, MACv1EXP and MACCEXP regarding the accuracy of the meteorological forecast. There are minor improvements in MACCEXP and/or MACv1EXP compared to the default HARMONIE setup regarding aerosols in TEGEXP for forecasts of near surface humidity, MSLP, precipitation and cloud cover (Table 2, **[I]**). The biases and RMSEs in experiments with different treatment of aerosols resulting from comparison between forecast parameters and measurements over Europe are shown in Table 2 for some meteorological parameters. The greatest improvements in aerosol-containing experiments are the more accurate forecasting of the downwelling SW radiation flux and the more accurate forecasting of the temperature in the lower troposphere. There is negative bias for temperature in CNTRLEXP at 925 to 700 hPa pressure levels and absolute value of this bias is decreased by up to 0.2 °C in the aerosol containing experiments (**[I]**).

Table 2: RMSE and bias for a range of meteorological parameters in different HARMONIE experiments. Here CNTRLEXP is without any aerosol.

Experiment name	CNTRLEXP	TEGEXP	MACv1EXP	MACCEXP
Downwelling SW flux bias (W/m^2)	15.07	1.49	-5.30	-2.79
Downwelling SW flux RMSE (W/m^2)	16.54	8.07	10.20	8.32
2 m specific humidity bias (g/kg)	0.16	0.13	0.10	0.12
2 m specific humidity RMSE (g/kg)	1.09	1.08	1.07	1.08
MSLP bias (hPa)	0.90	0.77	0.80	0.71
MSLP RMSE (hPa)	1.63	1.53	1.56	1.50

3.2.3 Influence of aerosols during wildfires in Russia in summer 2010

In paper **[II]**, it is described how very high AOD values led to a strong direct radiative effect during wildfires in the European part of Russia in summer 2010 and how the accuracy of the weather forecast was improved by including the direct radiative effect of aerosols based on the realistic aerosol distribution instead of the climatological one. In this subsection, different HARMONIE experiments are 1) CNTRLEXP using the default TEG97 aerosol climatology, 2) MACCEXP using the time-varying aerosol data from the MACC reanalysis and 3) SILAMEXP using the time-varying aerosol data from the SILAM model output.

The daily average net SW radiation flux at the surface is decreased by up to 100 W/m^2 in MACCEXP and up to 50 W/m^2 in SILAMEXP (Figure 9) compared to CNTRLEXP. The decrease is lower in SILAMEXP because of the underestimation of AOD in the SILAM model (Figure 4). The decrease in the SW radiation flux leads to a decrease in 2 m temperature more than 3 °C in MACCEXP and SILAMEXP (Figure 10). The reduction in the near surface temperature occurs in a narrower area in SILAMEXP due to the narrower aerosol plume in the SILAM simulation.

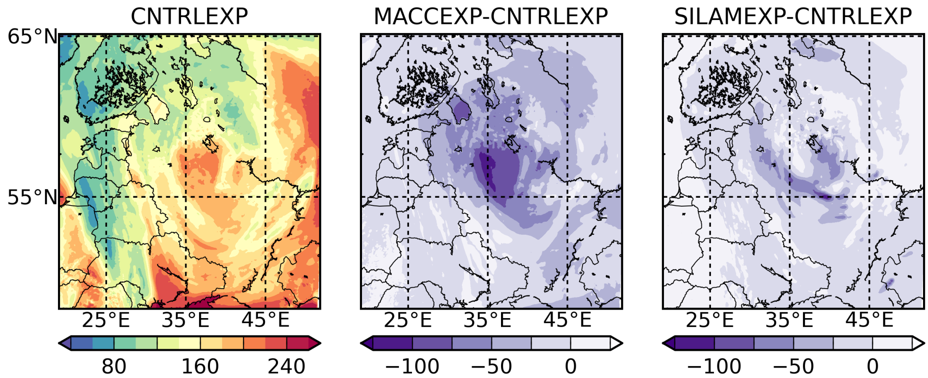

Figure 9: Daily average net SW radiation flux at the surface (W/m^2) on August 8, 2010 **[II]**. Here CNTRLEXP uses aerosol data from the TEG97 climatology.

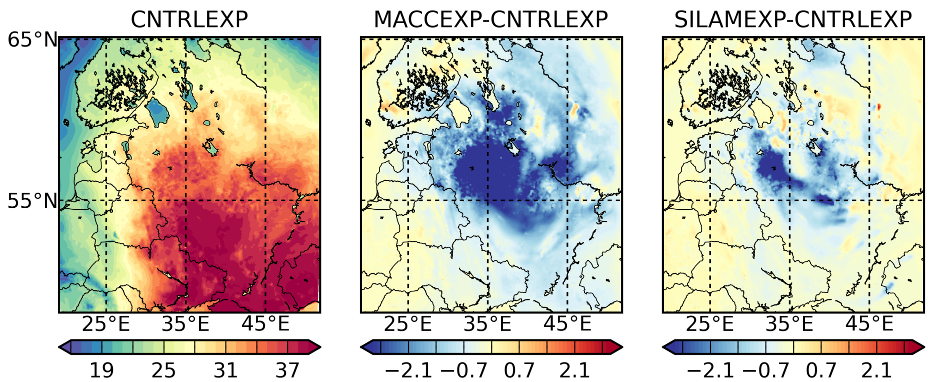

Figure 10: 2 m temperature (°C) at 12 UTC on August 8, 2010 **[II]**. Here CNTRLEXP uses aerosol data from the TEG97 climatology.

The near surface temperatures, vertical profile of temperature, 10 m wind speeds and MSLP are more accurately forecast in MACCEXP and SILAMEXP compared to CNTRLEXP assuming the climatological distribution of aerosols (**[II]**). Table 3 shows that biases and RMSEs are reduced more in MACCEXP than in SILAMEXP owing to the better quality of the aerosol input data. The 2 m temperature bias during the study period compared to observations is 1.55 °C, 0.45 °C and 1.12 °C in CNTRLEXP, MACCEXP and SILAMEXP respectively (Table 3). The spatial distribution of 2 m temperature biases during the study period is shown in Figure 11. In many stations the 2 m temperature is overestimated by 3 °C in CNTRLEXP, and temperature biases are considerably reduced at these locations in MACCEXP.

Table 3: RMSE and bias for 2 m temperature and MSLP in different HARMONIE experiments during August 6 to 11, 2010. Here CNTRLEXP uses aerosol data from the TEG97 climatology.

Experiment name	CNTRLEXP	SILAMEXP	MACCEXP
2 m temperature RMSE (° C)	3.28	3.06	2.79
2 m temperature bias (° C)	1.55	1.12	0.45
MSLP RMSE (Pa)	120.4	116.4	114.3
MSLP bias (Pa)	-25.6	-8.9	-7.1

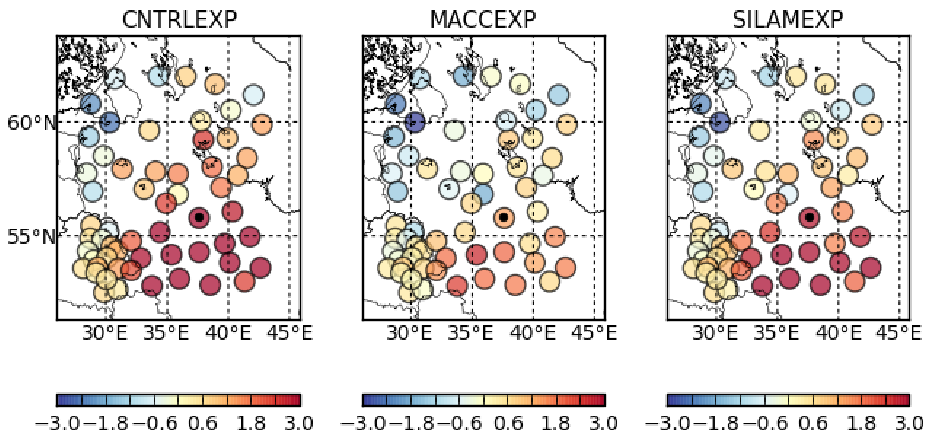

Figure 11: The 2 m temperature bias (°C) during August 6 to 11, 2010 **[II]**. The location of Moscow is given with the black dots. Here CNTRLEXP uses aerosol data from the TEG97 climatology.

The direct radiative effect of aerosols led to cooling at the surface and warming higher up in the aerosol layer. Such a change increased the static stability of the atmosphere. Figure 12 shows the unstable stratification of the atmospheric boundary layer over Moscow in CNTRLEXP and SILAMEXP, but the stable stratification of the boundary layer in MACCEXP is in a much better agreement with the observations. In MACCEXP the temperature is increased at the 850 hPa pressure level over Moscow by more than 1 °C compared to CNTRLEXP.

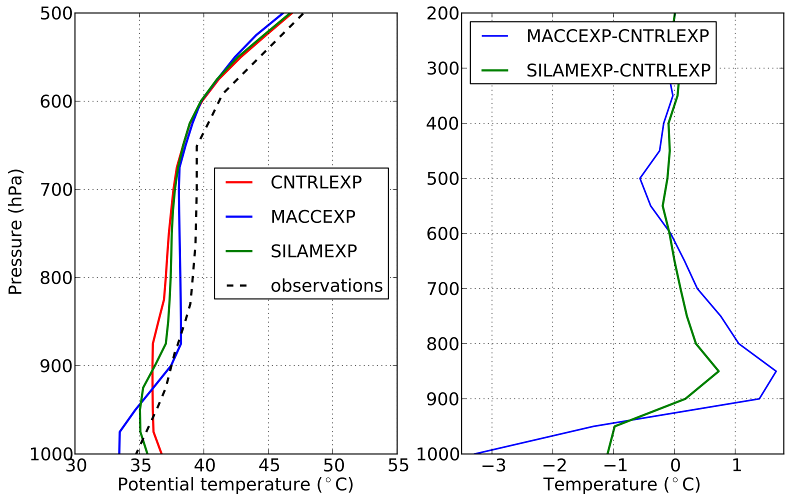

Figure 12: Potential temperature (°C) over Moscow and change in temperature (°C) at 12 UTC on August 7, 2010 **[II]**. Here CNTRLEXP uses aerosol data from the TEG97 climatology.

3.2.4 Influence of aerosols on deep convection

In paper **[III]**, the influence of smoke from Russian wildfires on a severe convective storm, which swept over the Baltic countries and Finland on the 8th of August, 2010, causing widespread wind damage on its path was studied. In paper **[IV]**, it was shown that the HARMONIE model was very well capable to simulate the convective storm, although the modelling results were sensitive to the initial conditions. Figure 13 shows that the precipitation intensity was underestimated. The maximum simulated precipitation intensity is below 9 mm/h and the maximum radar reflectivity-derived precipitation intensity exceeds 20 mm/h (Figure 13). The wind gusts were very well simulated, the modelled 10 m wind gusts exceeded 35 m/s (Figure 16) and the strongest measured wind gust was 36.5 m/s in Estonia.

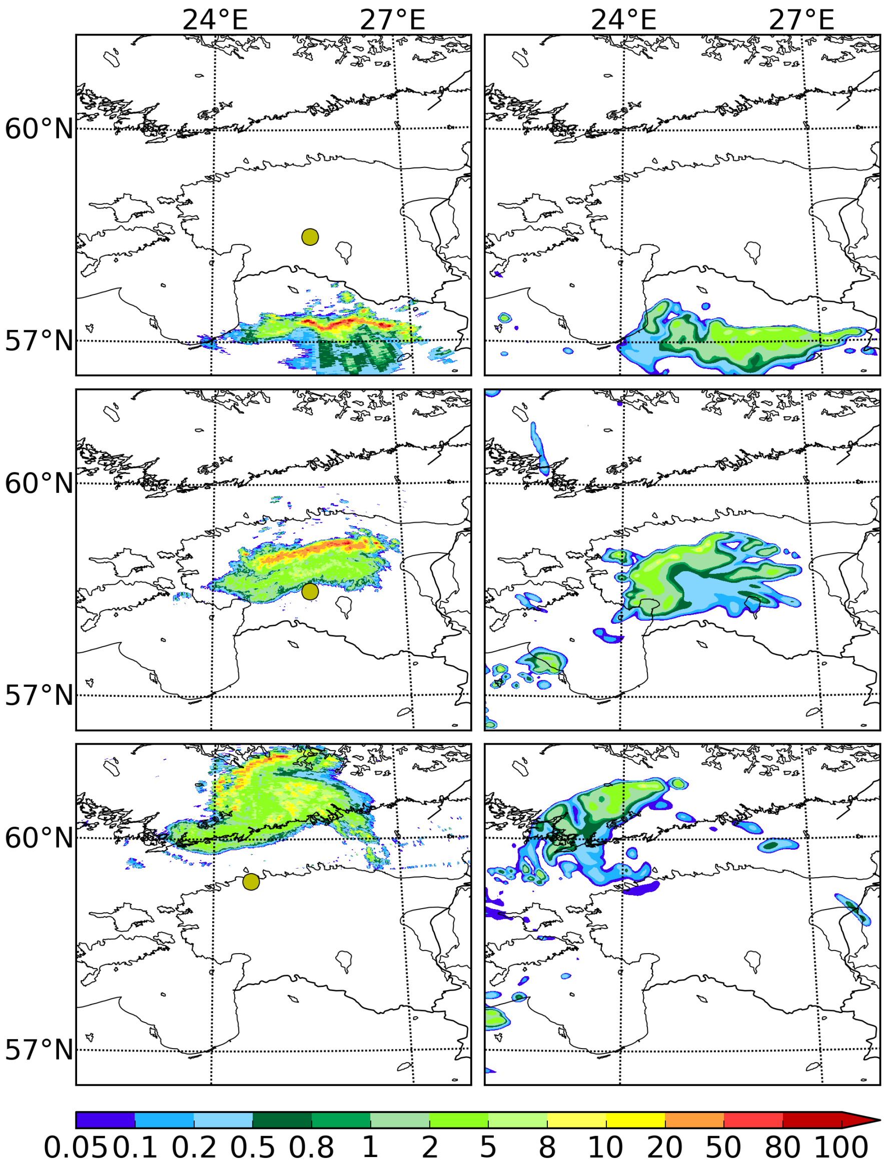

Figure 13: Precipitation intensity (mm/h) according to the Sürgavere and Harku radars in the left panel and in the HARMONIE simulation in the right panel on the 8th of August, 2010. In the left panel the radar locations are given with filled circles.

The direct radiative effect of aerosols had a strong impact on the meteorological conditions near the thunderstorm path, although the strongest impacts occurred in the area east of the storm path **[II, III]**. In the vicinity of the thunderstorm path, maximum AOD at 550 nm was more than 2 and an even higher AOD was present in the area situated east of the storm path (Figure 4). In the area close to the storm the downwelling SW radiation flux at the surface was decreased by more than 200 W/m^2 at 12 UTC and 2 m temperature was decreased by more than 3 °C (Figure 14). The influence of smoke was somewhat weaker in the storm area.

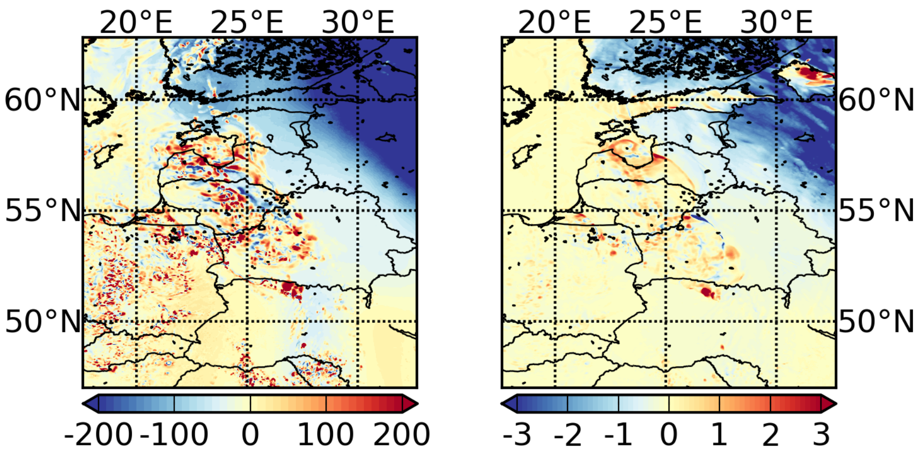

Figure 14: Difference in the downwelling SW radiation flux at the surface (W/m^2) in the left panel and in 2 m temperature (°C) in the right panel at 12 UTC on August 8, 2010, resulting from considering the direct radiative effect of aerosols based on the realistic aerosol distribution instead of the climatological one.

In addition to the cooling at the surface, there was warming in the aerosol layer which stabilized the atmosphere (this effect over Moscow during the wildfires was shown in Figure 12). Figure 15 shows that there was a high amount of CAPE in the storm area (more than 2000 J/kg). The amount of CAPE was reduced by 300 J/kg in the storm area through the direct radiative effect of aerosols. This led to a weaker convective storm, shown as weakened convective wind gusts in Figure 16. In addition, the 24h accumulated precipitation decreased from 30 mm/h to 20 mm/h in some areas affected by the storm, due to the direct radiative effect of smoke (**[III]**). To further test the influence of aerosols on this convective storm a numerical experiment with an artificially high AOD (AOD at 550 nm = 3 in the whole modelling domain) was performed and in this experiment there was no severe storm over Estonia (**[III]**). This result supports the finding that the convective storm was weakened through the direct radiative effect of smoke.

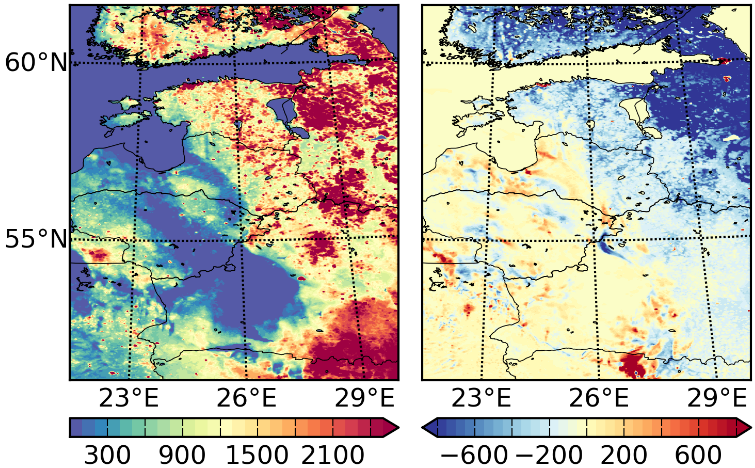

Figure 15: Simulated surface based CAPE (J/kg) in the left panel at 12 UTC on August 8, 2010, assuming the climatological distribution of aerosols and difference in CAPE (J/kg) in the right panel resulting from considering the direct radiative effect of aerosols based on realistic aerosol distribution instead of the climatological one.

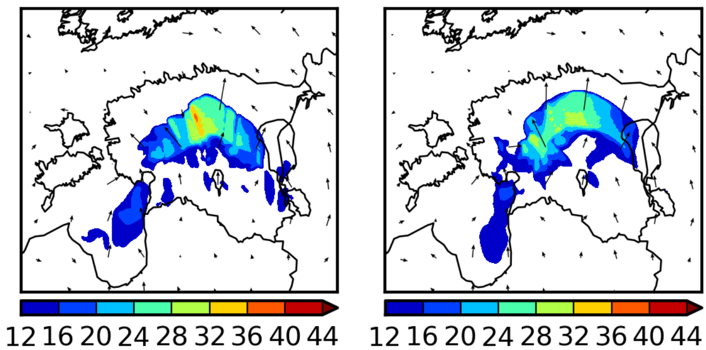

Figure 16: Simulated 10 m wind gusts (m/s) in last 30 minutes at 18 UTC over Estonia on August 8, 2010. Assuming the climatological distribution in the left panel and considering the direct radiative effect of aerosols based on realistic aerosol distribution in the right panel.

4 Discussion and outlook

In this thesis the direct radiative effect of aerosols was shown to be an important physical mechanism which has considerable influence on meteorological conditions over Europe and needs to be accounted for in NWP models. The accuracy of meteorological forecasts over Europe was found to be similar in meteorological simulations assuming the climatological average influence of aerosols and in simulations accounting for the direct radiative effect of aerosols based on realistic time-varying aerosol data from the MACC reanalysis for a time period when the AOD was close to the long-term average (**[I]**). Consequently, during conditions with near average aerosol distributions either the climatological or realistic time-varying aerosol data can be used to account for the direct radiative effect of aerosols in NWP forecasts over Europe. However, in regions with higher average and more variable AODs (e.g. south and east Asia, the Sahara desert region) it could be more important to account for the direct radiative effect of aerosols in NWP based on the realistic rather than the climatological aerosol distributions.

The use of climatologically averaged aerosol distributions in numerical weather forecasts over Europe was shown to be poor assumption during conditions when the AOD was high. During an intense wildfire period in summer 2010 in Russia meteorological forecasts of near surface temperature, downwelling SW radiation flux at the surface and vertical profile of temperatures were shown to be considerably improved when the direct radiative effect of aerosols based on realistic aerosol distributions was included instead of the climatological effect (**[II,V]**). These results suggest that at least during conditions with high AOD, the direct radiative effect of realistic aerosol distributions should be included in NWP forecasts. In addition, it is suggested that more extensive research on inclusion of the direct radiative effect of aerosols based on realistic aerosol distributions in numerical weather forecasts for different cases when the aerosol amounts in the atmosphere are high is carried out. A range of case studies and methodologies of varying complexity will help to further clarify the benefits of improving the representation of aerosol effects in the NWP framework.

The detected improvements in the NWP forecasts are unlikely to be enough to justify the inclusion of a prognostic treatment of aerosols in NWP models due to a possible significant increase in the computational cost. However, it is suggested that the climatological aerosol data should be replaced with the external aerosol data which is readily available. E.g. the MACC and SILAM aerosol data were used in the research presented in this thesis. Global near real-time forecasts of aerosol distributions are available via the MACC project (Eskes et al., 2015) under the Copernicus Atmosphere Monitoring Service, which could be used for operational limited area weather forecasts over Europe.

In addition to leading to more accurate weather forecasts in general, including a better representation of the direct radiative effect of aerosols enables more accurate forecasting of the surface SW radiation fluxes (which are needed for solar energy applications) as was demonstrated in papers **[I]** and **[V]**. The solar energy community is interested in forecasts of the direct fraction of SW fluxes in addition to total SW fluxes. The inclusion of the realistic influence of aerosols is even more important for simulating the direct fraction of the SW flux correctly, because the increase in the diffuse SW flux is generally partly compensating the decrease in the direct SW flux (Ruiz-Arias et al., 2014). Further research is needed on the impact of aerosols on the direct fraction of the downwelling SW flux at the surface in the HARMONIE weather forecasts. Further research is also needed on the importance of vertical profile of aerosols in NWP, e.g. in situations with elevated dust layers in the atmosphere. In the sensitivity experiments in study **[V]** it was shown that the vertical profile of aerosols can be very important for determining the vertical profile of SW heating rates.

Only the direct radiative effect of aerosols over Europe was studied in this thesis. It is suggested that research on including the indirect effects of aerosols in NWP forecasts over Europe should be carried out. The first tasks could be the development and testing of a parameterization scheme using near real-time aerosol concentrations present in the atmosphere to calculate the radiative transfer in clouds in the HARMONIE NWP model. The natural first step in investigating aerosol impacts in NWP framework was to improve the representation of the direct radiative effect of aerosols as this mechanism is better understood compared to the indirect effects (e.g. Lohmann and Feichter, 2005; Myhre et al., 2013b).

5 Conclusions

The main goal of this thesis was to study the influence of the direct radiative effect of aerosols on meteorological conditions over Europe. This was studied for short forecast time ranges of a few days using the NWP model HARMONIE. The increase in the accuracy of numerical weather forecasts by improving the representation of the direct radiative effect of aerosols in the meteorological model was investigated. The influence of aerosols on the Earth's climate has been previously extensively studied, but research on aerosol impacts on the accuracy of short-range numerical weather forecasts has been started more recently. The direct radiative effect of aerosols was studied 1) during conditions when the aerosol concentrations in the atmosphere were very high and 2) during a period with aerosol concentrations close to the long-term average. In addition, the influence of aerosols on a severe convective storm was simulated and the accuracy and sensitivities of the simulated direct radiative effect of aerosols were evaluated.

The main conclusions of this thesis are as follows:

1. During conditions with AOD close to the long-term average, the inclusion of the direct radiative effect of aerosols in the meteorological simulations over Europe increased the accuracy of simulated radiative fluxes and the accuracy of the simulated temperature and humidity distributions in the lower troposphere compared to the simulation where no aerosol influence was included. The bias and RMSE for the downwelling SW radiation flux at the surface (compared to measurements) were decreased by up to 13 W/m^2 and 8 W/m^2 respectively in the aerosol containing experiments. The downwelling SW radiation flux was decreased by up to 12% and the SW absorption rate in the atmosphere was increased by up to 30% in the aerosol containing experiments compared to the simulation without aerosols. Climatological aerosol data and more realistic time-varying aerosol data are equally suitable for calculating the direct radiative effect of aerosols when the aerosol distributions are close to the climatological average.

2. The high aerosol concentrations present in the atmosphere in summer 2010 in the European part of Russia had a strong influence on the meteorological conditions. The accuracy of the numerical weather forecast was considerably increased when the direct radiative effect based on a realistic aerosol distribution was taken into account instead of the average climatological effect. The bias in simulated 2 m temperature (compared to measurements) decreased by more than 2.5 °C in the intense wildfire area and by more than 1 °C in the wider area surrounding the wildfires. The daily average net SW radiation flux at the surface decreased by up to 100 W/m^2 and the 2 m temperature decreased by more than 3 °C when the direct radiative effect of

aerosols based on the realistic aerosol distribution was taken into account. The simulated stabilization of the atmosphere through the direct radiative effect of aerosols was in good agreement with the measurements. These results suggest that the NWP models should be developed to take into account the direct radiative effect of aerosols based on the real-time aerosol data.

3. The HARMONIE model was capable of simulating a severe convective storm that swept over the Baltic countries and Finland on the 8th of August, 2010. The severe wind gusts associated with the convective storm could have been forecast using the HARMONIE model with the explicit treatment of the deep convection with the 2.5 km horizontal grid spacing. The simulated wind gusts (up to 35 m/s) were similar to the measured gusts (up to 36.5 m/s). Intense wildfires coincided with the severe storm. The successful simulation of the storm dynamics with the HARMONIE model enabled investigation of the influence of heavy smoke on the storm. The simulations including the realistic direct radiative effect of the smoke suggest that the amount of CAPE in the atmosphere was decreased by up to 300 J/kg in the storm area and the severe convective storm was weakened through the influence of aerosols. These results imply that considering the influence of aerosols can be important for simulating convection over Europe. The demonstrated capability of HARMONIE in forecasting the convective storm and impacts of aerosols on it are of interest to European weather services running similar high resolution atmospheric models for operational weather forecasting.

4. The direct SW radiative effect of aerosols simulated using HARMONIE was found to be highly accurate even for high aerosol loads. The vertical profile of radiative heating rates is sensitive to the vertical distribution of aerosols. The influence of the vertical profile of aerosols should be therefore studied further.

The direct radiative effect of aerosols has considerable impacts on meteorological conditions over Europe. Among other parameters, the surface energy fluxes, the near surface temperature and humidity and the vertical temperature profile are affected by aerosols. In this thesis, the direct radiative effect of aerosols and the resulting impacts were studied. However, to gain complete knowledge of aerosol impacts in the NWP framework, the impacts of including indirect effects of aerosols in NWP over Europe should be studied in the future. Improving the representation of the direct radiative effect of aerosols enables more accurate forecasting of the surface SW fluxes which are necessary for solar energy applications. For conditions with aerosol concentrations which are close to the long-term average including the average climatological influence of aerosols in numerical weather forecasts is justified. However, it is desirable to replace the commonly assumed climatological aerosol distributions with near real-time aerosol data in NWP over Europe because during conditions with high aerosol concentrations the accuracy of the meteorological forecasts can be significantly improved.

Summary in Estonian

Atmosfääriaerosoolide otsene kiirguslik mõju meteoroloogilistele tingimustele Euroopas

Antud väitekirja põhieesmärk oli uurida atmosfääriaerosoolide kiirguslikku mõju meteoroloogilistele tingimustele Euroopa kohal. Aerosoolide, õhku pihustunud vedelate ja tahkete osakeste, otsene kiirguslik mõju tuleneb nende võimest neelata ja hajutada päikesekiirgust ja neelata, emiteerida ja hajutada soojuskiirgust. Töös uuriti aerosooli otsest kiirguslikku mõju atmosfääritingimustele lühikeses (mõne päeva pikkuses) ajamastaabis, mis on iseloomulik piiratud ala numbrilisele ilmaennustusele. Ehkki aerosooli mõju Maa kliimale on varasemalt põhjalikult uuritud, on aerosooli mõju lühiajalistes numbrilistes ilmaprognoosides seni vähe analüüsitud. Üldlevinud metoodika numbrilisel ilmaennustusel on olnud arvestada keskmist klimatoloogilist aerosooli kiirgusliku mõju.

Töös kasutati numbrilist ilmaennustusmudelit HARMONIE, mida rakendatakse teadustööks ja operatiivseks ilmaennustuseks paljudes Euroopa riikides. Analüüsiti, kuidas parandada numbriliste ilmaprognooside täpsust, võttes detailsemalt arvesse aerosooli mõju. Aerosooli mõju uuriti kõrgete ja keskmiselähedaste aerosooli kontsentratsioonidega tingimustes. Uuriti aerosooli mõju konvektiivsele tormile ja hinnati HARMONIE mudeli täpsust aerosooli kiirgusliku mõju arvutamisel.

Keskmiselähedase aerosooli kontsentratsiooniga tingimustes on numbrilises ilmaprognoosis sobilik arvestada kas klimatoloogilist keskmist aerosooli mõju või realistliku aerosooli hulga mõju. Klimatoloogilise keskmise mõju arvestamiseks kasutatakse kuukeskmisi aerosoolijaotusi. Kuukeskmiste tasemel kasvab aerosooli optiline paksus Euroopas kagu suunas ja aerosooli optiline paksus on madalaim talvekuudel ning kõrgeim suvekuudel. Antud uurimistöös arvutati ilmaprognoosid keskmiselähedastes tingimustes lähtuvalt kuukeskmistest aerosoolijaotustest, globaalsel järelanalüüsil põhinevalt ja aerosooli mõju arvestamata. Aerosooli kiirgusliku mõju arvestamine keskmiselähedastes tingimustes võimaldab täpsemini prognoosida päikesekiirguse kiiritustihedust aluspinnal ja temperatuuri ning niiskuse jaotust alumises troposfääris (võrreldes ennustusega, kus aerosooli mõju ei arvestata). Keskmine hälve mõõtmistest aluspinnale langeva päikesekiirguse kiiritustiheduse jaoks kahanes aerosooli mõju arvestamisel kuni 10 W/m^2. Aluspinnale langev päikesekiirguse kiiritustihedus kahanes kuni 12% ja päikesekiirguse neeldumine atmosfääris suurenes kuni 30%, kui arvestati aerosooli kiirguslikku mõju.

Kõige tugevam aerosooli mõju avaldub ootuspäraselt väga kõrgete aerosoolikontsentratsioonide puhul. Antud töös uuriti aerosooli kiirguslikku mõju 2010. aasta suvel Venemaal aset leidnud metsatulekahjude perioodil. Erinevate aerosooli mõju käsitlustega (klimatoloogiline vs. realistlik) meteoroloogilised prognoosid arvutati 5. kuni 12. augusti jaoks, mil maksimaalne aerosooli optiline paksus 550 nm juures oli üle 4. Intensiivsel tulekahjude perioodil kahanes ööpäeva keskmine aluspinnas neeldunud päikesekiirguse kiiritustihedus rohkem kui 100 W/m^2 ja 2 m temperatuur kahanes üle 3 °C kui arvestati realistlikku aerosooli mõju klimatoloogilise asemel. Realistliku aerosooli mõju arvestamisel kahanes keskmine prognoositud õhutemperatuuri hälve 2 m kõrgusel mõõtmistest rohkem kui 2,5 °C intensiivsete põlengute piirkonnas ja rohkem kui 1 °C ümbritseval alal. Modelleeritud muutus temperatuuri vertikaalses profiilis (jahtumine aluspinna lähedal ja soojenemine kõrgemal aerosoolikihis) ja sellest tulenev atmosfääri stabiliseerumine olid kooskõlas mõõtmisandmetega. Situatsioonis, kus aerosoolide kontsentratsioonid atmosfääris on väga kõrged, tuleks ilmaprognoosi täpsuse tõstmiseks arvesse võtta realistlikku (antud hetkele iseloomulikku) aerosooli mõju klimatoloogilise mõju asemel.

Lisaks uuriti 2010. aasta Venemaa metsapõlengute suitsu mõju konvektsioonile. Nimelt modelleeriti aerosooli mõju 2010. aasta 8. augustil üle Balti riikide ja Soome liikunud ägedale konvektiivsele tormile. HARMONIE mudel võimaldas edukalt simuleerida konvektiivse tormi dünaamikat ja HARMONIE mudeli kasutamisel oleks olnud võimalik tormi prognoosida. Modelleeritud tuulepuhangute kiirused (kuni 35 m/s) olid väga sarnased mõõdetud puhangute kiirustele (kuni 36,5 m/s). Tormi teekonnal oli maksimaalne aerosooli optiline paksus 550 nm juures kuni 2 ja tormist ida pool veelgi kõrgem. Põlengutest pärineva suitsu mõjul kahanes konvektiivse potentsiaalse energia hulk atmosfääris kuni 300 J/kg ja torm oli vähem intensiivne. Aerosoolil võib olla oluline kiirguslik mõju konvektsioonile Euroopa kohal. HARMONIE mudeli võimekus tormi prognoosida ja aerosooli mõju tormile on huvipakkuvad Euroopa ilmateenistustele, kus kasutatakse sarnase horisontaalse lahutusega ($\sim$ 2,5 km) atmosfäärimudeleid ilma prognoosimiseks.

HARMONIE mudeliga arvutatud aerosooli otsese kiirgusliku mõju hinnang on täpne ka kõrge aerosoolisisaldusega olukorras. Antud töös eeldati erinevat tüüpi aerosoolide vertikaalset jaotumist vastavalt klimatoloogilisele vertikaalsele profiilile ja aerosooli vertikaalse profiili rolli aerosooli kiirgusliku mõju määramisel tuleks edasi uurida. Aerosooli mõju täielikuks kirjeldamiseks tuleks tulevikus kaasata ilmaprognoosi arvutamisel ka aerosooli kaudne mõju meteoroloogilistele tingimustele. Kaudne mõju tuleneb asjaolust, et aerosooliosakesed on kondensatsioonituumadeks pilvepiiskade tekkel ja mõjutavad seetõttu pilvede omadusi ja sademete teket.

Aerosoolil on arvestatav kiirguslik mõju atmosfääritingimustele Euroopa kohal, mida on oluline numbrilisel ilmaennustusel prognoosi kõrge täpsuse tagamiseks arvesse võtta. Aerosooli mõju täpsem arvestamine tagab maapinnale jõudva päikesekiirguse kiiritustiheduse täpsema prognoosi, mis on vajalik päikeseenergia tootmise planeerimisel. Klimatoloogilise keskmise aerosooli kiirgusliku mõju arvestamise asemel, mida praegu laialdaselt kasutatakse, tuleks arvesse võtta realistlikku (antud hetkele iseloomulikku) aerosooli mõju.

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CURRICULUM VITAE

Name: Velle Toll
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Education

2013–2016	University of Tartu, PhD studies in Atmospheric Physics
2012	Uppsala University (Meteorology Master's course)
2011–2013	University of Tartu Master's course in Physics (Master's degree on Atmospheric Physics, cum laude)

Languages

Estonian (native speaker), English (fluent in speaking and writing), Russian (intermediate level)

Employment, research and development activity

2012–…	Estonian Environment Agency, Department of numerical modelling (Cooperation in the HIRLAM-ALADIN radiation working group for NWP model development; implementation of high resolution HARMONIE NWP model in Estonia)
2012–2015	University of Tartu, Institute of Physics, Department of Atmospheric Physics, Laboratory assistant (Research, numerical modelling of atmospheric processes, scientific computations on HPC)

Field of research

Natural Sciences and Engineering, atmospheric physics. Numerical modelling of the atmosphere, radiative transfer in the atmosphere, meteorological impacts of aerosol particles, convection.

Participation in research projects

Airborne nanoparticles and their role in meteorological processes (Institutional research grant IUT20-11 of the Estonian Research Council)

Substitute member of the management committee of the COST Action ES1004 (European framework for online integrated air quality and meteorology modelling)

Numerical modelling of derecho dynamics in Baltic Sea region (research grant No 9140 of the Estonian Science Foundation)

Development of the Numerical Weather Prediction Towards the Forecasting of Atmospheric Environment (Targeted Funding project SF0180038s08)

Lecture courses

2016	Modelling in Environmental Technology, University of Tartu (part of the course)
2015	Physical Climatology, University of Tartu
2014	Environmental Information Systems, University of Tartu
2012, 2015	Atmospheric Physics, University of Tartu (part of the course)

Professional training

2015	NWP training on physical parameterizations, ECMWF
2015	Summer school on meteorological radars, University of Tartu
2015	EUMETSAT training in satellite meteorology, EtEA
2014	STSM in the framework of COST ES1004, DMI
2014	Summer school on Online Integrated Modelling of Meteorological and Chemical Transport Processes, University of Aveiro
2012	HARMONIE model training, SMHI

Publications

Gleeson, E., **Toll, V.**, Nielsen, K.P., Rontu, L., Mašek, J., 2016. Effects of aerosols on clear-sky solar radiation in the ALADIN-HIRLAM NWP system. Atmospheric Chemistry and Physics 16, 5933–5948.

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Reis, K., **Toll, V.**, Ots, R., Kaasik, M., Soares, J., Sofiev, M., Prank, M., Männik, A., 2016. Evaluation of Simulated Particulate Matter Spread in 2010 Russian Wildfire Case Using Air Quality Monitoring Data. In Air Pollution

Modeling and its Application XXIV (pp. 547–551). Springer International Publishing.

Gleeson, E., Nielsen, K. P., **Toll, V.**, Rontu, L., Whelan, E., 2015. Shortwave radiation experiments in HARMONIE. Tests of the cloud inhomogeneity factor and a new cloud liquid optical property scheme compared to observations. ALADIN-HIRLAM Newsletter 5, 92–106.

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Toll, V., Männik, A., Luhamaa, A., 2014. Case study: derecho event in Estonia 08 August 2010 – Modelling derecho dynamics with NWP model HARMONIE. In 7th European Conference on Severe Storms ECSS 2013 Abstracts.

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Haridus

2013–2016 Tartu Ülikool, Doktorantuur atmosfäärifüüsikas
2012 Uppsala Ülikool (Meteoroloogia magistrikursus)
2011–2013 Tartu Ülikool MSc atmosfäärifüüsikas (magistrikraad füüsika erialal, cum laude)

Keelteoskus

Eesti (emakeel), inglise (suurepärane kõnes ja kirjas), vene (kesktase)

Teenistuskäik, teadus- ja arendustegevus

2012–… Keskkonnaagentuur, Prognoosmudelite osakond, atmosfääri numbrilise modelleerimise peaspetsialist (Numbrilise ilmaennustusmudeli arendus HIRLAM-ALADIN kiirguse töörühmas, kõrglahutusliku ilmaennustusmudeli HARMONIE prognooskeskkonna ülesseadmine Eestis)
2012–2015 Tartu Ülikool, Füüsika instituut, Atmosfäärifüüsika labor, laborant (Teadustöö, atmosfääriprotsesside numbriline modelleerimine, teadusarvutused klasterarvutitel)

Teadustöö põhisuunad

Loodusteadused ja tehnika, atmosfäärifüüsika. Atmosfääri numbriline modelleerimine, atmosfääri kiirguslevi, aerosooliosakeste meteoroloogilised mõjud, konvektsioon.

Projektides osalemine

Nanoosakesed õhus ja nende osa meteoroloogilistes protsessides (Institutsionaalne uurimistoetus projekt IUT20-11)

COST ES1004 juhtkomitee asendusliige (Õhukvaliteedi ja meteoroloogia ühendatud modelleerimine Euroopas)

Sirgäikesetormi dünaamika numbriline modelleerimine Läänemere regioonis (Eesti Teadusfondi uurimistoetus projekt ETF9140)

Numbrilise ilmaennustuse arendamine õhukeskkonna prognooside suunas (Sihtfinantseerimine projekt SF0180038s08)

Loengukursused

2016	Modelleerimine keskkonnatehnoloogias, Tartu Ülikool (osa kursusest)
2015	Füüsikaline klimatoloogia, Tartu Ülikool
2014	Keskkonna infosüsteemid, Tartu Ülikool
2012, 2015	Atmosfäärifüüsika, Tartu Ülikool (osa kursusest)

Erialane enesetäiendus

2015	Füüsikaliste parametriseeringute teemaline numbrilise ilmaennustuse koolitus, ECMWF
2015	Meteoradarite suvekool, Tartu Ülikool
2015	EUMETSAT satelliitmeteoroloogia koolitus, Keskkonnaagentuur
2014	Teadustöö visiit COST ES1004 raames, DMI
2014	Meteoroloogia ja atmosfäärikoostise ühendatud modelleerimise suvekool, Aveiro Ülikool
2012	HARMONIE mudeli koolitus, SMHI

Publikatsioonid

Gleeson, E., **Toll, V.**, Nielsen, K.P., Rontu, L., Mašek, J., 2016. Effects of aerosols on clear-sky solar radiation in the ALADIN-HIRLAM NWP system. Atmospheric Chemistry and Physics 16, 5933–5948.

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Toll, V., Männik, A., 2015. The direct radiative effect of wildfire smoke on a severe thunderstorm event in the Baltic Sea region. Atmospheric Research 155, 87–101.

Toll, V., Männik, A., Luhamaa, A., Rõõm, R., 2015. Hindcast experiments of the derecho in Estonia on 08 August, 2010: Modelling derecho with NWP model HARMONIE. Atmospheric Research 158, 179–191.

Toll, V., Reis, K., Ots, R., Kaasik, M., Männik, A., Prank, M., Sofiev, M., 2015. SILAM and MACC reanalysis aerosol data used for simulating the aerosol direct radiative effect with the NWP model HARMONIE for summer 2010 wildfire case in Russia. Atmospheric Environment 121, 75–85.

Reis, K., **Toll, V.**, Ots, R., Kaasik, M., Soares, J., Sofiev, M., Prank, M., Männik, A., 2016. Evaluation of Simulated Particulate Matter Spread in 2010 Russian Wildfire Case Using Air Quality Monitoring Data. In Air Pollution Modeling and its Application XXIV (pp. 547–551). Springer International Publishing.

Gleeson, E., Nielsen, K. P., **Toll, V.**, Rontu, L., Whelan, E., 2015. Shortwave radiation experiments in HARMONIE. Tests of the cloud inhomogeneity factor and a new cloud liquid optical property scheme compared to observations. ALADIN-HIRLAM Newsletter 5, 92–106.

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Männik, A., **Toll, V.**, Voormansik, T., 2014. Derecho on August 8, 2010, as seen from satellite and radar images. Kaugseire Eestis 2014 (pp. 166–174).

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DISSERTATIONES GEOPHYSICALES UNIVERSITATIS TARTUENSIS

1. **Andres Kuusk.** The hot-spot effect in plant canopy reflectance. Tartu, 1991.
2. **Tiit Nilson.** Radiative transfer in non-homogeneous plant canopies. Tartu, 1991.
3. **Helgi Arst.** Atmosfääri ja mere kiirguskarakteristikud looduskeskkonna seisundi informaatoritena (vene keeles). Tartu, 1991.
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