Interactive comment on "Effects of aerosols on solar radiation in the ALADIN-HIRLAM NWP system" by E. Gleeson et al.

Anonymous Referee #1
Received and published: 27 January 2016

General comments:

The paper addresses relevant scientific questions within the scope of ACP. The authors do not clearly support to present novel concepts, ideas, tools, and data, but they are interested about an important topic, i.e. the sensitivity of shortwave model outputs on aerosol and relative humidity.

- Thank you for reviewing our paper. We have addressed your comments below and took all of the comments marked on the PDF of the manuscript you attached to the review on board.

Some abbreviations used in the below responses:
AOD550 = AOD at 550nm
SWD = downwelling shortwave radiation
RH = relative humidity
NWP = numerical weather prediction
IOP = inherent optical property

The overall presentation is neither well-structured nor clear; improvements in the structure and the content of each section are needed.

- We have changed the structure of the paper and the content of each section following advice from both reviewers and hope that it is now clear and coherent.

1. *Introduction*
2. *Model set-up*
    - *2.1 ALADIN-HIRLAM*
    - *2.2 Radiation schemes*
        - *2.2.1 IFS*
        - *2.2.2 Hlradia*
        - *2.2.3 Acraneb2*
3. *Input and validation data*
    - *3.1 Aerosol climatology*
    - *3.2 Aerosol observations*
    - *3.3 BSRN radiative flux measurements*
    - *3.4 Atmospheric and surface input for MUSC*
4. *Experiments*
    - *4.1 Russian wildfire case study (WFEXP)*
    - *4.2 Aerosol sensitivity experiments (AODEXP, RHEXP and VPEXP)*
    - *4.3 Aerosol radiative transfer (RTEXP)*
5. *Results and discussion*
    - *5.1 Russian wildfire case study (WFEXP)*
    - *5.2 Aerosol sensitivity tests*
        - *5.2.1 AOD (AODEXP)*
        - *5.2.2 Relative humidity (RHEXP)*

5.2.3 Vertical distribution of aerosols (VPEXP)
5.2.4 Aerosol radiative transfer (RTEXP)
6. Conclusions and future work

There are three main issues that need careful attention prior to publication: 1) the language is not always fluent and precise. In particular, several phrases remain colloquial and simplistic. The repetition of the same words within the same phrase has not been eliminated. Indicative paradigms are highlighted in yellow or commented or replaced within the attached file.

- We agree and have made substantial changes to the text including all of the suggestions highlighted in your file.

2) there description of the tools and methods used is not precise and clear. The use of numerous names and/or acronyms throughout text makes the reader confused about the actual model system used, as well as the number of applied scenarios and their scope and

- Our description of the NWP models used has been updated and we hope that it is now clear. We used the HARMONIE-AROME canonical configuration of the ALADIN-HIRLAM system. In particular, we used the single column version of HARMONIE-AROME, which is called MUSC.
- the radiation schemes hlradia and acraneb2 have now been changed to lower case as the second reviewer presumed these were also acronyms.
- We have revised the descriptions of the experiments and include a summary table to make it easier for the reader to follow the series of experiments.

We added the following:

> *"The ALADIN-HIRLAM numerical weather prediction system is used for operational weather forecasting by 26 national meteorological services in Europe and North Africa which form the HIRLAM (High Resolution Limited Area Model) and ALADIN (Aire Limitée Adaptation dynamique Développement International) consortia. Pottier (2016) summarises 42 limited area configurations of the system used by the consortia members. This system can also be used for regional climate simulations (Lindstedt et al., 2015), where the direct radiative effect of aerosols can be of greater importance than in short range NWP applications.*
> *The HARMONIE-AROME configuration based on Seity et al., 2011 was used in this study. HARMONIE (HIRLAM ALADIN Regional Mesoscale Operational NWP in Europe) denotes the specific configuration of the ALADIN-HIRLAM system maintained by the HIRLAM consortium; AROME is a limited area model developed at Météo-France. Its default set-up for operational NWP uses a 2.5 km horizontal grid and 65 hybrid model levels with deep convection treated explicitly. This configuration uses ALADIN non-hydrostatic dynamics (Bénard et al., 2010), Meso-NH physics (Mascart and Bougeault, 2011) and the SURFEX externalised surface scheme (Masson et al., 2013). Surface physiographies are prescribed using the 1 km resolution ECOCLIMAP II database (Faroux et al., 2012) and surface elevation is based on GTOPO30 (USGS, 1998).*
> *We used the single column version of HARMONIE-AROME based on Malardel et al. (2006) for the experiments detailed in this paper. As in Malardel et al. we will refer to this model configuration as MUSC (Modèle Unifé Simple Colonne). It includes all of the atmospheric and surface parametrizations of HARMONIE-AROME but lacks the large-scale dynamics, horizontal advection, pressure gradient force and large-scale vertical motion. Because of the*

simplifying assumptions, MUSC is not suitable for operational weather forecasting. However, its value lies in the fact that it provides a useful means of studying the sensitivity of the model output to realistic atmospheric conditions and different physical parametrizations. The input to MUSC is derived from the output of a 3D HARMONIE-AROME experiment. This includes the initial conditions in the atmosphere and surface, surface properties, atmospheric temperatures, specific humidities and wind speeds. Details on the input data used in our experiments are provided in Section 3.4."

3) subsequently, the presentation of the scenarios, their inter-comparison and their differences is not clear and the main findings are not easily traceable.

- We agree and have restructured these sections as outlined above.

To my view, once the results are rewritten in a clearer and straightforward way, they will most probably be sufficient to support the conclusions. More interpretations are needed for some statements. All of the above comments (plus more) are specifically described below and/or in the attached file.

- We agree and have added proper interpretations of all of the results. For example the wildfire section is now as follows:

"The results presented in this section include a comparison of AOD550 for the Tegen and MACC reanalysis climatologies, time-series of spectral AOD, SSA and g from AERONET and experiments using MUSC run with observed and climatological aerosol data and the IFS, hlradia and acraneb2 radiation schemes. Figure 1 shows the AOD550 over northwestern Europe on 08 August 2010 in the Tegen climatology used in MUSC and the MACC reanalysis dataset (Inness et al., 2013). It is clear that the Tegen climatology greatly underestimates aerosols when pollution is heavy, as was the case over Estonia and eastern Russia on 08 August 2010. Overall, over northwestern Europe the values of the realistic MACC AOD550 (maximum 3.5) are an order of magnitude higher than in the Tegen climatology (maximum 0.33) for August which highlights a drawback of using the Tegen dataset.
Figure 2 shows a time-series of AOD at Tõravere on 08 August 2010 for 7 wavelengths (measurements from the AERONET archive). The strong spectral dependence of AOD is clear from the figure; AOD is higher for shorter wavelengths. This notable wavelength dependence is characteristic of biomass burning aerosols (Eck et al., 1999). The AOD550, also shown in Figure 2 (black dashed line), and used in the MUSC experiments involving observations rather than the Tegen climatology, was calculated using the AERONET AOD at 500 nm (cyan line) and the Ångström exponent in the 440-675 nm spectral interval. For comparison, the significantly lower AOD550 from the Tegen climatology (red dashed line) is also included in the figure.
The remaining aerosol IOPs, SSA and g, from the AERONET inversion products database are shown in Figure 3 where daily averages are plotted as a function of wavelength. Although daily averages are shown, the time dependence of SSA and g on 08 August was small. The asymmetry factor, g, varies from 0.56 to 0.7 across the wavelength range and has an average value of 0.634. The latter was used in the wildfire experiments run using hlradia or acraneb2 with aerosol observations. The spectral values of g were interpolated to the six SW bands of IFS for similar experiments using this scheme.
The aerosol scattering per extinction ratio, represented by SSA, is high (close to 0.96 with a spectral average of 0.955) at each wavelength with little SW spectral dependence (Figure 3). This is similar to results by Dubovik et al. (2002) who showed that the typical SSA of smoke from biomass burning in Boreal forests is high. However, the scattering of smoke particles from

this Russian wildfire event was higher than that of plumes from typical biomass burning in Boreal forests (Chubarova et al., 2012). As in the case of g, the average SSA was used in the hlradia and acraneb2 wildfire experiments involving aerosol observations while the spectral SSAs were interpolated to the IFS SW bands before use in the corresponding IFS experiments.
Figure 4a shows the global SWD radiative flux at the Earth's surface simulated using MUSC with the IFS radiation scheme for 08 August 2010 at Tõravere. We ran an experiment for each of the following 4 aerosol scenarios (also summarised in Table 2): 1) aerosol-free (red curve), 2) climatological AOD550 and parametrized IOPs (black curve), 3) observed AOD550 and parametrized IOPs (green curve) and 4) observed AOD550 and IOPs (cyan curve) and compared the global SWD fluxes to BSRN observations (blue curve). The discrepancy between simulated and observed SWD irradiance after 14 UTC is due to the development of convective clouds (Toll et al., 2015a) which are not accounted for in the MUSC clear-sky simulations.
The biases in global SWD flux (relative to observations) for the MUSC experiments using each radiation scheme (and not just IFS) and the 4 different aerosol scenarios are depicted in Figure 4b (IFS dotted continuous lines, hlradia continuous lines, acraneb2 dashed lines; the aerosol scenario colour scheme is the same as in Figure 4a). Overall, the results for the three schemes are similar (mostly to within 10-20 W/m2 of each other for global SWD irradiance which can be seen by comparing each group of three curves of the same colour), particularly in their response to the different aerosol scenarios. The largest discrepancies occur in the early morning; in hlradia this occurs because the sphericity of the atmosphere is not taken into account. When the direct radiative effect of aerosols was excluded, global SWD fluxes were overestimated by ~120 W/m^2 or 19 % (red curves) at midday compared to BSRN observations. Accounting for the climatological average effect of aerosols using the Tegen et al. (1997) dataset and Hess et al. (1998) IOP parametrizations (black curves) improves the simulation of global SWD flux compared to the aerosol-free simulation. However, there is still an overestimation of 60 W/m^2 or 10 % at noon, because the observed AOD is higher than the climatological average (see Figures 1 and 2).
The use of AOD550 and IOPs derived from AERONET observations gives very good agreement between the modelled and observed global SWD fluxes for each of the three radiation schemes (cyan curves, bias < 20 W/m2 or 4 % at noon). SWD flux was underestimated by ~70 W/m^2 or 11 % (green curves) at noon when the direct radiative effect of aerosols was accounted for using the observed AOD550 combined with parametrized SSA, g and spectral scaling factors of land aerosols. "

Specific comments:

Title: The title does not clearly reflect the contents of the paper. To my view, this study does not only aim at investigating the aerosol radiative impact, but also the sensitivity of model outputs on specific parameters. Thus, I would suggest the invention of a more appropriate title, which would reflect the principal motivation and focus of the authors.

- We have changed the title to "Effects of Aerosols on Clear Sky Solar Radiation in the ALADIN HIRLAM NWP System". Each of the sensitivity studies concerns aerosols although we used 3 different radiation schemes.
- We examined (1) the sensitivity of SWD to the aerosol AOD and IOPs for the wildfire case and the sensitivity of SWD to (2) AOD550 (3) the relativity humidity in the calculation of the radiative effect of aerosol IOPs [only in hlradia, the other schemes are based on the assumption that RH is 80% and this cannot easily be changed], (3) the vertical distribution of aerosol and (4) the radiative transfer through a homogeneous layer resembling aerosols for a range of optical depths.

Abstract: the abstract should be revised after all comments are taken into account, so that it serves as a concise and complete summary of the article. Indicative rewording is shown in the attached file.

- The abstract has been revised, taking your comments in to account and now includes a complete summary of the results.

> *"The direct shortwave radiative effect of aerosols under clear sky conditions in the ALADIN-HIRLAM numerical weather prediction system was investigated using three shortwave radiation schemes in diagnostic single-column experiments: the IFS scheme, the acraneb2 scheme and the hlradia radiation scheme. The aim was to evaluate the strengths and weaknesses of the NWP system in this regard and to prepare it for use of real-time aerosol information.*
> *The experiments were run with particular focus on the August 2010 Russian wildfire case. Each of the three radiation schemes accurately (within ± 4% at midday) simulates the direct shortwave aerosol effect when observed aerosol optical properties are used. When the aerosols were excluded from the simulations, errors of more than +15 % in global shortwave irradiance were found at midday, with the error reduced to +10 % when standard climatological aerosols were used. An error of -11 % was seen at midday if only observed aerosol optical depths at 550 nm, and not observation-based spectral dependence of aerosol optical depth, single scattering albedos and asymmetry factors, were included in the simulations. This demonstrates the importance of using the correct aerosol optical properties. The dependency of the direct radiative effect of aerosols on relative humidity was tested and shown to be within ± 6 % in this case. By modifying the assumptions about the shape of the IFS climatological vertical aerosol profile, the inherent uncertainties associated with assuming fixed vertical profiles were investigated. The shortwave heating rates in the boundary layer changed by up to a factor of 2 in response to the aerosol vertical distribution. Finally, we tested the radiative transfer approximations used in the three radiation schemes for typical aerosol optical properties compared to the accurate DISORT model. These approximations are found to be accurate to within ± 13 % even for large aerosol loads."*

Introduction: Each paragraph should have a clear and concise concept that serves to cover a specific aspect covered by this work. Also, they should (in)-directly try revealing the new/original contribution of the current study. Apart from these general statements, specific comments are given in the attached file. The authors give credit to related work and indicate their own contribution. Nevertheless, I would suggest an ultimate search in previous relevant studies (cf. attached file).

- We have rewritten and restructured the introduction section.

> *"The direct radiative effect of aerosols resulting from scattering and absorption of electromagnetic radiation at shortwave (SW) and longwave (LW) wavelengths has an impact on the Earth's radiation budget (e.g. Haywood and Boucher, 2000; Bellouin et al., 2005; Jacobson, 2001; Myhre et al., 2013; Yu et al., 2006; Loeb and Manalo-Smith, 2005) and on meteorology (e.g. Cook and Highwood, 2004; Takemura et al., 2005; Wang, 2004; Mulcahy et al. 2014, Bangert et al., 2012) which needs to be accounted for in numerical weather prediction (NWP) models. Climatological distributions of aerosols are commonly used in present-day operational NWP models for calculating the direct radiative effect of aerosols.*
> *Using unrealistic aerosol distributions can lead to considerable errors in meteorological forecasts. Milton et al. (2008) showed that excluding the direct radiative effect of mineral dust*

and biomass burning aerosols in forecasts using the UK Met Office Unified Model during the dry season in West Africa resulted in an inaccurate representation of the surface energy budget and a warm bias in screen level temperature. Carmona et al. (2008) presented significant correlations between errors in the aerosol optical depth (AOD) assumed in an NWP model and temperature forecast errors. Accurate simulation of the direct radiative effect of aerosols on SW radiation is important to the growing solar energy industry because under clear-sky conditions aerosols are the main modulator of SW fluxes (Breitkreuz et al., 2009).

The monthly aerosol climatology described in Tegen et al. (1997) is used in ECMWF's (the European Centre for Medium Range Weather Forecasts) global Integrated Forecast System, IFS, and in the Aire Limitee Adaptation dynamique Developpement INternational – High Resolution Limited Area Model (ALADIN-HIRLAM) limited area modelling system used in this study. Tompkins et al. (2005) showed that replacing the Tanre at al. (1994) fixed average aerosol distribution in ECMWF's IFS model by the Tegen climatology improved forecasts of the African Easterly Jet. This change in the aerosol climatology also improved the forecast skill and seasonal mean errors (Rodwell and Jung, 2008).

Including a more complete representation of the effects of aerosols in NWP models can improve the meteorological forecasts and is an active area of research (e.g. Mulcahy et al., 2014, Bangert et al., 2012). Using real-time aerosol distributions, rather than climatological datasets, to account for the direct radiative effect of aerosols further improves the quality of the forecasts. Toll et al. (2015b) showed that the accuracy of the forecasts of near-surface conditions by the ALADIN-HIRLAM system during severe wildfires in summer 2010 in Eastern Europe were improved when the direct radiative effect of the realistic aerosol distribution was included in the model hindcasts. Palamarchuk et al. (2016) also found a noticeable sensitivity of the ALADIN-HIRLAM forecasts to the treatment of aerosols. On the other hand, Toll et al. (2016) showed that when observed aerosol distributions are close to average, improvements in the SW radiation, temperature and humidity forecasts in the lower troposphere are only slightly greater when time-varying realistic aerosol data from the Monitoring Atmospheric Composition and Climate (MACC) reanalysis (Inness et al., 2013) is used in place of the Tegen climatology. Similar conclusions were drawn by Zamora et al. (2005) who showed that for small AODs accounting for the climatological average direct radiative effect of aerosols gives very good estimates of SW fluxes, but large biases occur when the AOD is large.

Baklanov et al. (2014), Grell and Baklanov (2011) and Zhang (2008) have suggested using coupled air quality and NWP models to improve forecasts of both air quality and weather. However, for operational NWP such coupled models are still too demanding computationally, and this added cost has to be evaluated versus improvements in the meteorological forecasts. Mulcahy et al. (2014), Morcrette et al. (2011) and Reale et al. (2011) describe improved forecasts of the radiation budget and near surface conditions in global NWP models when prognostic aerosols are included; however the impact of aerosols on large scale atmospheric dynamics is generally weak.

The AOD at 550 nm (AOD550 hereafter in this paper) and aerosol inherent optical properties (IOPs: spectral dependence of AOD, single scattering albedo (SSA) and asymmetry factor (g)) depend on the size, shape and the complex refractive indices of the aerosols and have a significant effect on global downwelling SW (SWD) fluxes. Hygroscopic induced changes in the IOPs of different aerosols types also alter the radiative effect of aerosols (e.g. Cheng et al., 2008; Bian et al., 2009; Markowicz et al., 2003; Zieger et al., 2013). For example, Magi and Hobbs (2003) present measurements of enhanced backscatter by biomass burning aerosols when the relative humidity (RH) is high. Pilinis et al. (1995) estimated that the global forcing due to aerosols doubles for a relative humidity increase from 40% to 80%.

The vertical profile of aerosols is also very important when estimating their direct radiative *effect. There are considerable variations in the vertical distributions of aerosols over Europe (Guibert et al., 2005; Matthias et al., 2004). Therefore, inaccuracies result when constant climatological profiles per aerosol species are used (as is the case in ALADIN-HIRLAM which uses the profiles of Tanre et al., 1984). For example, Guibert et al. (2005) analysed the vertical profiles of aerosol extinction over Europe and found that aerosols over southern Europe are concentrated higher in the atmosphere due to the occurrence of dust storm episodes. Meloni et al. (2005) showed that under clear-sky conditions the direct radiative effect of aerosols on surface radiation has a low dependence on the aerosol vertical profile, but that the profile has an impact on the top of the atmosphere forcing, especially for absorbing aerosols. Toll et al. (2015) evaluated the profile of the aerosol attenuation coefficient for land aerosols in ALADIN-HIRLAM against observations for the summer 2010 Russian wildfires. They found good agreement between the distribution assumed in the model and CALIOP measurements. However, a more general evaluation of the vertical profile of aerosols in the system has not been performed.*

The main goal of the present study is to focus on the impact of AOD550, aerosol IOPs, the vertical distribution of aerosols, relative humidity and radiative transfer algorithms on SW fluxes in diagnostic single column clear-sky experiments using the ALADIN-HIRLAM system. Such experiments are extremely useful for developing and testing parametrizations and for running idealised experiments that focus on atmospheric physics in a simplified framework. With these experiments we can evaluate the strengths and weakness of the NWP model regarding the treatment of the direct radiative effect of aerosols.

The paper is structured as follows: the model set-up and radiation schemes are described in Section 2; the aerosol datasets and atmospheric and surface input used in the experiments are detailed in Section 3; descriptions of each of the experiments and sensitivity tests are provided in Section 4; the results and discussion are presented in Section 5 and conclusions and future work are summarised in Section 6. "

Sect. 2: There are cases when the scientific methods and assumptions are not clearly outlined. Specific comments are given in the attached file.

- These have been addressed – for example Section 4.1:

"One of the worst cases of atmospheric pollution over Estonia in recent decades (Witte et al., 2011; Huijnen et al., 2012) occurred on 08 August 2010 when forest fires in the Baltic region coincided with severe thunderstorms (Toll and Männik, 2015). To study this extreme pollution event, we focussed MUSC single-column experiments on the Tõravere location in Estonia. This location was selected for three reasons: 1) the smoke plume had a strong impact on the area, 2) measurements of aerosol IOPs were available from a local AERONET station and 3) radiation flux measurements were available from the BSRN archive. We ran a series of 12 experiments using MUSC; 4 aerosol scenarios for each of the three radiation schemes (see Table 2 for summary). In particular, the following aerosol treatments were considered: 1) aerosol-free, 2) climatological AOD550 and parametrized IOPs, 3) observed AOD550 and parametrized IOPs and 4) aerosol observations (AOD550 and IOPs). In the experiments using observations (either AOD550 or both AOD550 and IOPs) the aerosols were assigned to the land/continental aerosol category while the remaining 5 categories of IFS aerosols (see Section 2.2.1) were set to zero. Accordingly, the climatological vertical distribution of IFS land aerosols was assumed.

In each experiment, a single time-step diagnostic MUSC simulation was run using the relevant input file (see Section 3.4) as the starting point and repeated for each hour between 00 UTC and 24 UTC. Thus, a series of single time-step simulations were run starting from the 00 UTC *input file, 01 UTC input file and so on up to 24 UTC. The model was run in diagnostic mode in order to focus on the radiative properties when the state of the atmosphere and surface had not yet evolved from the initial values."*

Sect. 3: here, my main concern is that the overall explanation of the concept and description of the model runs should answer and summarize the following: what is the scope of each scenario? Which are inter-compared? What is their code name, which should be easily translated to their main feature (in table 1) and in parallel should be analytically described (in the text). By the end of this section, the reader must have realized the structure of the setup of this study and the necessity of each scenario. It should also be clear that when he/she proceeds to the results and conclusions, he can follow without getting lost with the names of the simulations. This concern, plus other suggestions are highlighted in the attached file. Some comments about the description of experiments are also given. Please bear in mind that they should be sufficiently complete and precise to allow their reproduction by fellow scientists (tractability of results).

- Section 3 has been restructured and now only contains input and validation data. All of the experiments are described in section 4 and the results are discussed in section 5.

- The experiments are also summarised in table 2 which includes the radiation scheme used, the AOD550 and the IOPs used in each case. A more thorough description of each scenario is now presented, including exactly what is being compared.

Sect. 4: Again, the reader is at a loss on the topic of each subsection, the intercomparisons made and the results of them. Suggestions for improvements are highlighted in the attached file. Although the results seem sufficient to support the interpretations, their current way of presentation is rather chaotic.

- The paper has been completely restructured. The descriptions of the experiments and results have been rewritten.

Sect. 5: To my view, conclusions should be clearer and more concise. Comments for improvement are given in the attached file. I would expect that the revision will point out the substantial conclusions of this work.

- We have rewritten the conclusion section.

"We carried out single column diagnostic experiments using the MUSC model and three radiation schemes (IFS, hlradia and acraneb2) to examine the influence of the direct radiative effects of aerosols on SW radiative flux. In particular, we focused on the effect that AOD550, aerosol IOPs, the relative humidity, vertical profile of AOD and the radiative transfer formulations has on SW fluxes.
In the wildfire case study we showed that the bias in modelled global SWD flux relative to observations was lowest when observed AOD550 and IOPs were included in the simulations (within ± 4% at midday). This was true irrespective of the radiation scheme and its spectral resolution. Global SWD flux was greatly overestimated, by more than 15 % at midday, when aerosols were excluded and by +10 % at midday when the climatological aerosols were used (Tegen et al., 1997). On the other hand global SWD irradiance was underestimated by 11 % at noon, when observed AOD550 and parametrized IOPs, as opposed to observed IOPs, were used in the experiments. This highlights the need for accurate information on both aerosol

concentration and aerosol IOPs in order to improve the simulated radiation budget in the model. The importance of all of the aerosol IOPs, and not just AOD550, in the direct radiative effect of aerosols on solar radiation was clearly demonstrated. The over- and under-estimation of global SWD flux leads to errors in model temperatures and energy fluxes. Therefore, during heavy pollution episodes the use of real-time aerosols would greatly improve the radiation budget and meteorological forecasts. The wildfire experiments also illustrate that the performance of the broadband hlradia and acraneb2 schemes is comparable to that of the spectral IFS scheme. The results attained for the three schemes were similar, with simulated global SWD fluxes mostly within 10-20 W/m2 of each other for each aerosol scenario.

The dependency of the direct radiative effect of aerosols on relative humidity was up to ± 6 %. for an AOD of 1.0. As a first approximation, assuming a constant relative humidity is acceptable but we suggest that relative humidity dependent parametrizations of aerosol IOPs should be used. The effect of the vertical profile of IFS land aerosols (via the vertical scale height) on net SW irradiance near the surface was found to be small to vary by up to 4%. This is consistent with the finding of Meloni et al. (2015). The influence of the vertical profile on model-level SW heating rates was large, changing by up to a factor of 2 in the boundary layer in response to the aerosol vertical distribution. This highlights the need for using realistic vertical profiles of aerosols. In reality aerosols are distributed in discrete rather than continuous layers. The IFS, hlradia and acraneb2 radiative transfer approximations were tested for a range of optical depths and found to be accurate to within ± 13 % even for large aerosol loads compared to the DISORT model.

The influence of improvements in the representation of the direct radiative effect of aerosols on meteorological forecasts needs further study using 3D simulations. We plan to upgrade the aerosol climatology in the HARMONIE-AROME configuration of the ALADIN-HIRLAM system to the more realistic MACC reanalysis dataset. We will also investigate the option of acquiring real-time aerosol input, including the vertical profile of the aerosol properties, from 3D aerosol IOP estimates from the C-IFS model or chemical transport model simulations, possibly coupled to the NWP model. "

Comments in tables and figures are given in the attached file. Several questions are posed by the reviewer in the attached file. They mainly serve as a motivation to revise the respective document and not merely to be answered by the authors. A lot of the comments and questions are put in specific parts of the document, but they seemingly refer to the whole manuscript, i.e. to other similar parts, as well.

- Thank you – these have been addressed and the paper has been substantially restructured.

The presentation of one figure in 3 pages is not common – re Figure 4

- We decided to remove Figure 4c as we felt that it did not add to the discussion and caused some confusion instead.

Interactive Comment

Interactive comment on "Effects of aerosols on solar radiation in the ALADIN-HIRLAM NWP system" by E. Gleeson et al.

Anonymous Referee #2
Received and published: 1 February 2016

This manuscript, submitted to Atmospheric Chemistry and Physics, presents an interesting study of the sensitivity of the ALADIN-HIRLAM NWP system to the aerosol optical properties and the choice of the radiative scheme. The authors show the importance of considering realistic aerosols and their optical properties to simulate shortwave radiation. They have used a single-column NWP model to carry out simulation with different aerosol optical properties and radiative schemes. The dependence of the direct aerosol effect on relative humidity and aerosol vertical distribution has also been investigated. As a result, the authors present many sensitivity simulations that are not always completely exploited. The paper should be clarified to put forward the most important results. Moreover, the authors should pay more attention to the use of the English language. Consequently, I suggest a major revision of the paper before publication in ACP.

- Thank you for reviewing our paper and for your useful feedback which we have addressed in the paper and below.

Some abbreviations used in the below responses:
AOD550 = AOD at 550nm
SWD = downwelling shortwave radiation
RH = relative humidity
NWP = numerical weather prediction
IOP = inherent optical property

Main comments:

- Structure of the paper: The authors have written many small paragraphs where the different sensitivity experiments are briefly presented, without logical transitions between them. I suggest to reorganize the results, maybe remove some simulations that are not useful, and focus on the main results. Moreover, all the curves of the different figures should be exploited, otherwise they can be removed.

- We have completely restructured the paper following advice from both reviewers. We merged/removed short paragraphs and have discussed all curves on the plots, as well as making many other significant improvements.

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    - *2.1 ALADIN-HIRLAM*
    - *2.2 Radiation schemes*
        - *2.2.1 IFS*

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2.2.3 Acraneb2
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3.2 Aerosol observations
3.3 BSRN radiative flux measurements
3.4 Atmospheric and surface input for MUSC
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5.2.2 Relative humidity (RHEXP)
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6. *Conclusions and future work*

- Some hypotheses made by the authors seem to be very simplistic. For example, I wonder if it is really interesting to use radiative schemes with only one SW spectral band (especially in the case of wildfires, with aerosol optical properties highly dependent on wavelength), which are now scarcely used in NWP models. Another simplistic hypothesis is the absence of vertical aerosol distribution in the HLRADIA radiative scheme.

- Kangas et al have tested HARMONIE-AROME with the three different radiation schemes against SWD measurements in Sodankylä over several months. They show that the one SW spectral band hlradia and acraneb2 schemes give comparable results to IFS. Errors in radiation output are mostly due to uncertainties in the input to the radiation schemes rather than the formulations of the schemes themselves. The gain from using complex, computational resource-demanding multi-band band schemes is mainly seen in upper atmospheric heating rates that are essential for medium range and long range forecasting. For short range (typically up to 2 days) limited area forecasting, which is what HARMONIE-AROME is made for, the benefit of multiple spectral band SW computations is small. Since the main uncertainty is the cloud and aerosol input to the radiation scheme, the sparse computational resources are better spent on generating multiple ensemble members using a broadband SW scheme than to use the resources on running with a complex multi-band scheme. This may seem simplistic, but it is a fact of life for practical short range NWP forecasts run in an operational setting where it is no good to have a state-of-the-art NWP model that takes longer to run that the forecast period covered.

- Our results show that the differences between the schemes depend mainly on factors other than the spectral resolution. For aerosol-free conditions, Nielsen et al., 2014 showed that hlradia compares well to the 6 band IFS scheme for a range of clear sky, cloud liquid and cloud ice tests.

- The simulations have been run under clear-sky conditions, which is a first step to estimate the effect of aerosols on SW radiation. However I think that it limits a lot the results of this paper, as clouds highly modulate the direct effect of aerosols (and of course also the indirect effect which is unfortunately not considered in this paper). Indeed, in the presence of clouds, the direct effect of aerosols should be less important. Simulations with all-sky conditions would reinforce the results of this study.

- We've changed the name of the paper slightly in order to properly summarise its focus. Our aim was to study the direct effect of aerosols in the ALADIN-HIRLAM NWP system and this is the reason why we ran clear sky simulations. In addition, it is possible to compare the simulated direct radiative effect of aerosols with radiation measurements under clear-sky conditions. The indirect effect of aerosols is not included in the current version of the system. We agree that in the future the influence of aerosols should be also studied in cloudy situations to extend our study.

Specific comments:

- The abstract should be rewritten, to give more precise and concise results. It is also abnormal to mention only one radiative scheme and not the two others.

- We have rewritten the abstract – it now includes a proper summary of the results.

> *"The direct shortwave radiative effect of aerosols under clear sky conditions in the ALADIN-HIRLAM numerical weather prediction system was investigated using three shortwave radiation schemes in diagnostic single-column experiments: the IFS scheme, the acraneb2 scheme and the hlradia radiation scheme. The aim was to evaluate the strengths and weaknesses of the NWP system in this regard and to prepare it for use of real-time aerosol information.*
> *The experiments were run with particular focus on the August 2010 Russian wildfire case. Each of the three radiation schemes accurately (within ± 4% at midday) simulates the direct shortwave aerosol effect when observed aerosol optical properties are used. When the aerosols were excluded from the simulations, errors of more than +15 % in global shortwave irradiance were found at midday, with the error reduced to +10 % when standard climatological aerosols were used. An error of -11 % was seen at midday if only observed aerosol optical depths at 550 nm, and not observation-based spectral dependence of aerosol optical depth, single scattering albedos and asymmetry factors, were included in the simulations. This demonstrates the importance of using the correct aerosol optical properties. The dependency of the direct radiative effect of aerosols on relative humidity was tested and shown to be within ± 6 % in this case. By modifying the assumptions about the shape of the IFS climatological vertical aerosol profile, the inherent uncertainties associated with assuming fixed vertical profiles were investigated. The shortwave heating rates in the boundary layer changed by up to a factor of 2 in response to the aerosol vertical distribution. Finally, we tested the radiative transfer approximations used in the three radiation schemes for typical aerosol optical properties compared to the accurate DISORT model. These approximations are found to be accurate to within ± 13 % even for large aerosol loads."*

- Page 32520 lines 16-25: Many (simplistic?) statements without any reference in the beginning of the introduction.

- We have rewritten and restructured the introduction section.

> *"The direct radiative effect of aerosols resulting from scattering and absorption of*

electromagnetic radiation at shortwave (SW) and longwave (LW) wavelengths has an impact on the Earth's radiation budget (e.g. Haywood and Boucher, 2000; Bellouin et al., 2005; Jacobson, 2001; Myhre et al., 2013; Yu et al., 2006; Loeb and Manalo-Smith, 2005) and on meteorology (e.g. Cook and Highwood, 2004; Takemura et al., 2005; Wang, 2004; Mulcahy et al. 2014, Bangert et al., 2012) which needs to be accounted for in numerical weather prediction (NWP) models. Climatological distributions of aerosols are commonly used in present-day operational NWP models for calculating the direct radiative effect of aerosols.

Using unrealistic aerosol distributions can lead to considerable errors in meteorological forecasts. Milton et al. (2008) showed that excluding the direct radiative effect of mineral dust and biomass burning aerosols in forecasts using the UK Met Office Unified Model during the dry season in West Africa resulted in an inaccurate representation of the surface energy budget and a warm bias in screen level temperature. Carmona et al. (2008) presented significant correlations between errors in the aerosol optical depth (AOD) assumed in an NWP model and temperature forecast errors. Accurate simulation of the direct radiative effect of aerosols on SW radiation is important to the growing solar energy industry because under clear-sky conditions aerosols are the main modulator of SW fluxes (Breitkreuz et al., 2009).

The monthly aerosol climatology described in Tegen et al. (1997) is used in ECMWF's (the European Centre for Medium Range Weather Forecasts) global Integrated Forecast System, IFS, and in the Aire Limitee Adaptation dynamique Developpement INternational – High Resolution Limited Area Model (ALADIN-HIRLAM) limited area modelling system used in this study. Tompkins et al. (2005) showed that replacing the Tanre at al. (1994) fixed average aerosol distribution in ECMWF's IFS model by the Tegen climatology improved forecasts of the African Easterly Jet. This change in the aerosol climatology also improved the forecast skill and seasonal mean errors (Rodwell and Jung, 2008).

Including a more complete representation of the effects of aerosols in NWP models can improve the meteorological forecasts and is an active area of research (e.g. Mulcahy et al., 2014, Bangert et al., 2012). Using real-time aerosol distributions, rather than climatological datasets, to account for the direct radiative effect of aerosols further improves the quality of the forecasts. Toll et al. (2015b) showed that the accuracy of the forecasts of near-surface conditions by the ALADIN-HIRLAM system during severe wildfires in summer 2010 in Eastern Europe were improved when the direct radiative effect of the realistic aerosol distribution was included in the model hindcasts. Palamarchuk et al. (2016) also found a noticeable sensitivity of the ALADIN-HIRLAM forecasts to the treatment of aerosols. On the other hand, Toll et al. (2016) showed that when observed aerosol distributions are close to average, improvements in the SW radiation, temperature and humidity forecasts in the lower troposphere are only slightly greater when time-varying realistic aerosol data from the Monitoring Atmospheric Composition and Climate (MACC) reanalysis (Inness et al., 2013) is used in place of the Tegen climatology. Similar conclusions were drawn by Zamora et al. (2005) who showed that for small AODs accounting for the climatological average direct radiative effect of aerosols gives very good estimates of SW fluxes, but large biases occur when the AOD is large.

Baklanov et al. (2014), Grell and Baklanov (2011) and Zhang (2008) have suggested using coupled air quality and NWP models to improve forecasts of both air quality and weather. However, for operational NWP such coupled models are still too demanding computationally, and this added cost has to be evaluated versus improvements in the meteorological forecasts. Mulcahy et al. (2014), Morcrette et al. (2011) and Reale et al. (2011) describe improved forecasts of the radiation budget and near surface conditions in global NWP models when prognostic aerosols are included; however the impact of aerosols on large scale atmospheric dynamics is generally weak.

The AOD at 550 nm (AOD550 hereafter in this paper) and aerosol inherent optical properties

(IOPs: spectral dependence of AOD, single scattering albedo (SSA) and asymmetry factor (g)) depend on the size, shape and the complex refractive indices of the aerosols and have a significant effect on global downwelling SW (SWD) fluxes. Hygroscopic induced changes in the IOPs of different aerosols types also alter the radiative effect of aerosols (e.g. Cheng et al., 2008; Bian et al., 2009; Markowicz et al., 2003; Zieger et al., 2013). For example, Magi and Hobbs (2003) present measurements of enhanced backscatter by biomass burning aerosols when the relative humidity (RH) is high. Pilinis et al. (1995) estimated that the global forcing due to aerosols doubles for a relative humidity increase from 40% to 80%.

The vertical profile of aerosols is also very important when estimating their direct radiative effect. There are considerable variations in the vertical distributions of aerosols over Europe (Guibert et al., 2005; Matthias et al., 2004). Therefore, inaccuracies result when constant climatological profiles per aerosol species are used (as is the case in ALADIN-HIRLAM which uses the profiles of Tanre et al., 1984). For example, Guibert et al. (2005) analysed the vertical profiles of aerosol extinction over Europe and found that aerosols over southern Europe are concentrated higher in the atmosphere due to the occurrence of dust storm episodes. Meloni et al. (2005) showed that under clear-sky conditions the direct radiative effect of aerosols on surface radiation has a low dependence on the aerosol vertical profile, but that the profile has an impact on the top of the atmosphere forcing, especially for absorbing aerosols. Toll et al. (2015) evaluated the profile of the aerosol attenuation coefficient for land aerosols in ALADIN-HIRLAM against observations for the summer 2010 Russian wildfires. They found good agreement between the distribution assumed in the model and CALIOP measurements. However, a more general evaluation of the vertical profile of aerosols in the system has not been performed.

The main goal of the present study is to focus on the impact of AOD550, aerosol IOPs, the vertical distribution of aerosols, relative humidity and radiative transfer algorithms on SW fluxes in diagnostic single column clear-sky experiments using the ALADIN-HIRLAM system. Such experiments are extremely useful for developing and testing parametrizations and for running idealised experiments that focus on atmospheric physics in a simplified framework. With these experiments we can evaluate the strengths and weakness of the NWP model regarding the treatment of the direct radiative effect of aerosols.

The paper is structured as follows: the model set-up and radiation schemes are described in Section 2; the aerosol datasets and atmospheric and surface input used in the experiments are detailed in Section 3; descriptions of each of the experiments and sensitivity tests are provided in Section 4; the results and discussion are presented in Section 5 and conclusions and future work are summarised in Section 6. "

- A state of the art concerning the use of the indirect effect in NWP models should be added in the introduction, in the same way as it is done for the direct effect.

- The paper focusses on clear sky aerosol experiments. There is therefore no indirect effect so we do not wish to confuse the issue by including it in the introduction section. The title of the paper has been changed to reflect this.

- Page 32521 lines 26-27: optical properties also depend on the type and the size of the aerosols

- The concept of aerosol "type" is somewhat fuzzy. Often this entails one or more approximations of some sort. It is more correct to say that the optical properties depend on "size, shape and the complex refractive indices of the aerosols". We have updated this in the paper.

- Page 32522 lines 16-19: aerosol vertical distribution. Has the climatological vertical profile used in the ALADIN-HIRLAM system been evaluated against observations (e.g. lidar)? Where does it come from?

The vertical profile of aerosols in ALADIN-HIRLAM follows Tanre et al. (1984). AOD at 550nm serves as input to the radiation scheme and this is distributed vertically on the model levels. Toll et al. (2015) evaluated the vertical profile of the aerosol attenuation coefficient for land aerosols in ALADIN-HIRLAM against observations for the summer 2010 Russian wildfires. They found good agreement between the distribution assumed in the model and CALIOP measurements. However, a more general evaluation of the vertical profile of aerosols in ALADIN-HIRLAM has not been performed. This explanation has now also been added to the manuscript.

Tanre, D., Geleyn, J. F., & Slingo, J. (1984). First results of the introduction of an advanced aerosol-radiation interaction in the ECMWF low resolution global model. Aerosols and their climatic effects, 133-177.

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

- Please also add a reference for: “There are considerable variations in the vertical distribution of aerosols over Europe.”

- The following references have been added: Guibert et al., 2005; Matthias et al., 2004.

- Page 32522 line 29: For the LW effect, it could be interesting to have a case with dust particles.

- Yes it would be interesting and is planned for the future when we study LW radiation in ALADIN-HIRLAM in detail. This study is solely focussed on the shortwave radiation and the direct radiative effect; it is the reason why we chose the Russian wildfire case study.

- Page 32524 line 10: “the excluded terms can be estimated by prescribed forcings”. How is it done in your simulations? Why do you not consider horizontal advection?

- We used output from a 3D HARMONIE-AROME experiment (which contained proper dynamics) over Estonia to generate 1D input files for the Toravere location which were then used for the MUSC experiments. For example, the Russian wildfire experiment used on-the-hour input files (a file for 00 UTC, 01UTC, 02 UTC and so on) generated in the 3D run. In MUSC, horizontal advection is taken into account using temperature, specific humidity and wind forcings that are included in the input file (these forcings are also included in the 3D files).

- In our MUSC experiments we are only interested in testing the prescribed initial state of the atmosphere and surface (diagnostic rather than prognostic). Hence, horizontal advection and the forcings are not a factor in our experiments because we only focus on the output from the first time-step from MUSC before the state of the atmosphere has evolved. Using the output from the first time-step allows us to focus on the radiative processes when the state of the atmosphere is known. The aim of our experiments was to compare the radiation schemes and aerosol input and not the production of forecasts.

- The following has been added to the paper – Section 3.4:

> *"The input atmospheric and surface fields for the severe wildfire experiments at Tõravere were generated from hourly output snapshots from a 3D HARMONIE-AROME simulation. The simulation was carried out on a 2.5 km grid over Estonia for 08 August 2010 as described in Toll et al. (2015a) and the outputs were interpolated to the geographical coordinates of Tõravere for use by MUSC. As the experiments in this paper were run assuming clear-sky conditions, model level cloud water and cloud ice values were manually removed from each of the hourly atmospheric profile files generated for MUSC. These values were small but needed to be removed for direct comparison with observations."*

- Section 4.1 now has the following:

> *"In each experiment, a single time-step diagnostic MUSC simulation was run using the relevant input file (see Section 3.4) as the starting point and repeated for each hour between 00 UTC and 24 UTC. Thus, a series of single time-step simulations were run starting from the 00 UTC input file, 01 UTC input file and so on up to 24 UTC. The model was run in diagnostic mode in order to focus on the radiative properties when the state of the atmosphere and surface had not yet evolved from the initial values."*

- Page 32525 line 2: HLRADIA and ACRANEB2 are here mentioned for the first time, but are not defined.

- HLRADIA and ACRANEB2 are not actually acronyms. We've changes these to lower case to avoid confusion.

- *Page 32525 line 6: is the indirect effect of aerosols included in your simulations?*

- Indirect effects of aerosols are not currently considered in ALADIN-HIRLAM.

- Section 2.3: a comparative table with the different characteristics of the three radiation schemes would be useful for the reader.

- A new table has now been included which includes the number of SW/LW bands, the radiative transfer method used and details about ozone and radiatively active atmospheric gases (Table 1)

- Page 32525 line 13: what is this "new treatment of aerosols"?

-This has been rephrased "a new version of the HIRLAM radiation scheme hlradia containing aerosol parametrizations".

And the details of the improvement are contained in the section on hlradia (Section 2.2.2)

> *"In older versions of the scheme, aerosols were accounted for using constant coefficients. However, the scheme has recently been modified to include parametrizations of the direct and semi-direct effects of aerosols, calculated using the 2-stream approximation equations for anisotropic non-conservative scattering described by Thomas & Stamnes (2002).*
> *Hlradia uses the GADS/OPAC aerosol of Koepke et al. (1997) and includes the following species: soot, minerals (nucleation, accumulation, coarse and transported modes), sulphuric acid, sea salt (accumulation and coarse modes), water soluble, and water insoluble aerosols. The IFS aerosols types described in Section 2.2.1 are mapped to*

GADS/OPAC species in accordance with ECMWF (2004). The aerosol IOPs are averaged over the entire SW spectrum using spectral weightings calculated, using the libRadtran/DISORT software package (Mayer & Kylling 2005; Stamnes et al. 1988), at a height of 2 km and a solar zenith angle of 45 degrees for a standard mid-latitude summer atmosphere (Anderson et al. 1986).”

- Page 32525 lines 19-20: how many SW and LW radiation bands?

- This information is now included in table 1 which is referenced in Section 2.2.

- Page 32525 lines 25-28: what are the differences between these cloud liquid and ice IOP parameterizations? To what extent do they impact the results, knowing that you have run clear-sky simulations?

- Since we are only interested in clear sky results, we agree that the information on cloud water/ice schemes available in the radiation schemes is superfluous in this case, and we have now removed it.

- Page 32528 lines 13-14: I did not found the description of IFS aerosols in the introductory part of Sect.2. The work by Morcrette (ECMWF, 2004) is not in the references of the paper.

- Apologies it should have been Section 2.2 but now the paper has been restructured and it's in sections 2.2.1 and 3.1.
- The aerosol characteristics in Table 2.3 of the ECMWF 2004 documentation were used – this has been updated in the text. The reference has also been updated as the old ECMWF website has been removed.

- Section 2.3.3: how are the aerosols considered by the ACRANEB2 radiation scheme?

- We had included some text on this in Section 2.2.3:

“It also uses the same aerosol climatology as IFS but where the AODs and IOPs are spectrally averaged over the six IFS bands as is done for hlradia.”

- Page 32531 lines 10-11: why use only output from the first time-step each hour?

- Our simulations were run for 60 minutes (he way MUSC is configured we have to run it in multiples of 1-hour) starting from prescribed initial state of the atmospheric and surface variables. The time-series shown are composed from the first time step values of every hour --- we used MUSC in diagnostic and not prognostic mode.

- This was done in order to focus on the radiation processes when the state of atmosphere is known. No evolution due to advection, diabatic or other factors was allowed during the MUSC experiments to keep the simulations as exact and simplified as possible. Our aim was to compare parametrizations and aerosol input, and not the production of forecasts. However, the hourly initial states were based on 3D HARMONIE experiments (Toll et al. 2015a), which contained the proper 3D dynamics, physical parametrizations and surface interactions. For the aerosol input, these were modified using Toravere observations.

- Some of the above has been added to the text of the paper to qualify our usage of the first time-step.

- Page 32531 lines 13-14: three aerosol configurations are mentioned here, while there are four configurations in Table 1. More generally, Table 1 should be clarified, perhaps with more columns with the different options. Clear names should also be given to all simulations.

- The text has been updated and Table 1 (now Table 2) has been revised and contains information on the radiation schemes, AOD and other IOPs used for each of the curves shown in each set of results. We hope that this will make it much easier for the reader.

- Page 32532 lines 3 and 6: "parameterized aerosols IOPs" is not clear to define the simulations.

- By default, the aerosol IOPs for each spectral band and aerosol type are parametrized following Hess et al. (1998). We've added the following in Section 4.1 where the wild fire experiment set is summariised:

> *"We ran a series of 12 experiments using MUSC; 4 aerosol scenarios for each of the three radiation schemes (see Table 2 for summary). In particular, the following aerosol treatments were considered: 1) aerosol-free, 2) climatological aerosol AOD550 and parametrized IOPs, 3) observed AOD550 and parametrized IOPs and 4) aerosol observations (AOD550 and IOPs)."*

- Page 32532 lines 6-7: "This was only done using the HLRADIA parametrization". According to Table 1, relative humidity experiments were also run with IFS.

- The text of the paper and the table have been updated.

- Page 32532 line 10: "arbitrarily chosen" Could you explain this choice?

- The following has been included in the text:
"In the aerosol sensitivity experiments outlined below, the 10 UTC atmospheric and surface files generated for the wildfire case study were used as input. In each of the sensitivity experiments the relative effect of a different aerosol characteristic (AOD550, relative humidity and the vertical distribution of aerosols) on SWD is investigated." --- We could have chosen any of the wildfire input files, that's what we meant by arbitrary, and have now removed it. We tested the sensitivity of SWD to aerosol characteristics.

- Page 32532 lines 23-24: It is worth mentioning that the assimilation of AOD is included in the MACC reanalysis. I would say Northeastern Europe instead of "much of Europe".

- Thank you – we have added these changes.

- Page 32532 line 26: Please give precise values (averages / maxima) when you comment figures.

- We have now included these.

- Page 32533 lines 12-15: How have you calculated AOD for wavelengths beyond 1020 nm? The IFS radiation scheme ranges from 185 to 4000 nm, while AERONET measurements only range from 340 to 1020 nm.

- We have extrapolated the AERONET spectral measurements with the Ångström exponent. Although

this may result in an error in AOD in the first and sixth spectral intervals (1.19–2.38 µm and 2.38–4.00 µm) of the IFS radiation scheme, these spectral bands do not include a major part of the SW flux (they include respectively 18.06 % and 3.35 % of the SW radiation at the top of the atmosphere). This is now stated in the manuscript.

> *"The AERONET measurements range from 340 to 1020 nm whereas the IFS radiation scheme includes wavelengths from 185 to 4000 nm in the SW. Therefore, the first and sixth SW bands in the IFS scheme (1.19–2.38 µm and 2.38–4.00 µm) were extrapolated from the AERONET measurements. This may result in an error in these bands but the majority of the SW flux is contained in the remaining bands."*

- Page 32534 lines 7-10: Please comment also the simulation with Tegen AOD.

- Accounting for the climatological average effect of aerosols (black curves in Fig. 4b) improves the simulation of SWD compared to simulation without aerosols. However, there is still an overestimation of SWD of 60 W/m^2 at noon, as the observed AOD was higher than the climatological average value. This has been added to the manuscript.

> *"Figure 1 shows the AOD550 over northwestern Europe on 08 August 2010 in the Tegen climatology used in MUSC and the MACC reanalysis dataset (Inness et al., 2013), which includes the assimilation of observed AOD. It is clear that the Tegen climatology greatly underestimates aerosols when pollution is heavy, as was the case over Estonia and eastern Russia on 08 August 2010. Overall, over northwestern Europe the values of the realistic MACC AOD550 (maximum 3.5) are an order of magnitude higher than in the Tegen climatology (maximum 0.33) for August which highlights a drawback of using the Tegen dataset."*

- Page 32535 lines 21-23: I think the differences between the radiation schemes are not so "small". It would be interesting to have an idea of the bias of NWP models in terms of surface radiation.

- From above: Kangas et al have tested HARMONIE-AROME with the three different radiation schemes against SWD measurements in Sodankylä over several months. They show that the one SW spectral band hlradia and acraneb2 schemes give comparable results to IFS. Errors in radiation output are mostly due to uncertainties in the variables input to the radiation schemes rather than the formulations of the schemes themselves.

- SW point verification (year, season) at Sodankyla, Finland and Cabauw, the Netherlands (the verification websites are password protected) for HARMONIE-AROME vs observations gives average biases in SWD of 10% or 10-40W/m^2 but this includes both clear and cloudy days. In Figure 4b, the differences in SWD for the 3 radiation schemes is < 20 W/m^2.

- Section 4.2.1: The sensibility of AOD seems to be dominant in the diffuse radiation, can you comment on that?

- We presume that you mean the <u>sensitivity</u> of AOD?

- As can be seen in Figure 5, direct SWD is very sensitive to AOD because it is strongly affected by absorption and scattering.

- We've added the following to Section 5.2.1:

> *"Direct SW radiation is very sensitive to AOD because it is extinguished by both absorption and scattering. Due to forward scattering, the global SWD is less affected as the forward scattered irradiance reaches the surface as diffuse SWD."*

- Page 32536 lines 5-6: Even if the IFS and ACRANEB2 assume "a relative humidity of 0.8 for the climatological land aerosols", is it possible to make a test with a different assumption?

- We carried out the sensitivity test using the hlradia scheme and compared the RH effect to the IFS output, run using its default RH of 0.8. This value is inherently accounted for in the version of IFS used but in later versions of the IFS code (not yet available in the ALADIN-HIRLAM system) the aerosol radiative effects are RH dependent. At present it's not possible to change it without generating new IOP set-up files for the model, which is not a trivial task.

- Section 4.2.2 Please add a conclusion to this paragraph.

- Done.

- Page 32537 lines 10-11: I don't understand this statement: "in HLRADIA the vertical profile is considered for the heating rates at atmospheric levels". Please explain.

- Concerning the vertical distribution of aerosols in hlradia: The net SW irradiances and SW heating rates are calculated model level by model level in hlradia, but the upward and downward fluxes are only calculated at the top of the atmosphere and at the surface. This has now been clarified in the manuscript.

- Page 32538 lines 26-27: to what extent using "constant relative humidity" and "climatological vertical profiles" is "acceptable" ? There is no comparison to observations in this paper.

- In our results global SWD radiation changed by ~1 % when the relative humidity (RH) was varied from 0 to 1 for an AOD at 550 nm of 0.1 [~ average aerosol amount]. For a high AOD (1.0, heavy pollution) SWD increased by 11% when RH was increased from 0 to 1. Therefore, in most cases the impact of the use of a constant RH in the aerosol radiative calculations is small but it becomes significant as aerosol pollution increases. We've added the following to the paper:

> *"When the AODs are close to the climatological average (of the order of 0.1), the influence of RH on aerosol radiative transfer is less than 1%. In such cases, the assumption of a constant RH by the IFS and acraneb2 schemes is acceptable and is not a major source of error. On the other hand, for cases where pollution is high, the influence of RH on global SWD flux is ~ ± 6 % and could be important, particularly for solar energy applications."*

- Toll et al. (2015) evaluated the climatological vertical profile of the aerosol attenuation coefficient in HARMONIE-AROME against observations for the summer 2010 Russian wildfires. They found good agreement between the distribution assumed in HARMONIE-AROME and CALIOP measurements. However, a more general evaluation of the vertical profile of aerosols in HARMONIE-AROME has not been performed.

- Figure 7: Please clarify the caption.

- We have changed the caption to make it clearer.

“Figure 7. (a) Net SW radiation fluxes (normalised relative to the aerosol-free case) as a function of atmospheric pressure for four vertical scale heights (h) of IFS land aerosols (b) similar to (a) but shows the normalised SW heating rate. The experiments were carried out using the IFS radiation scheme.”

Effects of Aerosols on Clear Sky Solar Radiation in the ALADIN-HIRLAM NWP System

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Abstract

The direct shortwave radiative effect of aerosols under clear sky conditions in the ALADIN-HIRLAM numerical weather prediction system was investigated using three shortwave radiation schemes in diagnostic single-column experiments: the IFS scheme, the acraneb2 scheme and the hlradia radiation scheme. The aim was to evaluate the strengths and weaknesses of the NWP system in this regard and to prepare it for use of real-time aerosol information. The experiments were run with particular focus on the August 2010 Russian wildfire case. Each of the three radiation schemes accurately (within ± 4% at midday) simulates the direct shortwave aerosol effect when observed aerosol optical properties are used. When the aerosols were excluded from the simulations, errors of more than +15 % in global shortwave irradiance were found at midday, with the error reduced to +10 % when standard climatological aerosols were used. An error of -11 % was seen at midday if only observed aerosol optical depths at 550 nm, and not observation-based spectral dependence of aerosol optical depth, single scattering albedos and asymmetry factors, were included in the simulations. This demonstrates the importance of using the correct aerosol optical properties. The dependency of the direct radiative effect of aerosols on relative humidity was tested and shown to be within ± 6 % in this case. By modifying the assumptions about the shape of the IFS climatological vertical aerosol profile, the inherent uncertainties associated with assuming fixed vertical profiles were investigated. The shortwave heating rates in the boundary layer changed by up to a factor of 2 in response to the aerosol vertical distribution. Finally, we tested the radiative transfer approximations used in the three radiation schemes for typical aerosol optical properties compared to the accurate DISORT model. These approximations are found to be accurate to within ± 13 % even for large aerosol loads. ~~The direct shortwave radiative effect of aerosols in the ALADIN-HIRLAM numerical weather prediction system was investigated using three different shortwave radiation schemes in diagnostic single-column experiments. The aim was to evaluate the strengths and weaknesses of the model in this regard and to prepare the model for eventual use of real-time aerosol information. Experiments were run using observed, climatologically-averaged and zero aerosols, with particular focus on the August 2010 Russian wildfire case. One of these schemes is a revised version of the HLRADIA scheme with improved treatment of aerosols. Each radiation scheme accurately simulates the direct shortwave effect when observed aerosol optical properties are used rather than climatological averages or no aerosols which result in large errors, particularly for heavy pollution scenarios. The dependencies of the direct radiative effect of aerosols on relative humidity and the vertical profile of the aerosols on the shortwave heating rates were also investigated and shown to be non-negligible.~~

1 Introduction

~~High resolution numerical weather prediction (NWP) models resolve details about local weather. Accurate treatment of the interactions of radiation with clouds and surfaces, and the direct and indirect effects of aerosols, is therefore important. Shortwave (SW) radiation in particular strongly impacts on weather at the surface and the development of the atmospheric boundary layer. Therefore, improvements in the representation of SW radiation are important for the ongoing improvement of NWP forecasts. Accurate SW radiation output from short-range NWP models relies on the accuracy of 1) the assumed amount and distribution of gases, cloud (liquid and ice) and aerosol particles, 2) the parametrization of the cloud, gas and aerosol inherent optical properties (IOPs) and 3) the approximations of~~

~~radiative transfer through the atmospheric layers. We have previously investigated cloud optical and physical properties, radiative transfer assumptions and clear-sky gas transmittance in NWP models (Nielsen et al. 2014; Gleeson et al. 2015). This study focusses on the direct radiative influence of aerosols.~~

~~Climatological distributions of aerosols are commonly used in present-day operational NWP models when computing the direct radiative effect of aerosols. For example, monthly aerosol climatologies following Tegen et al. (1997) are assumed in ECMWF's~~ ~~*(the European Centre for Medium Range Weather Forecasts)*~~ ~~global Integrated Forecast System, IFS, and in the ALADIN-HIRLAM limited area modelling system used in this study. However, including a more complete representation of the effects of aerosols in NWP models can make the numerical weather forecast more accurate and is an active area of research (e.g. Mulcahy et al. 2014). Milton et al. (2008) showed that excluding the direct radiative effect of mineral dust and biomass burning aerosols during the dry season in West Africa resulted in an inaccurate representation of the surface energy budget and a warm bias in screen level temperature in forecasts using the UK Met Office Unified Model. Carmona et al. (2008) presented significant correlations between observed aerosol optical depth (AOD) and NWP model temperature errors. Pérez et al. (2006) also demonstrated that including the radiative effects of mineral dust in meteorological simulations can improve the representation of radiative balance, atmospheric temperature and mean sea-level pressure in numerical weather forecasts.~~

~~Toll et al. (2015b) showed that the accuracy of ALADIN-HIRLAM forecasts were improved during severe wildfires in summer 2010 in Eastern Europe when the direct radiative effect of the realistic aerosol distribution, as opposed to the Tegen et al. (1997) monthly averages, was included in the model hindcasts. Overall, it is important to include the direct radiative effect of aerosols in order to improve the forecasting of direct and diffuse irradiance for solar energy applications because under clear-sky conditions aerosols mainly affect the SW radiation budget (Breitkreuz et al., 2009).~~

~~The IOPs (mass extinction, single scattering albedo (SSA) and asymmetry factor (g)) and the direct radiative effect of aerosols depend on the physical properties of the aerosols. Changes in the IOPs of different aerosols types, induced by hygroscopic growth, change the radiative effect of aerosols (e.g. Cheng et al. 2008; Bian et al. 2009; Markowicz et al. 2003; Zieger et al. 2013). For example, Magi and Hobbs (2003) present measurements of~~

~~enhanced backscatter by biomass burning aerosols when the relative humidity is high. Pilinis et al. (1995) estimated that the global forcing due to aerosols would double for a relative humidity increase from 40% to 80%.~~

~~The direct radiative effect of aerosols is also dependent on the albedo of the underlying surfaces. Absorbing aerosols may induce a net cooling or a net warming effect depending on the surface albedo and the clouds below the aerosol layer. Chand et al. (2009) estimated that the regional warming induced by absorbing aerosols is three times higher when the covariation for aerosols and cloud cover is included in the calculation. Absorbing aerosols considerably modify the radiative heating rates in the aerosol layer and the vertical profile of temperature. For example Ramanathan et al. (2007) estimated that the 50-year average warming resulting from the so-called atmospheric brown cloud over Asia to be more than 0.5 K over a large area at the 700 hPa level.~~

~~Another important aspect to take into account when estimating the direct radiative effect of aerosols is the vertical profile of the aerosols. There are considerable variations in the vertical distributions of aerosols over Europe. Therefore, inaccuracies result from using constant climatological vertical profiles for different aerosol species as is the case in the ALADIN-HIRLAM system. For example, Guibert et al. (2005) analysed the vertical profiles of aerosol extinction over Europe and found that aerosols over southern Europe were concentrated higher in the atmosphere due to the occurence of dust episodes. Meloni et al. (2005) showed that under clear-sky conditions the direct radiative effect of aerosols on radiation at the surface has little dependence on the aerosol vertical profile, but that the vertical profile has an impact on the top of the atmosphere forcing, especially for absorbing aerosols.~~

~~The main goal of the present study is to compare the direct SW effect of aerosols in the ALADIN-HIRLAM system using three radiation schemes of varying complexity, with particular focus on an August 2010 Russian wildfire case study. We focus on the direct SW effect of aerosols which is more pronounced than the longwave (LW) effect. MUSC (Model Unifie Simple Colonne, Malardel et al., 2006), the single column version of three ALADIN-HIRLAM model configurations is used in the sensitivity experiments. Single-column models are extremely useful for developing and testing physical parametrizations and for running idealised experiments that focus on atmospheric physics in a simplified framework. The sensitivity of the direct radiative effect of aerosols to the aerosol vertical profile,~~

~~relative humidity and the spectral dependence of AOD is studied. Such a study is necessary in order to evaluate the strengths and weakness of the model regarding the treatment of the direct radiative effect of aerosols and for preparation of the model for utilisation of real-time aerosol information. Currently the model relies on the use of external aerosols in the form of monthly climatologies of aerosol optical depth (AOD) at 550 nm and parametrized IOPs (SSA,g and AOD scaling) to estimate the direct effect of aerosols on radiation. In the future, the model could obtain aerosol information from chemical transport model simulations, possibly coupled to the NWP model or from the analysis of aerosol observations.~~

~~The paper is outlined as follows: the model set-ups are described in Section 2; the datasets and experiments carried out are detailed in Section 3; the results and discussion are presented in Section 4 and conclusions and future work are summarised in Section 5.~~

The direct radiative effect of aerosols resulting from scattering and absorption of electromagnetic radiation at shortwave (SW) and longwave (LW) wavelengths has an impact on the Earth's radiation budget (e.g. Haywood and Boucher, 2000; Bellouin et al., 2005; Jacobson, 2001; Myhre et al., 2013; Yu et al., 2006; Loeb and Manalo-Smith, 2005) and on meteorology (e.g. Cook and Highwood, 2004; Takemura et al., 2005; Wang, 2004; Mulcahy et al. 2014, Bangert et al., 2012) which needs to be accounted for in numerical weather prediction (NWP) models. Climatological distributions of aerosols are commonly used in present-day operational NWP models for calculating the direct radiative effect of aerosols.

Using unrealistic aerosol distributions can lead to considerable errors in meteorological forecasts. Milton et al. (2008) showed that excluding the direct radiative effect of mineral dust and biomass burning aerosols in forecasts using the UK Met Office Unified Model during the dry season in West Africa resulted in an inaccurate representation of the surface energy budget and a warm bias in screen level temperature. Carmona et al. (2008) presented significant correlations between errors in the aerosol optical depth (AOD) assumed in an NWP model and temperature forecast errors. Accurate simulation of the direct radiative effect of aerosols on SW radiation is important to the growing solar energy industry because under clear-sky conditions aerosols are the main modulator of SW fluxes (Breitkreuz et al., 2009).

The monthly aerosol climatology described in Tegen et al. (1997) is used in ECMWF's *(the European Centre for Medium Range Weather Forecasts)* global Integrated Forecast System,

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IFS, and in the Aire Limitee Adaptation dynamique Developpement INternational – High Resolution Limited Area Model (ALADIN-HIRLAM) limited area modelling system used in this study. Tompkins et al. (2005) showed that replacing the Tanre at al. (1994) fixed average aerosol distribution in ECMWF's IFS model by the Tegen climatology improved forecasts of the African Easterly Jet. This change in the aerosol climatology also improved the forecast skill and seasonal mean errors (Rodwell and Jung, 2008).

Including a more complete representation of the effects of aerosols in NWP models can improve the meteorological forecasts and is an active area of research (e.g. Mulcahy et al., 2014, Bangert et al., 2012). Using real-time aerosol distributions, rather than climatological datasets, to account for the direct radiative effect of aerosols further improves the quality of the forecasts. Toll et al. (2015b) showed that the accuracy of the forecasts of near-surface conditions by the ALADIN-HIRLAM system during severe wildfires in summer 2010 in Eastern Europe were improved when the direct radiative effect of the realistic aerosol distribution was included in the model hindcasts. Palamarchuk et al. (2016) also found a noticeable sensitivity of the ALADIN-HIRLAM forecasts to the treatment of aerosols. On the other hand, Toll et al. (2016) showed that when observed aerosol distributions are close to average, improvements in the SW radiation, temperature and humidity forecasts in the lower troposphere are only slightly greater when time-varying realistic aerosol data from the Monitoring Atmospheric Composition and Climate (MACC) reanalysis (Inness et al., 2013) is used in place of the Tegen climatology. Similar conclusions were drawn by Zamora et al. (2005) who showed that for small AODs accounting for the climatological average direct radiative effect of aerosols gives very good estimates of SW fluxes, but large biases occur when the AOD is large.

Baklanov et al. (2014), Grell and Baklanov (2011) and Zhang (2008) have suggested using coupled air quality and NWP models to improve forecasts of both air quality and weather. However, for operational NWP such coupled models are still too demanding computationally, and this added cost has to be evaluated versus improvements in the meteorological forecasts. Mulcahy et al. (2014), Morcrette et al. (2011) and Reale et al. (2011) describe improved forecasts of the radiation budget and near surface conditions in global NWP models when prognostic aerosols are included; however the impact of aerosols on large scale atmospheric dynamics is generally weak.

The AOD at 550 nm (AOD550 hereafter in this paper) and aerosol inherent optical properties (IOPs: spectral dependence of AOD, single scattering albedo (SSA) and asymmetry factor (g)) depend on the size, shape and the complex refractive indices of the aerosols and have a significant effect on global downwelling SW (SWD) fluxes. Hygroscopic induced changes in the IOPs of different aerosols types also alter the radiative effect of aerosols (e.g. Cheng et al., 2008; Bian et al., 2009; Markowicz et al., 2003; Zieger et al., 2013). For example, Magi and Hobbs (2003) present measurements of enhanced backscatter by biomass burning aerosols when the relative humidity (RH) is high. Pilinis et al. (1995) estimated that the global forcing due to aerosols doubles for a relative humidity increase from 40% to 80%.

The vertical profile of aerosols is also very important when estimating their direct radiative effect. There are considerable variations in the vertical distributions of aerosols over Europe (Guibert et al., 2005; Matthias et al., 2004). Therefore, inaccuracies result when constant climatological profiles per aerosol species are used (as is the case in ALADIN-HIRLAM which uses the profiles of Tanre et al., 1984). For example, Guibert et al. (2005) analysed the vertical profiles of aerosol extinction over Europe and found that aerosols over southern Europe are concentrated higher in the atmosphere due to the occurrence of dust storm episodes. Meloni et al. (2005) showed that under clear-sky conditions the direct radiative effect of aerosols on surface radiation has a low dependence on the aerosol vertical profile, but that the profile has an impact on the top of the atmosphere forcing, especially for absorbing aerosols. Toll et al. (2015) evaluated the profile of the aerosol attenuation coefficient for land aerosols in ALADIN-HIRLAM against observations for the summer 2010 Russian wildfires. They found good agreement between the distribution assumed in the model and CALIOP measurements. However, a more general evaluation of the vertical profile of aerosols in the system has not been performed.

The main goal of the present study is to focus on the impact of AOD550, aerosol IOPs, the vertical distribution of aerosols, relative humidity and radiative transfer algorithms on SW fluxes in diagnostic single column clear-sky experiments using the ALADIN-HIRLAM system. Such experiments are extremely useful for developing and testing parametrizations and for running idealised experiments that focus on atmospheric physics in a simplified framework. With these experiments we can evaluate the strengths and weakness of the NWP model regarding the treatment of the direct radiative effect of aerosols.

The paper is structured as follows: the model set-up and radiation schemes are described in Section 2; the aerosol datasets and atmospheric and surface input used in the experiments are detailed in Section 3; descriptions of each of the experiments and sensitivity tests are provided in Section 4; the results and discussion are presented in Section 5 and conclusions and future work are summarised in Section 6.

2 Model Set-up~~s~~

2.1 ALADIN-HIRLAM ~~configurations and their single column version MUSC~~

~~The basic configuration of the ALADIN-HIRLAM system used in this study was HARMONIE-AROME based on Seity et al., 2011. In this, the acronym HARMONIE (*HIRLAM ALADIN Regional Mesoscale Operational NWP in Europe*) is used to denote the specific configuration of the ALADIN-HIRLAM NWP system maintained by the international HIRLAM programme. HARMONIE-AROME uses ALADIN non-hydrostatic dynamics (Bénard et al., 2010), Meso-NH physics (Mascart and Bougeault, 2011) and the SURFEX externalised surface scheme (Masson et al., 2013). Its default set-up for operational NWP uses a 2.5 km horizontal grid where deep convection is treated explicitly. Surface physiographies are prescribed using the 1 km resolution ECOCLIMAP database and surface elevation is based on GTOPO30 (USGS, 1998). The ALADIN-HIRLAM system can also be used for regional climate simulations (Lindstedt et al., 2015), where the direct radiative effect of aerosols can be of greater importance than in short range NWP applications.~~

~~The single column version of the ALADIN-HIRLAM model configurations (MUSC) includes all of the atmospheric and surface parametrizations but excludes large-scale dynamics, horizontal advection, the pressure gradient force and large-scale vertical motion. However, the excluded terms can be estimated by prescribed forcings. Because of the simplifying assumptions, a single column model is not suitable for real forecasting. Its value lies in the fact that it provides the possibility to study the sensitivity of the model to different formulations of the physical parametrizations for realistic atmospheric conditions.~~

~~The time integration in MUSC is done on a single atmospheric column with 65 hybrid model levels. The inputs to MUSC include the initial conditions in the atmosphere, the initial conditions at the surface, surface properties and possibly atmospheric forcing data (i.e. temperature, specific humidity and wind speed forcings) applied during the MUSC~~

~~experiment. These can be derived from the output from a 3D model experiment. In our experiments the initial state for MUSC was obtained from hourly snapshots of a 3D HARMONIE-AROME simulation. Single time step MUSC experiments were then run using each snapshot, which is sufficient for the diagnostics of radiative transfer.~~

The ALADIN-HIRLAM numerical weather prediction system is used for operational weather forecasting by 26 national meteorological services in Europe and North Africa which form the HIRLAM (High Resolution Limited Area Model) and ALADIN (Aire Limitée Adaptation dynamique Développement International) consortia. Pottier (2016) summarises 42 limited area configurations of the system used by the consortia members. This system can also be used for regional climate simulations (Lindstedt et al., 2015), where the direct radiative effect of aerosols can be of greater importance than in short range NWP applications.

The HARMONIE-AROME configuration based on Seity et al., 2011 was used in this study. HARMONIE (HIRLAM ALADIN Regional Mesoscale Operational NWP in Europe) denotes the specific configuration of the ALADIN-HIRLAM system maintained by the HIRLAM consortium; AROME is a limited area model developed at Météo-France. Its default set-up for operational NWP uses a 2.5 km horizontal grid and 65 hybrid model levels with deep convection treated explicitly. This configuration uses ALADIN non-hydrostatic dynamics (Bénard et al., 2010), Meso-NH physics (Mascart and Bougeault, 2011) and the SURFEX externalised surface scheme (Masson et al., 2013). Surface physiographies are prescribed using the 1 km resolution ECOCLIMAP II database (Faroux et al., 2012) and surface elevation is based on GTOPO30 (USGS, 1998).

We used the single column version of HARMONIE-AROME based on Malardel et al. (2006) for the experiments detailed in this paper. As in Malardel et al. we will refer to this model configuration as MUSC (Modèle Unifé Simple Colonne). It includes all of the atmospheric and surface parametrizations of HARMONIE-AROME but lacks the large-scale dynamics, horizontal advection, pressure gradient force and large-scale vertical motion. Because of the simplifying assumptions, MUSC is not suitable for operational weather forecasting. However, its value lies in the fact that it provides a useful means of studying the sensitivity of the model output to realistic atmospheric conditions and different physical parametrizations. The input to MUSC is derived from the output of a 3D HARMONIE-AROME experiment. This includes the initial conditions in the atmosphere and surface, surface properties, atmospheric temperatures, specific humidities and wind speeds. Details on the input data used in our experiments are provided in Section 3.4.

2.2 Radiation schemes

In this study three shortwave radiation schemes were applied in MUSC: 1) The IFS radiation scheme based on cycle 25r1 (Morcrette, 1991; White, 2004), 2) A new version of the HIRLAM radiation scheme called hlradia (Savijärvi 1990) containing aerosol parametrizations, 3) The acraneb2 scheme (Mašek et al., 2015). Table 1 summarises the main characteristics of these radiation schemes.

Each scheme treats the atmosphere as a 1D column consisting of a set of plane-parallel homogeneous layers. The grid box is split into a cloudy fraction and a clear-sky fraction and does not allow lateral exchanges between them. Atmospheric composition (i.e. aerosols, clouds and atmospheric gases) and the radiative properties of the surface are required as input to the radiation schemes. MUSC was run under clear-sky conditions for the experiments and sensitivity studies presented in this paper. Thus, details on cloud particles and cloud cover are not included. Further information on the basic differences between the radiation schemes is given in the following sub-sections.

2.2.1 IFS

The IFS SW radiation scheme (ECMWF, 2004; IFS cycle 25R1) is used by default in MUSC and is the most detailed of the three schemes applied in our experiments. It contains six SW spectral bands (0.185–0.25–0.44–0.69–1.19–2.38–4.00 µm), three in the ultraviolet/visible spectral range and three in the solar infrared range (Mascart and Bougeault, 2011; White, 2004), and 14 LW bands. The IFS clear-sky SW radiative transfer is calculated using the Fouquart and Bonnel (1980) two-stream equations in Mascart and Bougeault (2011) where the reflectance, absorption and transmittance of the atmospheric layers are calculated in a similar manner to that outlined in Coakley and Chylek (1975). These calculations use the IOPs of aerosols and atmospheric molecules. Monthly climatologies of vertically integrated AOD550 for six aerosol categories - continental, sea, urban, desert, volcanic and background stratospheric are used (Tegen et al., 1997). These aerosols are distributed among the model levels using Tanre et al. (1984) climatological vertical profiles for each type as described in Section 3.1; these profiles are used in the calculations of model-level fluxes and heating rates. The aerosol IOPs are parametrized following Hess et al. (1998). Monthly climatologies of ozone and a fixed composition mixture of CO_2, N_2O, CH_4 and O_2 are also used. Further details on the aerosols are given in Section 3.1.

2.2.2 Hlradia

Hlradia, the simplest of the three schemes, considers 1 SW and 1 LW spectral band. Clear-sky transmittance, reflectance and absorptance of SW flux are taken into account at each model-level to obtain the radiative heating (vertical divergence of the net SW flux) and net SW fluxes. The radiative transfer is parametrized rather than solved explicitly, in order to make the scheme very fast for NWP use (Savijärvi, 1990). The impact of ozone, oxygen and carbon dioxide on SW irradiance is assumed to be constant over time and space. In older versions of the scheme, aerosols were accounted for using constant coefficients. However, the scheme has recently been modified to include parametrizations of the direct and semi-direct effects of aerosols, calculated using the two-stream approximation equations for anisotropic non-conservative scattering described by Thomas & Stamnes (2002).

Hlradia uses the GADS/OPAC aerosols of Koepke et al. (1997) and includes the following species: soot, minerals (nucleation, accumulation, coarse and transported modes), sulphuric acid, sea salt (accumulation and coarse modes), water soluble, and water insoluble aerosols. The IFS aerosols types described in Section 2.2.1 are mapped to GADS/OPAC species in accordance with ECMWF (2004). The aerosol IOPs are averaged over the entire SW spectrum using spectral weightings calculated, using the libRadtran/DISORT software package (Mayer & Kylling 2005; Stamnes et al., 1988), at a height of 2 km and a solar zenith angle of 45 degrees for a standard mid-latitude summer atmosphere (Anderson et al., 1986). These IOPs are referred to as broadband IOPs hereafter in the paper. Hlradia uses the same vertical distributions of aerosols as the IFS scheme.

2.2.3 Acraneb2

The acraneb2 scheme (Mašek et al., 2015), which is more complex than hlradia but simpler than IFS, was developed as part of the ALARO-1 suite of physics parametrizations. Similar to hlradia, it is a broadband scheme using a single SW radiation interval. However, it uses the Ritter and Geleyn (1992) delta two-stream system for the clear-sky radiative transfer calculations with coefficients computed according to Räisänen (2002) i.e. by averaging the coefficients of all of the radiatively active species, weighted by their optical thicknesses.

Acraneb2 uses the same climatologies of ozone and fixed composition mixture of CO_2, N_2O, CH_4 and O_2 as IFS. It also uses the same aerosol climatology as IFS but where the IOPs are spectrally averaged over the six IFS bands as is done for hlradia. One of the strengths of acraneb2 is that it possesses selective intermittency where slowly-varying gaseous transmissions are updated on a time-scale of hours (using a simple correction to the actual sun elevation).

3 Input and validation data

3.1 Aerosol climatology

The direct SW radiative effect of aerosols in MUSC is calculated using vertically integrated AOD550 and the following aerosol IOPs: AOD spectral scaling coefficients, spectral SSA and g. The spectral scaling coefficients are particularly important in the wildfire case study experiments because of the high dependence of the AOD of biomass burning aerosols on wavelength. The indirect radiative effect of aerosols is not included in the current version of the ALADIN-HIRLAM NWP system.

Monthly climatologies of Tegen et al. (1997) vertically integrated AOD550 for six aerosol categories (see Section 2.2.1) are used by default in MUSC. The aerosol IOPs for each spectral band and aerosol type are parametrized following Hess et al. (1998). The default aerosol types in MUSC are translated to GADS aerosol species before being used by hlradia as outlined in Section 2.2.2. Spectrally averaged IOPs are used in both hlradia and acraneb2 as outlined in Sections 2.2.2 and 2.2.3.

Each radiation scheme uses Tanre et al. (1984) climatological vertical profiles to distribute the AODs for each aerosol type on model levels. In these schemes the surface-normalized vertical distribution of AOD, $\alpha(z)$, is described using the following exponential form which results in a decrease in aerosol attenuation with height

$$\alpha(z)= \exp(-z/h)$$

where z is the height above the ground and h is a vertical scale height.

It is also possible to replace the monthly Tegen climatology available in MUSC with other datasets such as the Max-Planck-Institute Aerosol Climatology version 1 (MACv1, Kinne et al., 2013) or the MACC reanalysis (Inness et al., 2013) dataset, which includes assimilated

AOD measurements. For comparison, the MACC and Tegen aerosol datasets for August 2010 are shown in Figure 1 (see Section 5.1 for further details).

3.2 Aerosol observations

In the Russian wildfire case study (see Section 4.1 for details) we ran some of the simulations using AOD and IOPs derived from CIMEL sun/sky radiometer measurements recorded at the Aerosol Robotic Network (AERONET, Holben et al., 1998) station in Tõravere (58.3°N; 26.5°E), Estonia. Quality controlled level 2 AERONET data (Smirnov et al., 2000) were used. The AOD was derived (by AERONET) from measurements of the direct SW radiation flux at various wavelengths (Holben et al., 1998). SSA and g were calculated from diffuse irradiance measurements using an inversion algorithm by Dubovik and King (2000).

AOD550 and AOD scaling coefficients for the six IFS SW bands, assumed valid for the land (soot) aerosol type, were derived from the spectral AERONET measurements. These measurements range from 340 to 1020 nm whereas the IFS radiation scheme includes wavelengths from 185 to 4000 nm in the SW. Therefore, the first and sixth SW bands in the IFS scheme (1.19–2.38 µm and 2.38–4.00 µm) were extrapolated from the AERONET measurements. This may result in an error in these bands but the majority of the SW flux is contained in the remaining bands. As in the case of climatological aerosols, spectral averages of the IOPs are derived for use in the hlradia and acraneb2 schemes.

3.3 BSRN radiative flux measurements

Global SWD radiation measurements recorded at Tõravere were compared to simulated fluxes for the August 2010 wildfire case study (see Section 4.1). These measurements are independent of the AERONET network but are part of the Baseline Surface Radiation Network (BSRN, Kallis, 2010) measurements described by Ohmura et al. (1998).

3.4 Atmospheric and surface input for MUSC

The input atmospheric and surface fields for the severe wildfire experiments at Tõravere were generated from hourly output snapshots from a 3D HARMONIE-AROME simulation. The simulation was carried out on a 2.5 km grid over Estonia for 08 August 2010 as described in Toll et al. (2015a) and the outputs were interpolated to the geographical coordinates of Tõravere for use by MUSC. As the experiments in this paper were run assuming clear-sky conditions, model level cloud water and cloud ice values were manually removed from each of the hourly atmospheric profile files generated for MUSC. These values were small but needed to be removed to allow direct comparison with observations.

~~2.2 Aerosols in MUSC~~

~~Regarding aerosols, monthly climatologies of vertically integrated AOD at 550 nm (Tegen et al., 1997) for six aerosol (continental, sea, urban, desert, volcanic and background stratospheric) types are available by default in the model. The aerosol IOPs (SSA, g and AOD scaling for each of the six IFS SW radiation bands) are parametrized following Hess et al. (1998) and Koepke et al. (1997). The 550 nm AOD and spectral IOPs are used directly by the IFS radiation scheme but are spectrally averaged over the six IFS SW intervals before being used by HLRADIA and ACRANEB2. Climatological vertical profiles of the aerosol types are assumed to distribute the aerosols on model levels (Tanre et al., 1984) which results in an exponential decrease in the aerosol attenuation coefficients with height. The spatial distribution of AOD is used to calculate the direct radiative effect of aerosols whereas the indirect radiative effect of aerosols has not yet been extensively studied in the system.~~

~~2.3 Tested radiation schemes~~

~~In this study we tested three shortwave radiation schemes in the HARMONIE-AROME/MUSC framework (denoted as MUSC hereafter): 1) The IFS radiation scheme based on cycle 25r1 (Morcrette, 1991; White, 2004), which is the default scheme in HARMONIE-AROME, 2) The HIRLAM radiation scheme HLRADIA (Savijärvi 1990; Wyser et al. 1999) including a new treatment of aerosols, 3) The ACRANEB2 scheme (Mašek et al., 2015) from ALARO-1 physics. For the testing, HLRADIA and ACRANEB2 were imported to the HARMONIE-AROME framework.~~

~~Each scheme treats the atmosphere as a 1D column, consisting of a set of plane-parallel homogeneous layers. All grid boxes are split into a cloudy fraction and a clear-sky fraction with no lateral exchanges between them. The three schemes vary in complexity. The IFS scheme is the most complex of the three, consisting of several SW and LW radiation spectral bands. Its complexitity means that it is also computationally slow and is thus called intermittently in an operational forecasting set-up (by default the frequency of radiation computations is every 15 minutes in HARMONIE-AROME). The HLRADIA scheme is the~~

~~simplest of the three schemes. As well as being broadband in SW and LW, the radiative transfer equations are parametrized which makes the scheme very fast. The complexity of ACRANEB2 lies between that of IFS and HLRADIA. It is also a broadband scheme but posesses selective intermittency where slowly-varying gaseous transmissions are updated on a time-scale of hours but quickly-varying cloud IOPs, for example, are recomputed at each model time-step.~~

~~Atmospheric composition (i.e. aerosols, clouds and atmospheric gases) and the radiative properties of the surface are needed as input for each of the radiation schemes.~~

~~3D cloud liquid and cloud ice particle concentrations and fractional cloud cover used by the radiation schemes are provided by the corresponding parametrization schemes and model dynamics. However, in the sensitivity tests presented in this paper the model was run under clear-sky conditions.~~

~~Monthly climatologies of ozone and a fixed composition mixture of~~ $\cancel{CO_2}$, $\cancel{N_2O}$, $\cancel{CH_4}$ ~~and~~ $\cancel{O_2}$ ~~are used by IFS and ACRANEB2 but the impact of ozone, oxygen and carbon dioxide on SW irradiance in HLRADIA is assumed to be constant over time and space.~~

~~Diffuse and direct surface albedos are provided by the SURFEX surface module. Albedos for 1 ultraviolet, 1 visible and 1 infrared SW band are available from SURFEX and remapped to the 6 bands in IFS. These albedos are spectrally averaged over the six IFS SW intervals for use in ACRANEB2 and HLRADIA. In fact, HLRADIA only uses the broadband diffuse albedo because in this scheme the direct albedo is computed by adding the direct albedo correction factor (i.e. 0.2/(1+cos(SZA)-0.12) to the diffuse albedo (Hannu Savijärvi, personal communication). In the version of MUSC used in the sensitivity tests, the effects of orography on radiation are not taken into account.~~

~~Further details on some of the differences between the three radiation schemes are given in the following sub-sections.~~

~~2.3.1 The IFS radiation scheme~~

~~The default SW radiation scheme in HARMONIE-AROME is the IFS scheme (ECMWF cycle 25R1) with six SW spectral bands (0.185- 0.25- 0.44- 0.69- 1.19- 2.38- 4.00 μm), three~~

~~in the ultraviolet/visible spectral range and three in the solar infrared range (Mascart and Bougeault, 2011; White, 2004).~~

~~There are several SW cloud liquid and cloud ice IOP schemes available in the model. By default, the SW cloud liquid and cloud ice IOPs are calculated with the Fouquart (1987) and the Ebert and Curry (1992) parametrizations respectively. It is also possible to use the Slingo (1989) SW cloud liquid IOP parametrization and the Fu (1996) SW cloud ice IOP parametrization. The cloud water load is modified by so-called cloud SW and cloud LW inhomogeneity factors before being used for radiation calculations, each of which is set to 0.7 in the default set up. For detailed tests of the IFS SW cloud physics in the model see Nielsen et al. (2014), who suggested an improved SW cloud IOP scheme, the removal of the cloud inhomogeneity factor, and that the Fu SW cloud ice IOP scheme (Fu, 1996) be used. We followed these suggestions in the tests presented in this paper.~~

~~The SW radiative transfer for the clear-sky fraction is calculated using the two-stream equations (Fouquart and Bonnel, 1980) explained by Mascart and Bougeault (2011) where the reflectance and transmittance of the atmospheric layers is calculated similar to Coakley and Chylek (1975). The scheme uses IOPs (optical depth, SSA, g) of clouds, aerosols and molecules as input where the IOPs of clouds depend on the cloud droplet effective radius ($r_{e,water}$) and cloud ice effective dimension ($d_{e,ice}$). In IFS the Martin et al. (1994) scheme is used to calculate $r_{e,water}$. The Ou and Liou (1995) scheme is the default scheme for cloud ice effective dimension where $r_{e,ice} = 0.5d_{e,ice}$ (i.e. the crystals are assumed to be spherical). However, the advance Sun and Rikus (2000, 2001) scheme is also available; this scheme assumes hexagonal ice cyrstals (i.e. $r_{e,ice} = 0.6435d_{e,ice}$). On the other hand, the two-stream delta-Eddington approximation (Joseph et al., 1976; Fouquart and Bonnel, 1980) is used for the cloudy sky fraction radiative transfer calculations. Thus, the radiative transfer calculations in the clear-sky fractions are different to the radiative transfer calculations in the cloudy sky fractions. The results from tests of both of these radiative transfer approximations are detailed in section 4.3. In the IFS scheme a maxium-random overlap algorithm is employed between cloud layers.~~

~~2.3.2 The HLRADIA radiation scheme~~

~~One SW spectral band is considered in the HLRADIA scheme and both the clear-sky and cloudy transmittances and absorptances, or radiative transfer, are parametrized in order to~~

~~make the scheme very fast (Savijärvi, 1990; Wyser et al., 1999). In HLRADIA $d_{e,ice}$ is parametrized according to Sun and Rikus (2000,2001). $r_{e,water}$ is based on Martin et al. (1995). The effective radius used in the radiative transfer parametrization is determined from $r_{e,water}$ and r_{eq}, where an ice cloud with particles of size $r_{e,ice}$ has the same IOPs as a water cloud with $r_{e,water}=r_{eq}$. Thus, in the SW in HLRADIA cloud water and ice are treated together. This scheme uses a maximum overlap cloud algorithm.~~

~~In older versions of the scheme, aerosols were accounted for using constant coefficients (Savijärvi, 1990). However, the scheme has recently been augmented with parametrizations of the direct and semi-direct effects of aerosols. Direct and semi-direct effects were realised by implementing new fast analytical SW aerosol transmittances, reflectances and absorptances. The 2-stream approximation equations for anisotropic non-conservative scattering described by Thomas & Stamnes (2002) are used for these calculations. HLRADIA uses the GADS/OPAC aerosol IOPs of Koepke et al. (1997) and the IFS aerosols described in the introductory part of section 2 are translated into GADS aerosols following the definition of Morcrette (ECMWF, 2004). The species include soot, minerals (nucleus, accumulation, coarse and transported modes), sulphuric acid, sea salt (accumulation and coarse modes), water soluble, and water insoluble aerosols. In order to make the calculations fast, the IOPs are averaged over the entire SW spectrum using spectral weightings calculated at a height of 2 km and a solar zenith angle of 45 degrees for a standard mid-latitude summer atmosphere (Anderson et al. 1986) using the libRadtran/DISORT software package (Mayer & Kylling 2005; Stamnes et al. 1988).~~

~~2.3.3 The ACRANEB2 radiation scheme~~

~~The ACRANEB2 scheme (Mašek et al., 2015) was developed as part of the ALARO-1 suite of physics parametrizations. Similarly to HLRADIA, it uses a single SW radiation interval (0.245–4.642 µm). ACRANEB2 uses the Reid et al. (1999) conversion formula to diagnose $r_{e,water}$ and the Heymsfield and McFarquhar (1996) equation to parametrize $r_{e,ice}$. Using these, the broadband cloud liquid IOPs were derived from Hu and Stamnes (1993) spectral data and Key et al. (2002) spectral data were used to derive cloud ice crystal IOPs, where a rough aggregate of hexagonal crystals is used as the most representative of cirrus clouds.~~

~~The Ritter and Geleyn (1992) delta two-stream system, including partial cloudiness according to Geleyn and Hollingsworth (1979), is used for both the clear-sky and cloudy~~

~~radiative transfer calculations in ACRANEB2. The coefficients are computed according to Räisänen (2002), i.e. by averaging the coefficients of all of the radiatively active species, weighted by their optical thicknesses. The scheme uses a delta-linear phase function (similar to the delta-Eddington approximation used in IFS) but with hemispherically constant intensities of diffuse radiation.~~

~~Like IFS, ACRANEB2 uses intermittency to reduce computational costs. However, it differs in that the intermittency is partial with slowly evolving gaseous transmissions updated hourly (using a simple correction to the actual sun elevation), but rapidly changing cloud IOPs updated at every model time-step, followed by solving the delta two-stream equations. Such partial intermittency proved to be more accurate than the full intermittency employed by the IFS radiation scheme, which scales broadband SW fluxes using the elevation of the Sun but does not recompute the IOPs.~~

4 Experiments

Three sets of experiments were conducted in this study (short names for each experiment have been included in brackets): 1) a case study of the summer 2010 Russian wildfires where smoke plumes affected Estonia (WFEXP) and the global SWD irradiance from MUSC was compared to observations, 2) the sensitivity of SWD fluxes to AOD (AODEXP), the aerosol vertical profile (VPEXP) and relative humidity (RHEXP) and 3) aerosol radiative transfer (transmittances) compared to the accurate DISORT scheme (RTEXP). 2) and 3) are sensitivity experiments and do not simulate the summer 2010 wildfires. A summary of these experiments in terms of the aerosols and radiation schemes used is given in Table 2.

4.1 Russian wildfire case study (WFEXP)

One of the worst cases of atmospheric pollution over Estonia in recent decades (Witte et al., 2011; Huijnen et al., 2012) occurred on 08 August 2010 when forest fires in the Baltic region coincided with severe thunderstorms (Toll and Männik, 2015). To study this extreme pollution event, we focussed MUSC single-column experiments on the Tõravere location in Estonia. This location was selected for three reasons: 1) the smoke plume had a strong impact on the area, 2) measurements of aerosol IOPs were available from a local AERONET station and 3) radiation flux measurements were available from the BSRN archive. We ran a series of 12 experiments using MUSC; 4 aerosol scenarios for each of the three radiation schemes (see Table 2 for summary). In particular, the following aerosol treatments were considered: 1) aerosol-free, 2) climatological AOD550 and parametrized IOPs, 3) observed AOD550 and parametrized IOPs and 4) aerosol observations (AOD550 and IOPs). In the experiments using observations (either AOD550 or both AOD550 and IOPs) the aerosols were assigned to the land/continental aerosol category while the remaining 5 categories of IFS aerosols (see Section 2.2.1) were set to zero. Accordingly, the climatological vertical distribution of IFS land aerosols was assumed.

In each experiment, a single time-step diagnostic MUSC simulation was run using the relevant input file (see Section 3.4) as the starting point and repeated for each hour between 00 UTC and 24 UTC. Thus, a series of single time-step simulations were run starting from the 00 UTC input file, 01 UTC input file and so on up to 24 UTC. The model was run in diagnostic mode in order to focus on the radiative properties when the state of the atmosphere and surface had not yet evolved from the initial values.

4.2 Aerosol sensitivity experiments (AODEXP, RHEXP and VPEXP)

In the aerosol sensitivity experiments outlined below, the 10 UTC atmospheric and surface files generated for the wildfire case study were used as input. In each of the experiments the relative effect of a different aerosol characteristic (AOD550, relative humidity and the vertical distribution of aerosols) on SWD fluxes was investigated. In each case single time-step diagnostic MUSC simulations were conducted for a range of values of each aerosol characteristic (see Table 2 for the summary).

Six experiments were carried out to investigate the effect of AOD550 on SWD fluxes (AODEXP). In particular, two aerosol IOP configurations (observed and parametrized) were used with the IFS, hlradia and acraneb2 radiation schemes. In each case we varied AOD550 from 0 (no aerosols) to 5 (extremely polluted) in steps of 0.1 to investigate its influence on SW radiation fluxes at the surface.

The aerosol radiative transfer algorithms in the IFS and acraneb2 radiation schemes in the current version of the ALADIN-HIRLAM system assume a constant RH of 80%. In this regard, the hlradia scheme is more advanced as the RH dependence has been incorporated into the calculation of the radiative effect of aerosol IOPs. Four RH experiments (RHEXP) were carried out: 2 using hlradia and 2 using IFS where the latter were used to normalise the results from hlradia. As in AODEXP, the 10 UTC atmospheric and surface input files were used for the RHEXP experiments. Parametrized aerosol IOPs were employed in each case. Using hlradia, a series of single time-step diagnostic MUSC experiments were run for RH in the range 0 to 1.0 in increments of 0.1. The input atmospheric file was not edited to achieve the required RH. Instead, we hard-coded RH only for the aerosol transmission calculations. The series of RH simulations were run for an AOD550 of 0.1 and 1.0, which covers average and extreme aerosol quantities. Using IFS, it was only necessary to run one diagnostic MUSC simulation for each AOD550 because the IFS aerosol calculations were formulated using an assumed RH of 80%.

In the VPEXP experiments we tested the sensitivity of SWD fluxes and the SW heating rate to the vertical scale height h (see Section 3.1) using MUSC with the IFS radiation scheme. The experiments were initialised using the 10 UTC input files from the wildfire experiment and observed AOD550 and IOPs assigned to the land aerosol category. In MUSC, h has a default value of 1000 m for land aerosols. We ran single time-step diagnostic experiments using the following values of h for land aerosols: 527 m, 1000 m (default), 2109 m and 8343 m. For smaller h the aerosols are concentrated closer to the ground while larger values of h spread the aerosols higher into the atmosphere. The acraneb2 and hlradia schemes use the same vertical distribution of aerosols as IFS and exhibit a similar sensitivity in terms of SWD fluxes and the SW heating rate (results not included).

4.3 Aerosol radiative transfer (RTEXP)

Accurate aerosol radiative transfer is of equal importance to accurate aerosol IOPs. To examine the performance of the aerosol radiative transfer algorithms in MUSC, we extracted the relevant subroutines from the IFS, hlradia and acraneb2 radiation scheme codes and ran these as stand-alone formulations. These calculations require optical thickness, SSA, g and the cosine of the solar zenith angle as input.

We ran experiments using the IFS Fouquart and Bonnel (1980) clear sky formulation, the two-stream approximation (Thomas & Stamnes, 2002) used in hlradia and the acraneb2 Ritter and Geleyn (1992) two-stream approximation to calculate SW transmission through a homogeneous atmospheric layer with optical properties resembling those of aerosols. In particular, we used SSA = 0.95, g = 0.7 and cosine of the solar zenith angle of 0.6 while varying the optical depth between 0.1 and 5. Additionally, we used the accurate DISORT radiative transfer scheme (Stamnes et al., 1988) with 30 streams and the same input as the IFS, hlradia and acraneb2 radiative transfer calculations.

~~3 Experiments and datasets~~

~~Three sets of experiments are detailed in this section (short names for each experiment have been included in brackets): 1) the case study of the summer 2010 Russian wildfires whose smoke plumes affected Estonia (WFEXP), 2) AOD (AODEXP), aerosol vertical profile (VPEXP) and humidity sensitivity tests (RHEXP) and 3) tests of aerosol radiative transfer (RTEXP). A summary of these experiments in terms the aerosols and radiation schemes used is given in Table 1. Further details are provided in subsequent subsections. Tõravere in Estonia on 08 August 2010 was selected to be studied because the smoke had reached the area by then and measurements of aerosol IOPs and broadband radiation fluxes at Tõravere were available from AERONET and BSRN measurements respectively.~~

~~3.1 Aerosol data in MUSC~~

~~In addition to the aerosol climatology described in Section 2, simulations were also run using observed AOD and derived IOPs from the CIMEL Sun/sky radiometer measurements recorded at the Aerosol Robotic Network (AERONET, Holben et al., 1998) station in Tõravere, Estonia. The AOD was derived from measurements of the direct SW radiation at various wavelengths (Holben et al., 1998). SSA and g were derived from sky diffuse irradiance measurements using an inversion algorithm by Dubovik and King (2000). Quality controlled (level 2) AERONET data (Smirnov et al., 2000) were used in this study.~~

~~3.2 BSRN radiative flux measurements~~

~~SW radiation measurements recorded at Tõravere were used in comparisons to simulated fluxes for the August 2010 wildfire case study. These measurements are independent of the AERONET network and are in fact part of the Baseline Surface Radiation Network (BSRN) described by Ohmura et al. (1998). Downwelling SW radiation fluxes (W/m^2) simulated by a range of different MUSC experiments for Tõravere on 08 August 2010 were compared to measurements recorded at the Tõravere BSRN station (Kallis, 2010).~~

~~3.3 Experiments using MUSC~~

~~The first suite of aerosol experiments focused on the Russian wildfire case study (WFEXP) of summer 2010 which affected parts of Eastern Europe including Estonia. Severe thunderstorms coincided with forest fires in the Baltic region on 08 August 2010 (Toll and~~

~~Männik, 2015). These wildfires (Witte et al. (2011); Huijnen et al. (2012)) resulted in one of the worst cases of atmospheric pollution over Estonia in recent decades. The radiative effects of smoke from these wildfires are described by Chubarova et al. (2012). However, here we have conducted a focused study of the direct radiative effect of the smoke aerosols which reached Tõravere on 08 August 2010.~~

~~3D simulations on a 2.5 km horizontal grid for 08 August 2010, described by Toll et al. (2015a), were carried out to provide meteorological input data for the MUSC experiments for the severe wildfire case study over Tõravere (58.3°N; 26.5°E). Atmospheric and surface fields from the 3D simulation at hourly intervals were used to generate input data for MUSC sensitivity experiments to ensure realistic time evolution of the forcing. These single column experiments were run assuming clear-sky conditions, obtained by removing cloud water and cloud ice from each of the hourly initial profiles. For the analysis of the results, only output from the first time-step was used each hour.~~

~~For the wildfire test case three MUSC experiments were carried out, differing in their treatment of aerosols: 1) no aerosols 2) climatological aerosols and 3) observed aerosols. For tests using observed aerosols, the aerosols were assigned to the land or continental aerosol type with the remaining aerosol categories (there are six categories in the ALADIN-HIRLAM system) set to zero. In this way, the climatological vertical distribution of land aerosols was assumed for the observed IOPs. This assignment affects the SSA, g and wavelength dependence of AOD used by default in the model.~~

~~Two variations of the experiment using observed aerosols were carried out. In the first of these, observed AOD at 550 nm and observed aerosol IOPs (SSA, g and wavelength dependence of AOD) were used, whereas in the second, climatological or parametrized aerosol IOPs were used along with observed AOD at 550 nm. Single time-step MUSC experiments were then carried out using hourly forcing from the 3D experiments for 08 August 2010 for each aerosol experiment separately. As well as this, the experiments were repeated using the three radiation schemes: IFS, HLRADIA and ACRANEB2.~~

~~The second suite of experiments consisted of sensitivity tests using MUSC, including tests of AOD at 550 nm (AODEXP), relative humidity (RHEXP) and the vertical distribution of aerosols (VPEXP). The Tõravere location was also used for each of these tests. In the tests of AOD at 550 nm the AOD was varied from 0 (no aerosols) to 5 (extremely heavily polluted) to investigate its influence on SW radiation fluxes at the surface. Both observed~~

~~and parametrized aerosol IOPs were tested for each of the three radiation schemes in MUSC.~~

~~The effect of relative humidity (varying from 0 to 1) was tested using 550 nm AODs of 0.1 and 1 and parametrized aerosol IOPs. This was only done using the HLRADIA parametrization as the IFS and ACRANEB2 schemes assume a constant relative humidity of 80%.~~

~~To test the effects of the vertical distribution of the aerosols in MUSC the observed 550 nm AOD at 10 UTC on 08 August 2010 at Tõravere was arbitrarily chosen. The effect of varying the vertical scale height (*h*) of land aerosols in the surface-normalized vertical distribution of AOD was investigated. This exponential function distributes the AOD across the 65 model levels in the model.~~

~~The final suite of tests presented in this paper focus on aerosol radiative transfer (RTEXP). Accurate aerosol radiative transfer is of equal importance to accurate aerosol IOPs. We therefore tested clear-sky radiative transfer through a homogeneous layer, with optical properties resembling those of aerosols, using the IFS Fouquart and Bonnel (1980) formulation, the IFS delta-Eddington approximation, the HLRADIA formulation and the Ritter and Geleyn (1992) delta-two-stream approximation compared to the accurate DISORT model (Stamnes et al. 1988).~~

-5 Results and Discussion

5.1 Russian wildfire case study (WFEXP)

The results presented in this section include a comparison of AOD550 for the Tegen and MACC reanalysis climatologies, time-series of spectral AOD, SSA and g from AERONET and experiments run using MUSC with observed and climatological aerosol data and the IFS, hlradia and acraneb2 radiation schemes. Figure 1 shows the AOD550 over northwestern Europe on 08 August 2010 in the Tegen climatology used in MUSC and the MACC reanalysis dataset (Inness et al., 2013). It is clear that the Tegen climatology greatly underestimates aerosols when pollution is heavy, as was the case over Estonia and eastern Russia on 08 August 2010. Overall, over northwestern Europe the values of the realistic MACC AOD550 (maximum 3.5) are an order of magnitude higher than in the Tegen climatology (maximum 0.33) for August which highlights a drawback of using the Tegen dataset.

Figure 2 shows a time-series of AOD at Tõravere on 08 August 2010 for 7 wavelengths (measurements from the AERONET archive). The strong spectral dependence of AOD is clear from the figure; AOD is higher for shorter wavelengths. This notable wavelength dependence is characteristic of biomass burning aerosols (Eck et al., 1999). The AOD550, also shown in Figure 2 (black dashed line), and used in the experiments involving observations rather than the Tegen climatology, was calculated using the AERONET AOD at 500 nm (cyan line) and the Ångström exponent in the 440-675 nm spectral interval. For comparison, the significantly lower AOD550 from the Tegen climatology (red dashed line) is also included in the figure.

The remaining aerosol IOPs, SSA and g, from the AERONET inversion products database are shown in Figure 3 where daily averages are plotted as a function of wavelength. Although daily averages are shown, the time dependence of SSA and g on 08 August was small. The asymmetry factor, g, varies from 0.56 to 0.7 across the wavelength range and has an average value of 0.634. The latter was used in the wildfire experiments run using hlradia or acraneb2 with aerosol observations. The spectral values of g were interpolated to the six SW bands of IFS for experiments using this scheme.

The aerosol scattering per extinction ratio, represented by SSA, is high (close to 0.96 with a spectral average of 0.955) at each wavelength with little SW spectral dependence (Figure 3). This is similar to results by Dubovik et al. (2002) who showed that the typical SSA of smoke from biomass burning in Boreal forests is high. However, the scattering of smoke particles from this Russian wildfire event was higher than that of plumes from typical biomass burning in Boreal forests (Chubarova et al., 2012). As in the case of g, the average SSA was used in the hlradia and acraneb2 wildfire experiments involving aerosol observations while the spectral SSAs were interpolated to the IFS SW bands before use in the corresponding IFS experiments.

Figure 4a shows the global SWD radiative flux at the Earth's surface simulated using MUSC with the IFS radiation scheme for 08 August 2010 at Tõravere. We ran an experiment for each of the following 4 aerosol scenarios (also summarised in Table 2): 1) aerosol-free (red curve), 2) climatological AOD550 and parametrized IOPs (black curve), 3) observed AOD550 and parametrized IOPs (green curve) and 4) observed AOD550 and IOPs (cyan curve) and compared the global SWD fluxes to BSRN observations (blue curve). The discrepancy between simulated and observed SWD irradiance after 14 UTC is due to the development of convective clouds (Toll et al., 2015a) which are not accounted for in the MUSC clear-sky simulations.

The biases in global SWD flux (relative to observations) for the experiments using each radiation scheme (and not just IFS) and the 4 different aerosol scenarios are depicted in Figure 4b (IFS dotted continuous lines, hlradia continuous lines, acraneb2 dashed lines; the aerosol scenario colour scheme is the same as in Figure 4a). Overall, the results for the three schemes are similar (mostly to within 10-20 W/m2 of each other for global SWD irradiance which can be seen by comparing each group of three curves of the same colour), particularly in their response to the different aerosol scenarios. The largest discrepancies occur in the early morning; in hlradia this occurs because the sphericity of the atmosphere is not taken into account. When the direct radiative effect of aerosols was excluded, global SWD fluxes were overestimated by ~120 W/m2 or 19 % (red curves) at midday compared to BSRN observations. Accounting for the climatological average effect of aerosols using the Tegen et al. (1997) dataset and Hess et al. (1998) IOP parametrizations (black curves) improves the simulation of global SWD flux compared to the aerosol-free simulation. However, there is still an overestimation of 60 W/m2 or 10 % at noon, because the observed AOD is higher than the climatological average (see Figures 1 and 2).

The use of AOD550 and IOPs derived from AERONET observations gives very good agreement between the modelled and observed global SWD fluxes for each of the three radiation schemes (cyan curves, bias < 20 W/m2 or 4 % at noon). SWD flux was underestimated by ~70 W/m2 or 11 % (green curves) at noon when the direct radiative effect of aerosols was accounted for using the observed AOD550 combined with parametrized SSA, g and spectral scaling factors of land aerosols. This underestimation can be explained by two factors.

Firstly, using the climatological AOD scaling factors for Tõravere in August leads to AOD values which are 60% higher than those estimated from the AERONET spectral measurements. Secondly, using a delta-Eddington optical depth scaling factor (1-SSA*g2; Joseph et al. 1976) based on the climatological SSA and g values causes this factor to be approximately 7% lower than the corresponding scaling factor based on the observed SSA and g values. The combination of these two factors results in a scaled SW AOD of land aerosols that is 48% larger than the observation-based value.

5.2 Aerosol sensitivity tests

5.2.1 AOD (AODEXP)

The sensitivity of global SWD fluxes to AOD550 is shown in Figure 5a for MUSC experiments run using the IFS, hlradia and acraneb2 radiation schemes. The results depicted by the cyan curves are for the case where observed IOPs (i.e. 10 UTC observation at Tõravere from the AERONET archive) were used in the simulations. Parametrized IOPs were used where the experiment results shown in green. For an AOD550 of 1, global SWD irradiance is ~100 W/m2 lower when parametrized rather than observed IOPs were used, regardless of the radiation scheme. The reason for this difference has been discussed in Section 5.1.

The effect of AOD550 on direct SWD flux is shown in Figure 5b for the three radiation schemes and observed (cyan curves) and parametrized (green curves) IOPs. For example, when parametrized IOPs were used an increase in AOD550 from 0 to 1 (i.e. no aerosols to heavy pollution) reduced the global SWD irradiance by ~200 W/m2 or 27 % (Figure 5a) but had a greater effect on the direct SWD flux (~330 W/m2 or 49 %, Figure 5b). Direct SWD flux is very sensitive to AOD because it is extinguished by both absorption and scattering. Due to forward scattering, the global SWD flux is less affected as the forward scattered irradiance reaches the surface as diffuse SWD irradiance. The influence of AOD550 on global SWD flux is similar for each radiation scheme. Global SWD fluxes are lower when the parametrized IOPs are used; this is because of the combination of a higher AOD scaling factor and lower delta-Eddington optical depth scaling factor than based on observations as discussed in Section 5.1. This sensitivity test clearly illustrates the large effect AOD550 and the IOPs have on SW radiative fluxes at the surface and emphasizes the importance of using the correct aerosol IOPs in NWP.

5.2.2 Relative humidity (RHEXP)

The impact of relative humidity (RH), accounted for in the aerosol radiative transfer calculations in the hlradia scheme, on global and direct SWD fluxes is shown in Figure 6a. RH was varied from 0 to 1 in steps of 0.1; the AOD550 was set to 0.1 in the grey curves and to 1.0 (significant pollution) in the black curves. IFS land aerosol parametrized IOPs at Tõravere were used. Increasing RH from 0 to 1 increases global SWD flux by 1.5 % when AOD550 = 0.1 (grey line with filled circles) and by 12 % when AOD550 = 1.0 (black line with filled circles). The effect on the corresponding direct SWD fluxes is greater as expected (increases of 2.5 % and 24 % for AOD550 = 0.1 and 1.0 respectively, grey and black continuous lines). Figure 6b shows global SWD irradiance from the experiments run using hlradia, an AOD550 of 0.1 (grey) and 1.0 (black) and RH varying from 0 to 1.0 as before. In this case, the global SWD fluxes are normalised using global SWD flux from a corresponding experiment run using the IFS radiation scheme. In the IFS scheme a constant RH of 80 % is assumed for “land” aerosols. For AODs close to the climatological value (i.e. 0.1 here) the relative differences between global SWD fluxes for experiments using hlradia and IFS are small, and negligible at a RH of 0.8. As the humidity deviates from 0.8, particularly for larger AODs, the differences between the global SWD fluxes from experiments using hlradia and IFS grow to ± 6 %. When the AODs are close to the climatological average (of the order of 0.1), the influence of RH on aerosol radiative transfer is less than 1%. In such cases, the assumption of a constant RH by the IFS and acraneb2 schemes is acceptable and is not a major source of error. On the other hand, for cases where pollution is high, the influence of RH on global SWD flux is ~ ± 6 % and could be important, particularly for solar energy applications.

5.2.3 Vertical distribution of aerosols (VPEXP)

The inherent uncertainties associated with assuming fixed vertical profiles were investigated by modifying the assumptions about the shape of the IFS climatological vertical aerosol profile. Figure 7a shows normalised net SW fluxes on pressure levels for MUSC experiments run with the IFS radiation scheme and vertical scale heights (h, of land aerosols) of 527 m (red), 1000 m (default, green), 2109 m (cyan) and 8343 m (blue). AERONET aerosol observations at 10 UTC over Tõravere were used as input. The net SW is normalised relative to the aerosol-free case and varies by no more than 4% at each pressure level for the range of h plotted. For example, at 1000 hPa net SW varies by less than 3% with h, and by less than 4% at 800 hPa.

Figure 7b shows the SW heating rates for the same experimental set-up as in Figure 7a, where the heating rate is normalised relative to the corresponding aerosol-free simulations. The heating rates in the boundary layer changed by up to a factor of 2 in response to the aerosol vertical distribution (e.g. when h is halved (red curve) compared to the default (green curve) the SW heating rate approximately doubles). Figure 7b also clearly illustrates that large values of h spread the aerosol higher in the atmosphere (blue curve) while for smaller values, the aerosols are more concentrated closer to the ground (red curve).

5.3 Aerosol radiative transfer (RTEXP)

Figure 8a shows transmission as a function of optical depth through a homogeneous atmospheric layer containing aerosol (SSA = 0.95, g = 0.7, cosine of the solar zenith angle set to 0.6). Transmittances calculated with the IFS Fouquart and Bonnel (1980) clear-sky radiative transfer formulation, the Thomas & Stamnes (2002) two-stream approximation used for aerosol transmittance in hlradia and the Ritter and Geleyn (1992) two-stream approximation used in acraneb2 are compared to the transmittance from the accurate DISORT radiative transfer scheme (Stamnes et al., 1988) run using 30 streams. Figure 8b shows the relative differences in transmittance between these radiative transfer schemes and DISORT. As can be seen from Figures 8a and 8b the IFS, hlradia and acraneb2 radiative transfer approximations give transmittances that are within a few percent of the accurate 30-stream DISORT calculations for optical thicknesses less than 1. Even for optical thicknesses of up to 5, the approximations remain within ± 13 % of the DISORT results.

~~4 Results and Discussion~~

~~4.1 Russian wildfire case study (WFEXP)~~

~~Figure 1b shows the 550 nm AOD from the MACC reanalysis (Inness et al., 2013) over much of Europe on 08 August 2010 compared to the 550 nm climatological AOD in the model (Figure 1a) which greatly underestimates aerosols when pollution is heavy. The values of the realistic MACC AOD (up to over 3.5) are an order of magnitude higher than in the default climatology for August. Figure 2 shows the AOD at Tõravere on 08 August 2010 for 7 wavelengths (data from the AERONET archive) which highlights the strong spectral dependence of AOD; AOD is higher for shorter wavelengths. This notable wavelength dependence is characteristic of biomass burning aerosols (Eck et al., 1999). The AOD at 550 nm (Figure 2), used in some of the model simulations, was calculated using the AERONET AOD at 500 nm and the Ångström exponent in the 440-675 nm spectral interval.~~

~~In addition to 550 nm AOD, the model also requires the following inherent IOPs of aerosols in order to calculate the direct radiative effect of aerosols: AOD spectral scaling coefficients and spectral SSA and g. The AOD spectral scaling coefficients are particularly important~~

~~because of the high dependence of AOD on wavelength for biomass burning aerosols. Observed AOD scaling coefficients for the six SW bands in the model, assumed valid for the land (soot) aerosol, were derived from the spectral AERONET measurements. These coefficients were then used to derive the AOD for the six SW spectral intervals for the IFS radiation scheme.~~

~~A broadband AOD scaling coefficient of 0.959, for use in HLRADIA and ACRANEB2, was derived from the six spectral values derived for IFS using spectral weightings from the standard solar spectrum in the lower troposphere described in section 2.2.2. The remaining IOPs, SSA and g for 08 August 2010 at Tõravere are shown in Figure 3 for four wavelengths. The asymmetry factor varies from 0.56 to 0.7 across the wavelength range with an average value of g = 0.634 for broadband applications (HLRADIA and ACRANEB2 schemes). The aerosol scattering, represented by SSA, remains high (close to 0.96) at each wavelength with little SW spectral dependence. A value of 0.955 was used for the broadband cases. This is similar to results by Dubovik et al. (2002) who showed that the typical SSA of smoke from biomass burning in Boreal forests is high. However, the scattering or SSA from the smoke in this Russian wildfire event was in fact higher than for typical aerosols from biomass burning in Boreal forests (Chubarova et al., 2012).~~

~~The results of the wildfire test case experiments in terms of downwelling global SW radiation (SWD) at the Earth's surface in comparison to BSRN observations are shown in Figure 4a and 4b (*continuous lines*) for the IFS radiation scheme. The results from HLRADIA and ACRANEB2 are also depicted relative to observations in Figure 4b (*dashed lines and dotted continuous lines*). As expected, when the direct radiative effect of aerosols was excluded SWD was overestimated by ~120 W/m^2 (Figure 4b, *red curves*) at midday. When the direct radiative effect of aerosols was accounted for using only the observed AOD at 550 nm, but default (i.e. climatological/parametrized) SSA, g and spectral scaling factors of land aerosols, SWD was underestimated by ~100 W/m^2 (*green curves* in Figure 4b).~~

~~This underestimation can be explained by two factors. Firstly, the climatological spectral scaling factors for the IFS land aerosol AOD give a broadband scaling factor that is more than 30% higher than the factor estimated from the AERONET spectral measurements. Secondly, the differences in the climatological spectral SSA and g values in the model lead to a delta-Eddington optical depth scaling factor (1-SSA*g^2, Joseph et al. 1976) that is approximately 15% lower than observed. The combination of these factors results in a~~

~~broadband SW AOD of IFS land aerosols that is approximately 15% larger than the observed value. This can be seen from the cyan curve in Figure 4b, which shows the results obtained when all of the aerosol IOPs are based on the AERONET observations rather than climatology.~~

~~The use of AOD and IOPs derived from AERONET observations gives excellent agreement between the modelled and observed SWD for each of the three radiation schemes. The discrepancy between simulated and observed SWD after 14 UTC is due to the development of convective clouds (Toll et al., 2015a) which are not accounted for in the MUSC clear-sky simulations. SWD is underestimated, particularly at high solar angles when the observed 550 nm AOD is used with climatological IOPs.~~

~~Overall, the results for the three schemes are similar (mostly to within 10-20 W/m^2 for global SWD), particularly in their response to the different aerosol cases. The schemes mostly agree to within a few percent at high sun elevations as can be seen in Figure 4b for the hours around noon. The largest discrepancies occur in the early morning but a detailed investigation into the reasons for this have not been carried out in this study.~~

~~Figure 4c shows the unscaled broadband AOD used in HLRADIA and ACRANEB2 for the following three cases: 1) Climatological aerosols (i.e. climatological 550 nm AOD and parametrized/climatological IOPs, black line), 2) Observed 550 nm AOD and IOPs (cyan line) and 3) Observed 550 nm AOD but parametrized IOPs (green line). The broadband AOD shown in this figure can be compared to the observed AOD at Tõravere shown in Figure 2 for different wavelengths. The broadband AODs were scaled using g and SSA in the HLRADIA and ACRANEB2 SW radiation schemes to produce the broadband SWD fluxes used to generate the HLRADIA and ACRANEB2 curves in Figure 4b. Therefore, the differences in SWD between the various Tõravere wildfire experiments are mainly due to the differences in the unscaled broadband AOD shown in Figure 4c.~~

~~4.2 Aerosol sensitivity tests~~

~~4.2.1 AOD sensitivity (AODEXP)~~

~~3D model input and AERONET observations for 10 UTC on 08 August 2010 for Tõravere were used for the AOD sensitivity tests, which show the influence of 550 nm AOD on SWD for each of the radiation schemes for both observed and parametrized IOPs. Global SWD is~~

~~shown in Figure 5a and the direct component of this is shown in Figure 5b. Clearly, in the case of global SWD, the differences between the SW radiation schemes is small compared to the differences between the results when observed rather than parametrized IOPs are prescribed. While this experiment is a sensitivity test, it clearly illustrates the significant effect that the IOPs have on SW radiation. Direct (Figure 5b) and diffuse fluxes cannot be compared to observations because the direct irradiances assumed in the models include circumsolar irradiances that cover a broader field of view than standard measurements of direct irradiances.~~

~~4.2.2 Relative humidity sensitivity (RHEXP)~~

~~Tests were done for 550 nm AOD values of 0.1 and 1.0 and parametrized rather than observed aerosol IOPs. 3D model input files for 10 UTC on 08 August 2010 were used as initialisation and the relative humidity was hard-coded to vary between 0.0 and 1.0. In the IFS and ACRANEB2 radiation schemes, the aerosol IOP parametrizations assumes a relative humidity of 0.8 for the climatological land aerosols. In this regard, the HLRADIA scheme is more advanced as its aerosol IOPs vary with relative humidity. This is shown in Figure 6a where global, direct and diffuse SWD for the HLRADIA scheme is plotted as a function of relative humidity for 550 nm AODs of 0.1 and 1.0. For large AODs (1.0) the influence of relative humidity is significant and of the order of 10s of W/m^2 for global and direct SWD. Figure 6b shows the relative difference between the HLRADIA and IFS global SWD as a function of relative humidity, where the latter is independent of relative humidity. For AODs close to the climatological value (i.e. 0.1 here) the relative differences between HLRADIA and IFS are very small and negligible at a relative humidity of 0.8. As the humidity deviates from 0.8, particularly for larger AODs, the differences between HLRADIA and IFS grow to ±5%.~~

~~4.2.3 Vertical distribution of aerosols sensitivity (VPEXP)~~

~~In these tests of aerosols a 550 nm AOD value of 0.7 for Tõravere on 08 August 2010 (i.e. the observed value at 10 UTC) was used. The tests were run using the IFS radiation scheme but the ACRANEB2 scheme uses the same vertical distribution as IFS. However, the vertical profile is not considered in HLRADIA. The surface-normalized vertical distribution of AOD, $\alpha(z)$, has the following exponential form~~

$$\cancel{\alpha(z) = \exp(-z/h)}$$

~~where *z* is the height above the ground and *h* is a vertical scale height. *h* has a default value of 1000 m for land aerosols in the model. We varied the scale height *h* in order to change the distribution of the land aerosols, and to determine its relative effects on SW radiation and the SW radiative heating rate. For smaller *h* the aerosols are concentrated closer to the ground while for bigger *h* they are spread higher into the atmosphere.~~

~~The effect of aerosols, and in particular the vertical scale height for land aerosols, on net SW radiation and the SW radiation heating rate as a function of pressure is shown in Figure 7. The results are scaled relative to the case where aerosols are not included. At each model level, the relative net SW radiation for each of the vertical scale heights, varies by less than 3% (Figure 7a). It is reassuring that the variation with scale height is small because the HLRADIA scheme does not consider vertical profile for overall aerosol transmittance. However, in HLRADIA the vertical profile is considered for the heating rates at atmospheric levels. Unlike SW fluxes, where the differences remains within 3% throughout the atmosphere, the impact on SW heating rates is significant (ratio of up to ~1.5 compared to the default vertical profile when the vertical scale height is approximately halved). The main reason for this is presumably that the heating rate is proportional to flux divergence.~~

~~4.3 Aerosol radiative transfer (RTEXP)~~

~~The IFS radiation scheme uses different two-stream radiative transfer approximations (Joseph et al., 1976; Fouquart & Bonnel, 1980) for aerosols under the clear-sky and cloudy fractions of a given grid box. We tested both of these radiative transfer approximations as well as the two-stream approximation (Thomas & Stamnes, 2002) used in HLRADIA and the Ritter and Geleyn (1992) two-stream approximation in ACRANEB2 and compared the results to the accurate DISORT scheme (Stamnes et al., 1988) run with 30 streams. Sample transmittance results are shown in Figures 8 and 9 where the optical thickness is varied but the cosine of SZA (μ_0) is set to 0.6, g to 0.7 and SSA to 0.95.~~

~~As can be seen from these figures the IFS, HLRADIA and ACRANEB2 radiative transfer approximations give transmittances that are within a few percent of the accurate 30-stream DISORT calculations for optical thicknesses which are less than 1. Even for optical thicknesses up to 5, the approximations remain within +/- 12% of the DISORT results. Thus, it can be concluded that the three (IFS, HLRADIA, ACRANEB2) approximations are~~

~~sufficiently accurate. Additional results from tests of the IFS delta-Eddington radiative transfer scheme can be found in the supplement to the paper by Nielsen et al. (2014).~~

~~5 Conclusions and future work~~

~~When the 550 nm AOD and IOPs (spectral AOD scaling, SSA and g) of aerosols are accurately known, the SW direct radiative effect of aerosols is accurately simulated with the IFS, HLRADIA and ACRANEB2 radiation schemes available in the ALADIN-HIRLAM NWP system. Global SWD radiation was underestimated during the wildfire event in summer 2010, especially at high solar angles, when the observed AOD at 550 nm was used with the climatological or parametrized IOPs in each of the radiation schemes rather than the observed IOPs.~~

~~This highlights the need for accurate information on both aerosol concentration and aerosol IOPs in order to improve the simulated radiation budget in the model and possibly to result in an improvement in weather forecasts in the future. The model could acquire this information, including the vertical profile of the aerosol properties, from 3D aerosol IOP estimates from the C-IFS model or chemical transport model simulations coupled to the NWP model.~~

~~The IFS, HLRADIA and ACRANEB2 radiative transfer approximations were tested and found to be accurate to within +/- 12% even for large aerosol loads.~~

~~The dependency of the direct radiative effect of aerosols on the relative humidity and the dependency of the SW heating rates on the vertical distribution of aerosols were shown to be non-negligible. We therefore suggest that a relative humidity dependent parametrization of aerosol IOPs should be used (like in HLRADIA) as well as realistic vertical profiles of aerosols. Nevertheless, as a first approximation, assuming a constant relative humidity and climatological vertical profiles are acceptable.~~

~~For cases of heavy pollution the climatological AOD in MUSC is much smaller than observed and when used with either observed or parametrized IOPs, global SWD radiation is overestimated. This is similar to the case where aerosols are completely omitted. This overestimation of global SWD radiation leads to other model errors. Thus, during heavy pollution considerable improvements in the representation of the radiation budget are possible when real rather than climatological aerosols are included.~~

~~The influence of improvements in the representation of the direct radiative effect of aerosols on meteorological forecasts needs to be further studied using 3D simulations. In this study the direct SW radiative effect of aerosols was studied; in the future the indirect effects of aerosols on cloud microphysics and the longwave effect of aerosols also need to be investigated.~~

~~Additionally, our results highlight the issues with having IOPs for each aerosol type but a fixed 550 nm AOD. This is important for aerosol data assimilation which should include all of the aerosol IOPs and not only 550 nm AOD.~~

6 Conclusions and future work

We carried out single column diagnostic experiments using the MUSC model and three radiation schemes (IFS, hlradia and acraneb2) to examine the influence of the direct radiative effects of aerosols on SW radiative flux. In particular, we focused on the effect that AOD550, aerosol IOPs, the relative humidity, vertical profile of AOD and the radiative transfer formulations has on SW fluxes.

In the wildfire case study we showed that the bias in modelled global SWD flux relative to observations was lowest when observed AOD550 and IOPs were included in the simulations (within ± 4% at midday). This was true irrespective of the radiation scheme and its spectral resolution. Global SWD flux was greatly overestimated, by more than 15 % at midday, when aerosols were excluded and by +10 % at midday when the climatological aerosols were used (Tegen et al., 1997). On the other hand global SWD irradiance was underestimated by 11 % at noon, when observed AOD550 and parametrized IOPs, as opposed to observed IOPs, were used in the experiments. This highlights the need for accurate information on both aerosol concentration and aerosol IOPs in order to improve the simulated radiation budget in the model. The importance of all of the aerosol IOPs, and not just AOD550, in the direct radiative effect of aerosols on solar radiation was clearly demonstrated. The over- and under-estimation of global SWD flux leads to errors in model temperatures and energy fluxes. Therefore, during heavy pollution episodes the use of real-time aerosols would greatly improve the radiation budget and meteorological forecasts. The wildfire experiments also illustrate that the performance of the broadband hlradia and acraneb2 schemes is comparable to that of the spectral IFS scheme. The results attained for the three schemes were similar, with simulated global SWD fluxes mostly within 10-20 W/m2 of each other for each aerosol scenario.

The dependency of the direct radiative effect of aerosols on relative humidity was up to ± 6 %. for an AOD of 1.0. As a first approximation, assuming a constant relative humidity is acceptable but we suggest that relative humidity dependent parametrizations of aerosol IOPs should be used. The effect of the vertical profile of IFS land aerosols (via the vertical scale height) on net SW irradiance near the surface was found to be up to 4%. This is consistent with the finding of Meloni et al. (2015). The influence of the vertical profile on model-level SW heating rates was large, changing by up to a factor of 2 in the boundary layer in response to the aerosol vertical distribution. This highlights the need for using realistic vertical profiles of aerosols. In reality aerosols are distributed in discrete rather than continuous layers. The IFS, hlradia and acraneb2 radiative transfer approximations were tested for a range of optical depths and found to be accurate to within ± 13 % even for large aerosol loads compared to the DISORT model.

The influence of improvements in the representation of the direct radiative effect of aerosols on meteorological forecasts needs further study using 3D simulations. We plan to upgrade the aerosol climatology in the HARMONIE-AROME configuration of the ALADIN-HIRLAM system to the more realistic MACC reanalysis dataset. We will also investigate the option of acquiring real-time aerosol input, including the vertical profile of the aerosol properties, from 3D aerosol IOP estimates from the C-IFS model or chemical transport model simulations, possibly coupled to the NWP model.

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Figure 1. (a) AOD550 for August in the default climatology in the ALADIN-HIRLAM NWP system (Tegen et al., 1997) (b) AOD for 08 August 2010 from the MACC reanalysis (Inness et al., 2013). The location of Tõravere (58.3°N; 26.5°E), for which the MUSC single column experiments are run, is shown as a red dot in both panels. Note the factor of 10 difference in AOD between the Tegen climatology and the MACC reanalysis.

~~Figure 1. (a) 550 nm AOD for August from the default climatology in ALADIN-HIRLAM (Tegen et al., 1997) (b) AOD for 08 August 2010 from MACC reanalysis (Inness et al., 2013). The location of Tõravere (58.3°N; 26.5°E) for which the MUSC experiments are run is shown as a red dot in both panels. Note the factor of 10 difference in AOD between the climatology and the MACC reanalysis.~~

Figure 2. AERONET measurements of AOD at Tõravere on 08 August, 2010 for 7 SW wavelengths (nm). The AOD550 derived from these measurements (*black dashed line*) and the default climatological AOD550 at Tõravere (*red dashed line*) are also shown in the figure. Data are not available after 14UTC due to the presence of clouds.

~~Figure 2. AERONET measurements of AOD at Tõravere on 08 August, 2010 for 7 SW wavelengths (nm). The derived 550 nm AOD for Tõravere in August (black dashed line) and the default constant climatological 550 nm AOD (red dashed line) are also shown in the figure. Data are not available after 14UTC due to the presence of clouds.~~

Figure 3. Single scattering albedo (SSA) and asymmetry factor (g) at Tõravere on 08 August 2010 as a function of wavelength attained from the AERONET inversion products database. The data are averaged over the day – data at three different times were available but the time dependence was small.

Figure 4. (a) Time-series of global SWD radiation flux (W/m^2) at Tõravere on 08 August 2010 simulated using MUSC (with the IFS radiation scheme) for four aerosol scenarios (*red*: aerosol free; *black*: climatological AOD550 and parametrized IOPs; *green*: observed AOD550 and parametrized IOPs; *cyan*: observed AOD550 and IOPs). BSRN global SWD flux measurements are shown in *blue* (b) Time-series of the bias in global SWD flux relative to BSRN observations for the same four aerosol scenarios as in (a). The results when the IFS radiation scheme was used are depicted by a dotted continuous line; the hlradia (hlr) and acraneb2 (acr) biases are shown using continuous and dashed lines respectively. Only data up to 14 UTC are shown because clouds developed after that, which were not included in the MUSC simulations

~~Figure 4. Simulated global SWD radiation flux (W/m^2) for Tõravere on 08 August 2010, compared to measurements recorded at the Tõravere BSRN station (Kallis, 2010) for a range of aerosol options using (a) the IFS scheme (b) IFS, HLRADIA and ACRANEB2 biases relative to observations. The broadband AOD used in the HLRADIA and ACRANEB2 experiments is shown in subplot (c). In Figure 4b only data up to 14 UTC are shown because clouds develop after that and are not included in the MUSC simulations.~~ ~~*(obs based = observed 550 nm AOD and IOPs (scaling, SSA and g); param opt = observed*~~

~~*550 nm AOD but parametrized or climatological IOPs; climate based = climatological 550 nm AOD and IOPs; no aero = zero aerosols)*~~

Figure 5. Global SWD flux as a function of AOD550 for MUSC experiments run using the IFS (*dotted continuous curve*), hlradia (*continuous curve*) and acraneb2 (*dashed curve*) radiation schemes. The results depicted by the *cyan curves* are for the cases where observed IOPs (SSA, *g* and AOD scaling) were used. Parametrized IOPs were used for those shown in green. Direct SWD flux for MUSC experiments using the same aerosol scenarios and radiation schemes as in (a) is shown in (b).

~~Figure 5. (a) Global SWD as a function of 550 nm AOD for the IFS, HLRADIA and ACRANEB2 radiation schemes and observed or parametrized aerosol IOPs (b) similar to (a) but direct SWD is shown.~~

Figure 6. (a) Global (*dotted continuous curves*) and direct (*continuous curves*) SWD fluxes, as a function of relative humidity, simulated using MUSC with the hlradia radiation scheme for AOD550 values of 0.1 (*grey*) and 1.0 (*black*) (b) similar to (a) but shows global SWD flux normalised relative to a corresponding experiment run using the IFS radiation scheme. The IFS scheme assumes a RH of 80% for land aerosols.

~~Figure 6. (a) Global, direct and diffuse SWD radiation simulated using the HLRADIA scheme in MUSC for 550 nm AODs of 0.1 and 1.0 and relative humidities varying between 0.0 and 1.0 (b) similar to (a) but shows the HLRADIA global SWD radiation relative to the IFS scheme which uses a constant relative humidity of 0.8.~~

Figure 7. (a) Net SW radiation fluxes (normalised relative to the aerosol-free case) as a function of atmospheric pressure for four vertical scale heights (h) of IFS land aerosols (b) similar to (a) but shows the normalised SW heating rate. The experiments were carried out using the IFS radiation scheme.

~~Figure 7. The influence of the vertical scale height (*h*) of land aerosols on (a) net SW radiation and (b) the SW heating rate as a function of atmospheric pressure relative to the case where aerosols are not included.~~

~~Figure 8. Comparison of layer transmittances calculated using the IFS Delta-Eddington~~

~~(green curve), IFS clear-sky (blue curve), the HLRADIA (magenta curve) and the ACRANEB2 Ritter and Geleyn (cyan curve) algorithms to the accurate 30-stream DISORT model (red curves). The optical thickness is varied but the cosine of SZA (μ_0) is set to 0.6, g to 0.7 and SSA to 0.95.~~

~~Figure 9. This is similar to figure 8 but shows the differences relative to the accurate 30-stream DISORT model.~~

Figure 8. (a) Transmission as a function of optical depth through a homogeneous atmospheric layer containing aerosol (SSA = 0.95, *g* = 0.7, cosine of the solar zenith angle set to 0.6) for the following radiative transfer algorithms: IFS Fouquart and Bonnel (1980) clear-sky radiative transfer formulation (*cyan curve*), the Thomas & Stamnes (2002) two-stream approximation used for aerosol transmittance in hlradia (*black curve*) and the Ritter and Geleyn (1992) two-stream approximation used in acraneb2 (*red curve*) and the accurate 30-stream DISORT (Stamnes et al., 1988) radiative transfer scheme (*blue curve*). (b) As for (a) but shows the transmission differences relative to the accurate DISORT scheme.

~~**Experiment**~~	~~**SW radiation scheme**~~	~~**Aerosol**~~
~~WFEXP~~	~~IFS, HLRADIA, ACRANEB2~~	~~- Observed i.e. observed 550 nm AOD and IOPs (scaling, SSA and g)~~ ~~- climatological i.e. climatological 550 nm AOD and IOPs~~ ~~- parametrized i.e. observed 550 nm AOD but climatological IOPs~~ ~~- zero aerosols~~
~~AODEXP~~	~~IFS, HLRADIA, ACRANEB2~~	~~Observed and climatological IOPs~~
~~VPEXP~~	~~IFS~~	~~Observed (but this is arbitrary)~~
~~RH-EXP~~	~~HLRADIA, IFS~~	~~Climatological IOPs (but this is arbitrary)~~
~~RTEXP~~	~~IFS, HLRADIA, ACRANEB2~~	~~Wide range of IOPs tested.~~

~~Table 1. Summary of aerosol-radiation experiments, including details of the radiation~~

Table 1. Summary of aerosol-radiation experiments including details of the radiation schemes and aerosol datasets used.

	IFS	hlradia	acraneb2
SW bands	6	1	1
LW bands	14	1	1
Ozone	Monthly climatology	Impact of O_3 constant over time and space	Monthly climatology
Radiatively active gases	Fixed composition mixture of CO_2, N_2O, CH_4 and O_2	Impact of CO_2 and O_2 constant over time and space	Fixed composition mixture of CO_2, N_2O, CH_4 and O_2
Radiative transfer	Fouquart and Bonnel (1980) two-stream equations	Savijärvi, 1990 and the Thomas & Stamnes (2002) two stream equations	Ritter and Geleyn (1992) delta two-stream system

Table 2. Summary of aerosol-radiation experiments including details of the radiation schemes and aerosol datasets used.

Experiment	SW radiation scheme	AOD550	Other IOPs (AOD scaling, SSA, *g*)
Russian wildfire experiments: WFEXP	IFS	Aerosol-free	Aerosol-free
		Tegen climatology	Hess parametrizations
		Observed	Hess parametrizations
		Observed	Observed
	hlradia	Aerosol-free	Aerosol-free
		Tegen climatology	Hess parametrizations
		Observed	Hess parametrizations
		Observed	Observed
	acraneb2	Aerosol-free	Aerosol-free
		Tegen climatology	Hess parametrizations
		Observed	Hess parametrizations
		Observed	Observed
AOD550 experiments: AODEXP	IFS	Range [0,5] in steps of 0.1	Hess parametrizations
			Observed
	hlradia	Range [0,5] in steps of 0.1	Hess parametrizations
			Observed
	acraneb2	Range [0,5] in steps of 0.1	Hess parametrizations
			Observed
Vertical profile of aerosols experiments: VPEXP	IFS	Observed (10 UTC)	Observed (10 UTC)
Relative humidity experiments: RHEXP	hlradia	0.1	Hess parametrizations
		1.0	Hess parametrizations
	IFS	0.1	Hess parametrizations
		1.0	Hess parametrizations
Radiative transfer experiments: RTEXP	IFS	total AOD (not 550 nm) in the range [0.01,5]	SSA=0.95, *g*=0.7
	hlradia	total AOD in the range [0.01,5]	SSA=0.95, *g*=0.7
	acraneb2	total AOD in the range [0.01,5]	SSA=0.95, *g*=0.7
	DISORT	total AOD in the range [0.01,5]	SSA=0.95, *g*=0.7