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.

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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

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.

1. Introduction
2. Model set-up
    2.1 ALADIN-HIRLAM
    2.2 Radiation schemes
        2.2.1   IFS

- 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.

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."