Bachelor Thesis

The weekly cycle in cloud and radiation variables to detect indirect cloud-aerosol effects

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Matriculation number: 3684941
Date submitted: November 29, 2016
Abstract

A weekly cycle in aerosol concentration is observed in observation data over Europe and various studies claim significance of weekly cycles in various meteorological variables. In a previous study Quaas et al. [2009] simulated a weekly cycle in anthropogenic aerosol emissions in two general circulation models, finding significant weekly cycles in aerosol concentration and optical depth as well as cloud droplet number concentration for a simulation length of 5 years.

In this present study it was tested if making model simulations longer and implementing a higher aerosol efficiency for cloud droplet nucleation leads to significant weekly cycles in further cloud and radiation variables due to further aerosol indirect effects.

It was found that extending model simulations to a length of 10 years does not lead to weekly cycles in further cloud and radiation variables over Europe nor over the far extended data of global land. Simulations with increased aerosol efficiency confirmed more intense aerosol effects due to higher cloud droplet number concentration but did not show distinct weekly cycles except in aerosol concentration after 15 years of model simulation.

Finding mostly negative results prevents further process understanding about weekly cycles in cloud and radiation variables. Consequently using weekly cycles for conclusions about the aerosol impact on meteorological variables currently seems not to be auspicious.
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1 Introduction

Due to its global consequences, prediction of climate change is a major topic in atmospheric science. There is a broad agreement about significant anthropogenic impact on global climate scale, but with high uncertainty in the extend of the anthropogenic factor. While radiative forcing due to well mixed greenhouse gases is well understood with a relatively high confidence level, radiative forcing due to aerosol effects is quite uncertain. IPCC [2013] As aerosol particles can act as cloud condensation nuclei (CCN) altering cloud droplet number concentration (CDNC) [Twomey, 1974], complex indirect effects of anthropogenic aerosol have to be considered. This is confirmed by aerosol-radiation and aerosol-cloud effects holding the largest uncertainty in total anthropogenic radiative forcing. [IPCC, 2013]

There are various approaches to better estimate the extend of anthropogenic aerosol effects, basically based on comparing situations with a different magnitude of aerosol concentration and hence the associated effects. [Quaas, 2015] The analysis of large-scale weekly cycles in cloud and radiation variables due to anthropogenic caused aerosol effects may be an auspicious approach, as there is no evidence for a distinct natural 7-day cycle this variables. There are various studies claiming the detection of weekly cycles in cloud, radiation, temperature and even precipitation variables in observation data as well as studies neglecting significance of these findings. [Sanchez-Lorenzo et al., 2012]

To improve this unclear results on observation data, Quaas et al. [2009] used a different approach by simulating a weekly cycle in anthropogenic emissions in a general circulation model (GCM) to examine if such a cycle may lead to a weekly cycle in indirect aerosol effects. They found a weekly cycle aerosol concentration and CDNC, confirming a weekly cycle in anthropogenic emissions may lead to weekly cycles in aerosol concentration and CDNC which are the basis for further aerosol effects. Further weekly cycles related to more complex indirect aerosol effects were not found in the analysed 5-year model data.

To extend this study’s results longer GCM simulations were performed for this thesis to examine how long model simulation must be to get significant results in further cloud and radiation variables. Furthermore a simulation with higher aerosol efficiency was examined, testing the capability of current GCM to simulate such weekly cycles in aerosol effects at all.
2 Theoretical background

2.1 Aerosol effects

Aerosol particles affect atmospheric processes in various ways. Basically there are two categories of aerosol effects. First the so-called direct effects, as aerosol particles scatter and absorb solar radiation and scatter, absorb and emit thermal radiation. Second the so-called indirect effects as aerosol particles can act as cloud condensation nuclei (CCN) or ice nuclei (IN) and thus alter cloud properties. Furthermore a so-called semi-direct effect, which results of direct aerosol effects, but additionally alters cloud properties is postulated. [Lohmann and Feichter, 2005] As this thesis focuses on consequences of aerosol-cloud-interactions, mainly the indirect and semi-direct aerosol effects are examined. In the following a brief overview of these effects is given.

- **Cloud albedo effect/first indirect effect:** Aerosol particles can act as CCN, leading to a higher CDNC and smaller droplets while cloud liquid water remains constant. [Twomey, 1959] The consequence is a higher scattering cross section which enhances the cloud albedo. [Twomey, 1974]

- **Cloud lifetime effect/second indirect effect:** Smaller cloud droplets may decrease precipitation efficiency leading to a increased cloud lifetime, cloud liquid water path (LWP) and finally higher total cloud cover (TCC). [Albrecht, 1989]

- **Semi-direct effect:** Aerosol may absorb solar radiation and thus increase air temperature. This can lead to evaporation of cloud droplets and partially offset the indirect effects. [Grassl, 1979]

- **Glaciation effect:** Aerosol particles may act as IN in a supercooled cloud, leading to an increase in precipitation via the ice phase an therefore reduced cloud lifetime. This may reduce the TCC and the average cloud optical depth. [Lohmann, 2002]

- **Thermodynamic effect:** Smaller cloud droplets (due to aerosol particles acting as CCN) may delay forming of large droplets, resulting in a delay or suppression of downdrafts and precipitation. Overall updrafts in the cloud may be stronger due to release of latent heat via condensation and damped downdrafts due to suppressed large droplet forming, resulting in increased cloud top height. If the cloud freezes, further latent heat will be released and additionally increase convection. The increased cloud top height will lead to an enhanced cloud greenhouse effect which can be observed as reduced outgoing longwave radiation. [Koren et al., 2005]
2.2 Weekly cycles in literature

As Sanchez-Lorenzo et al. [2012] summarizes, there is a large amount of studies concerning weekly cycles in literature. Whilst previous studies were mostly focused on smaller scales, e.g. urban areas as major sources of emissions, more recent studies examine weekly cycles in different meteorological variables on large-scales. As large-scale weekly cycles cannot be related to urban emissions only, there is the need of different explanation for this climate impact.

There are various studies for regions all over the globe claiming to have found large-scale weekly cycles in observation data. For example Forster and Solomon [2003] analysed global observation data from surface stations and satellite data for a long-time period of 40+ years, finding a weekly cycle in diurnal temperature range for many stations with highest magnitude in North America, but also over China, Japan and Mexico, however showing a different timing of maxima and minima, suggesting weekly cycles might be wide spread but with varying pattern. Gong et al. [2007] found a distinct weekly cycle in aerosol concentrations over urban regions in east China with minimum at midweek and maximum at the weekend, matching with weekly cycles in temperature and wind speed. Kim et al. [2009] found weekly cycles in fraction, insolation and temperature variables over south Korea, speculating this weekly cycles being induced by aerosol-cloud interactions with a weekly cycle due to anthropogenic aerosol emissions. Bäumer and Vogel [2007] claimed for significant weekly cycles in fraction, precipitation and temperature variables, consistent over urban and rural regions in Germany, concluding large-scale weekly cycles cannot be explained by local emissions only. Bäumer and Vogel [2008] found weekly cycles in aerosol optical thickness over Central Europe, demonstrating weekly cycles in the intensity of aerosol effects being likely.

As many studies show positive results for the existence of weekly cycles in me-
terological variables, statistical significance might often be questionable. Hendricks Franssen [2008] doubted significance of Bäumer and Vogel [2007] results, by showing that significant weekly cycles may be obtained by chance. Barmet et al. [2009] analysed station data from Switzerland by testing significance with different statistical techniques. They showed that significance of results obtained by a t-test might be fairly overestimated compared to other statistical tests.

To summarize literature about weekly cycles in observation data it can be said, that there are no consistent results in spatial and temporal patterns, as well as in statistical significance. As aerosol concentration seems to show a weekly cycle on large scales, aerosol-cloud effects are supposed to be responsible for weekly cycles in other variables.

2.3 Modelling anthropogenic cycles

Due to unclear results about large-scale weekly cycles in observation data, modelling this phenomenon can provide important results for understanding. Quaas et al. [2009] used HadGem2 and ECHAM5 GCMs with a modelled weekly cycle in anthropogenic emissions (aerosols and aerosol precursors) to examine if significant weekly cycles in different variables can be obtained (and hence associated to aerosol effects) due to a weekly cycle in human induced pollution. They analysed aerosol concentration, different radiation and cloud variables as well as temperature and precipitation over Europe and compared the model results with a weekly cycle in emissions to a control simulation with constant emissions as well as to ground and satellite based observation data.

They found significant weekly cycles in aerosol concentration, AOD and CDNC in the models that were consistent with observation data from MODIS and showed that a weekly cycle in emissions may lead to such cycles via the first indirect aerosol effect. Satellite data from MODIS satellites showed a weekly cycle in LWP and planetary albedo which might be due to the second indirect aerosol effect, but could not be confirmed by the models results that did not show a distinct weekly cycle compared to the control simulation. For other variables no weekly cycles consistent to observation data and with distinct difference from control simulations were found. They conclude that such observed weekly cycles (e.g. in temperature or precipitation variables) could be accidental.
2.4 Further examination of weekly cycles in models

Natural reasons for a distinct 7-day cycle in meteorological variables are unlikely hence these periodicities are supposed to be anthropogenic. [Forster and Solomon, 2003] As various studies investigating observation data supposed and Quaas et al. [2009] showed, aerosol indirect effects may at least partially trigger such cycles. If it could be achieved to assign such weekly cycles to anthropogenic emissions this could be used to improve quantification of anthropogenic aerosol impact on climate scale. As observation data is already available, mainly further understanding of such cycles is needed to advance this auspicious approach which finally could be used to reduce uncertainty in anthropogenic caused aerosol effects on climate. [Quaas, 2015] Quaas et al. [2009] showed in GCMs a weekly cycle in CDNC respectively the first aerosol effect can be triggered by a weekly cycle in anthropogenic emissions. Significant weekly cycles in further variables were not found.

In this context this thesis is trying to extend Quaas et al. [2009] approach to analyse weekly cycles in a GCM. Therefore a more recent GCM was used to test how long the model simulation must be to get (further) significant results about weekly cycles in cloud and radiation variables that are caused by a weekly cycle in anthropogenic emissions and corresponding aerosol effects. Furthermore it was tested if models are capable to simulate such weekly cycles at all or to affirm such weekly cycles being possibly due to other reasons.
3 Methods

3.1 ECHAM6-HAM2

The GCM used here is ECHAM6 coupled with the comprehensive microphysical aerosol module HAM2. HAM2 provides the simulation of typical aerosol life-cycles with reasonable physical background. Furthermore HAM2 contains parametrisations of aerosol activation and ice nucleation that provide links between aerosol population and the simulated number concentrations of cloud droplets and ice crystals. This makes it possible to simulate the effect of aerosol on clouds and therefore to investigate aerosol direct and indirect effects in the model. For a comprehensive overview over ECHAM-HAM see Stier et al. [2005], for a summary of improvements contained in the new HAM2 see Zhang et al. [2012].

3.2 Model implementation

Two perturbed simulations with a weekly cycle in anthropogenic emissions and length of about 10 years respectively 15 years and a control simulation with a length of about 30 years without a weekly cycle in emissions were carried out in ECHAM6-HAM2 model. The perturbed 10-year simulation and the control simulation were performed with standard aerosol efficiency, the 15-year perturbed simulation was performed with an increased exponent for aerosol efficiency. Each model simulation was performed on a T63 grid and lead by a 3-month spin-up time.

For emissions the ECLIPSE emission data set was used which provides substantial progress compared to older emission data as previously unaccounted types of emission sources were included. [Stohl et al., 2015] The simulations were performed starting at 1. Jan. 1980.

Weekly cycle in emissions

The weekly cycle in anthropogenic emissions was implemented as an increase of about 13% on weekdays and decrease of 33% during weekends of anthropogenic emissions, keeping the weekly average constant. This was done for emissions of sulfur dioxide ($\text{SO}_2$), sulfate ($\text{SO}_4$) black carbon and organic carbon. The code section altering the emissions for a weekly cycle is summarized in listing 3.1. The implementation and the downloaded simulation data was provided by the adviser Prof. Dr. J. Quaas.

There is no diurnal cycle implemented in emissions, which may shorten the weekend effect in the models compared to the real world, as mentioned in Quaas et al. [2009].
[...]  
weekend = .FALSE.
IF ( MOD(iday,7) .eq. 0 .or. MOD(iday,7).eq.1 ) weekend = .TRUE.

[...]  
IF ( weekend ) THEN
   pfactor(idx_mbcki) = pfactor(idx_mbcki)*0.67
   pfactor(idx_nbccki) = pfactor(idx_nbccki)*0.67
ELSE
   pfactor(idx_mbcki) = pfactor(idx_mbcki)*1.132
   pfactor(idx_nbccki) = pfactor(idx_nbccki)*1.132
ENDIF

Listing 3.1: Code section for implementation of the weekly cycle in emissions in ECHAM6-HAM2 model.

Increased aerosol efficiency

To test ECHAM6-HAM2s capability to simulate a distinct weekly cycle in aerosol indirect effects at all, a further 15-year simulation with increased aerosol efficiency for cloud droplet nucleation was carried out. The cloud droplet nucleation $Q_{\text{nucl}}$ in ECHAM-HAM is normally parametrised with the scheme of Lin and Leaitch [1997] as follows:

$$Q_{\text{nucl}} = \max \left[ \frac{1}{\Delta t} \left( 0.1 \left( \frac{N_a w}{w + \alpha N_a} \right)^{1.27} - N_{l,\text{old}} \right), 0 \right]$$

With $N_a$ as the number concentration of the aerosol particles per m$^3$ and wet radius greater than 0.035 $\mu$m, $w$ as the vertical velocity in m s$^{-1}$, $\Delta t$ one timestep, $N_{l,\text{old}}$ the aerosol number concentration from the previous timestep and an empirically obtained constant $\alpha = 0.023$ cm$^{-4}$. [Lohmann et al., 2007] For increasing aerosol efficiency the exponent 1.27 was increased to 5, which is expected to lead to a highly increased CDNC. For analysis the same tests were performed as described on the following pages.
3.3 Data analysis

Analysed region

The region focused here is Europe (35° N – 70° N, 10° W – 30° E), additionally restricting the analysis to land areas to make the results comparable to the study of Quaas et al. [2009]. Further analysis was performed for global land data to examine the effect of a much larger dataset. This is possible as the weekly cycle is implemented with global synchronicity.

![Analysed area](image)

**Figure 3.1:** Grid-boxes (red) from ECHAM T63 output used for analysis of weekly cycles over Europe.

Analysis of weekly cycles

The analysis was performed by first computing a daily average for each grid point out of all available 6h values, second computing an area-weighted average for each day and then analysing a weekly cycle from that data. This was done by averaging the absolute values for each weekday and comparing these results to the absolute weekly average to get relative deviations from the mean. Analysis was performed for aerosol concentration and aerosol optical depth (AOD) as the precondition for further weekly cycles in cloud and radiation variables, CDNC and albedo variables for the first aerosol indirect effect, LWP, TCC and albedo variables for a second aerosol indirect effect and outgoing longwave radiation (OLR) as indicator for a thermodynamic effect.
Significance criteria

To get information about significance, patterns found in the disturbed simulation were compared to the patterns in the control simulation. Furthermore the analysed variables were tested for patterns in hypothetical 6- and 8-day weeks. If patterns in perturbed simulation were clearly more intense and different from patterns in the control simulation and patterns for hypothetical 6- and 8-day periods showed no distinct or far less intense weekly cycles the results were classified as significant.

Filtering data

Most of the here analysed variables are highly affected by frontal zones. Due to the focus on Europe as a region in the mid-latitudes, surpassing frontal zones are a common meteorological condition which may have a significant impact on the analysis results. To reduce this noise in the analysis respectively to improve significance of the results for a general case it was attempted to filter the model-data for only using timesteps or grid points were the effects of frontal zones are low. Therefore different attempts and criteria were defined, using vertical velocity, large scale precipitation and a defined zonal gradient of the 500 hPa geopotential pressure level. These filters are summarized here:

Filtering weather situations:

- Average subsidience: As frontal zones are usually connected to low pressure regions, selecting only timesteps with high pressure influence may decrease the effect of frontal zones in the data. Therefore the updraft motion in low, respectively downdraft motion in high pressure systems was used by calculating an area average of the vertical velocity over land and selecting only timesteps with average downdraft (subsidience).

- Low large scale precipitation: Using ECHAMs large scale precipitation parameter to select only timesteps where the area-average of large scale precipitation is relatively low.

- Low zonal geopotential gradient: As surpassing frontal zones in Europe are often connected to a high zonal gradient in geopotential, a defined criteria for the zonal gradient in geopotential is used. Therefore the differences of zonal maxima and minima are averaged over the analysed region, only timesteps with a low average zonal gradient in geopotential were used for analysis.

Filtering grid-points:

- Subsidience regions: Same background as above but selecting only grid-points with subsidience from each timestep.

- Low or no large scale precipitation: Same background as above but selecting only grid-points without large scale precipitation from each timestep.
4 Results

4.1 Results for European land data

The analysis of European land data was performed after 1, 3, 5 and 10 years to observe the effect on the results by making model simulations longer. The observed patterns after 10 years can be found in figure 4.1, the absolute and relative differences as well as the timing of extrema after 10 years are summarized in table 4.1. For a summary of analysis plots see appendix, A.1. All differences are peak-to-trough differences, percentage changes are relative to the average weekly mean. Comparisons of the perturbed simulation to the control simulation and hypothetical 6- and 8-day weeks are used to classify significance.

For the aerosol precursor SO$_2$ a distinct weekly cycle with maximum during the weekdays and minimum during weekend was found, being time consistent already after one year. SO$_4$ in gas form, which is not implemented with a weekly cycle and therefore simulated by the model, shows a similar weekly cycle being time consistent after one year but with lower amplitude. AOD shows a matching pattern but also a weekly cycle with similar amplitude in the control simulation, that might be noise of the model, as its amplitude gets lower with extending the analysis time period to more than 10 years. As hypothetical 6- or 8-day weeks do not show any clear differences between disturbed and control simulation and the pattern in AOD is consistent with aerosol concentration it is likely that it is triggered by the weekly cycle in emissions. The observed patterns in aerosol concentration and AOD match with Quaas et al. [2009] results but being slightly more realistic now than in their model simulations compared to their analysed observation data. Here ECHAM6-HAM2 shows a weekly cycle in AOD whose minimum is offset about one day resulting in a minimum on Monday and a maximum during the weekend. This fits to the pattern in observation data analysed by Quaas et al. [2009], indicating ECHAM6-HAM2 possibly simulating the aerosol processes time scale better than ECHAM5.

For CDNC a weekly cycle with a clear minimum on Monday and maximum during the second half of the week was found which matches the patterns in concentration and AOD. However the control simulation and hypothetical 6- or 8-day weeks show weekly cycles with similar amplitudes, so significance of a weekly cycle in CDNC can not be claimed. As the observed cycle is time consistent for the minimum on Monday and the maximum during the second half of the week after about 3 years and matches patterns in aerosol concentration and AOD it is likely that it is triggered by the weekly cycle in emissions. This indicates the model simulating the basis for the first indirect effect and further aerosol indirect effects but does not provide more distinct or positive results compared to the 5-year simulation by Quaas et al. [2009].
For a second indirect effect LWP and TCC were analysed. For LWP only a weak weekly cycle was observed even after 10 years and the control simulation shows a weekly cycle with similar amplitude. The comparison to 6- and 8-day periods which also show similar amplitudes, a fast declining amplitude with increasing analysed simulation time and no consistence with the weekly cycle in MODIS observation data in Quaas et al. [2009] study makes it likely that the pattern in LWP is due to noise of the model. For TCC no significant weekly cycle was found, neither a pattern consistent with increasing analysed simulation time nor a clear difference compared to the control simulation or 6- and 8-day periods. As LWP and total cloud cover do not show a distinct weekly cycle over the European land after 10 years of model simulation it can be concluded that even by extending the simulation length to 10 years does not lead to a significant weekly cycle of a second indirect effect in the model.

As aerosol concentration, AOD and CDNC show plausible weekly cycles, the basis for the first indirect effect and a thermodynamic effect is simulated by the model. To examine these effects, radiation variables like total planetary albedo, clear-sky albedo, cloud albedo and OLR were analysed.

For total planetary albedo no significant weekly cycle was found compared to the control simulation and 6- or 8-day weeks. A comparison with the patterns in total cloud cover shows that the patterns in total planetary albedo are likely due to patterns in cloud cover. For clear-sky albedo a weekly cycle with a clear minimum on Tuesday and a maximum during Saturday was found, which matches with the weekly cycle found in AOD. Also the timing of extrema is consistent after 3 years of analysis period and longer. However the control simulation shows a weekly cycle in clear-sky albedo which is congruent to the cycle in AOD. As 6- and 8-day periods also show patterns with similar amplitude, no significance of a weekly cycle in clear-sky albedo can be claimed.

For getting a discrete variable for the cloud brightening due to first indirect effect, cloud albedo was calculated using albedo, clear-sky albedo and cloud fraction. Analysis of cloud albedo shows a clear maximum on Saturday that is time consistent after 3 years of analysis period whereas no clear other extrema nor any intense pattern in the control simulation were observed. Despite of plausibility of an increased cloud albedo during Saturday when CDNC is also high in the model, no significance can be claimed for a weekly cycle in cloud albedo as 6- or 8-day periods do also show clear and even more intense extrema. Consequently no clear indicator for a weekly cycle in cloud brightening due to the first indirect effect was found even after an analysed simulation time of 10 years.

Also for OLR no significant weekly cycle could be observed. There is no pattern being consistent with increasing analysed simulation time and a far more intense
cycle in the control simulation than in the disturbed simulation. Consequently no
weekly cycle in a thermodynamic aerosol effect could be proved by the model after
an analysis period of 10 years.

In summary there were found clear weekly cycles in concentration of directly emitted
and in model aerosol produced aerosols, which show ECHAM6-HAM2s basic capa-
bility to simulate such cycles. Also weekly cycles in AOD and CDNC were found,
but not being significant compared to 6- or 8-day weeks and the control simulation.
This only partially confirms Quaas et al. [2009] results and shows that extending the
model simulation to a 10 year period does not yet lead to more significant results
than already obtained after about 5 years. For further investigation either more
model data should be analysed by either extending the analysis time or extending
the analysed region or data could be filtered to analyse only data with less model
noise.

<table>
<thead>
<tr>
<th></th>
<th>Absolute range</th>
<th>Relative range</th>
<th>Day of max/min</th>
<th>Range disturbed</th>
<th>Range control</th>
<th>Time for significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO\textsubscript{2} emissions</td>
<td>676 (\mu g \text{ m}^{-2} \text{day}^{-1})</td>
<td>46.4%</td>
<td>weekdays/weekend</td>
<td>-</td>
<td>always</td>
<td>-</td>
</tr>
<tr>
<td>SO\textsubscript{2} surf. conc.</td>
<td>0.690 (\mu g \text{ m}^{-3})</td>
<td>42.7%</td>
<td>Fr/Su</td>
<td>9.18</td>
<td>1 month</td>
<td>-</td>
</tr>
<tr>
<td>SO\textsubscript{4} gas surf. conc.</td>
<td>0.0003 (\mu g \text{ m}^{-2})</td>
<td>24.7%</td>
<td>Tu/Su</td>
<td>10.19</td>
<td>1 month</td>
<td>-</td>
</tr>
<tr>
<td>AOD</td>
<td>0.0040</td>
<td>6.27%</td>
<td>Sa/Tu</td>
<td>1.11</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CDNC</td>
<td>4.88 (\text{cm}^{-3})</td>
<td>6.40%</td>
<td>We/Mo</td>
<td>1.12</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>LWP</td>
<td>0.042 mm</td>
<td>4.66%</td>
<td>Sa/Tu</td>
<td>1.16</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total cloud cover</td>
<td>0.0043</td>
<td>0.70%</td>
<td>Th/Sa</td>
<td>0.32</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total planetary albedo</td>
<td>0.0042</td>
<td>1.06%</td>
<td>Th/Tu</td>
<td>0.59</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Clear-sky albedo</td>
<td>0.0008</td>
<td>0.40%</td>
<td>Sa/Tu</td>
<td>1.39</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cloud albedo</td>
<td>0.0202</td>
<td>4.32%</td>
<td>Sa/Tu</td>
<td>5.45</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>OLR</td>
<td>0.229 W m\textsuperscript{-2}</td>
<td>0.10%</td>
<td>Su/Th</td>
<td>0.22</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 4.1:** Summary of results about European land data after simulation time of 10
years. All differences are peak-to-trough differences, percentage changes are
relative to the average weekly mean.
Figure 4.1: Analysed patterns in the perturbed simulation (red) and the control simulation (grey) for cloud and radiation variables over European land after 10 years of analysis time period. Relative deviations are deviations from absolute weekly mean.
4.2 Results for global land data

As analysis of a 10 year time period over European land areas did not show further results than Quaas et al. [2009] obtained with a 5 year period, the analysis area was extended to global land areas. The aim was to examine the effect of using far more data and including the regions where emissions are highest (e.g. China and India) into analysis as well as testing ECHAM6-HAM2’s capability to simulate distinct weekly cycles due to further aerosol indirect effects resulting from a weekly cycle in emissions at all.

The analysis of Global land data was performed as for the European data. The observed patterns after 10 years can be found in figure 4.2, the absolute and relative differences as well as the timing of extrema after 10 years are summarized in table 4.2. For a summary of analysis plots see appendix, A.2.

Aerosol concentration, AOD and CDNC show distinct weekly cycles over global land areas, being highly significant after a maximum of about 2 years compared to the control simulation and 6- or 8-day periods. This confirms once more the models high capability to simulate cycles in basic aerosol processes.

LWP shows a weak weekly cycle with decreasing amplitude while extending the analysis period. Compared to the control simulation which also shows a weekly pattern and 6- or 8-day periods which show pattern with similar amplitude no significance of a weekly cycle can be claimed in global land data. TCC shows a clear weekly cycle in the perturbed simulation, but comparison with 6- or 8-day periods and the control simulation also leads to no significance for this. Since no significant weekly cycles could be observed in LWP and total cloud cover even for the large dataset of global land values and 10 years of analysis time it can be concluded that ECHAM6-HAM2 in the here used configuration can not confirm a weekly cycle due to the second indirect effect caused by a cycle in anthropogenic emissions.

In radiation variables mixed results were found for global land data. Total planetary albedo shows a weak weekly cycle in the perturbed simulation as well as in the control simulation and 6- or 8-day periods and no time consistent pattern. Hence no significance can be claimed. In contrast clear-sky albedo shows a clear weekly cycle in the perturbed simulation with a time consistent pattern with the minimum on Monday and the maximum about Friday. Comparison with the control simulation which only shows a very weak cycle and 6- and 8-day periods leads to significance of the weekly cycle after about 5 years of analysis time. This finding matches with the weekly cycle in AOD, confirming this plausible connection. For the cloud albedo a weak weekly cycle with the minimum on Monday and maximum around Friday was found that possibly matches with the weekly cycle in CDNC. Since the control simulation as well as analysis for 6- or 8-day periods show other pattern with similar amplitudes the weekly cycle can not be classified as significant. Also for OLR results remain negative.
To summarise the results of analysing global data, it can be said that ECHAM6-HAM2 is capable to simulate a clear weekly cycle in aerosol concentration, AOD, CDNC and likely the clear-sky albedo triggered by a weekly cycle in anthropogenic emissions. This confirms that a weekly cycle in emissions can lead to a clearly distinguishable first indirect effect. Significant results can be obtained after about 2 to 5 years of analysis time. For a second indirect effect or a thermodynamic effect no clear indicators were found, not even after 10 years of analysis time of global land data. Since there were no clear time consistent patterns observed in LWP, cloud cover or OLR and patterns with similar amplitudes for 6- and 8-year periods it is unlikely that making model simulations longer (e.g. 20 years) would change the results significantly.

It also has to be noted here that due to first calculating an area-average and thereafter calculating the relative deviations from the weekly mean, results are highly dominated by areas with high variable values at all, which are mostly the areas with high emissions. As the analysis results are much clearer when including these areas, weekly cycles in anthropogenic aerosol concentration and effects seem to show more distinct absolute and relative patterns in the model respectively are better distinguishable from noise when dealing with higher absolute values.

Table 4.2: Summary of results about global land data after simulation time of 10 years.

<table>
<thead>
<tr>
<th></th>
<th>Absolute range</th>
<th>Relative range</th>
<th>Day of max/min</th>
<th>Range disturbed</th>
<th>Time for significance</th>
</tr>
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<tbody>
<tr>
<td>SO$_2$ emissions</td>
<td>908 µg m$^{-2}$ day$^{-1}$</td>
<td>46.2%</td>
<td>weekdays/weekend</td>
<td>-</td>
<td>always</td>
</tr>
<tr>
<td>SO$_2$ surf. conc.</td>
<td>0.932 µg m$^{-3}$</td>
<td>37.8%</td>
<td>Fr/Su</td>
<td>46.6</td>
<td>1 month</td>
</tr>
<tr>
<td>SO$_4$ gas surf. conc.</td>
<td>0.0002 µg m$^{-3}$</td>
<td>20.3%</td>
<td>We/Su</td>
<td>63.9</td>
<td>1 month</td>
</tr>
<tr>
<td>AOD</td>
<td>0.0040</td>
<td>3.90%</td>
<td>Fr/Mo</td>
<td>4.37</td>
<td>1 year</td>
</tr>
<tr>
<td>CDNC</td>
<td>4.56 cm$^{-3}$</td>
<td>5.32%</td>
<td>Fr/Mo</td>
<td>7.90</td>
<td>2 years</td>
</tr>
<tr>
<td>LWP</td>
<td>0.012 mm</td>
<td>1.68%</td>
<td>Tu/Su</td>
<td>2.51</td>
<td>-</td>
</tr>
<tr>
<td>Total cloud cover</td>
<td>0.003</td>
<td>0.47%</td>
<td>Tu/Sa</td>
<td>1.39</td>
<td>-</td>
</tr>
<tr>
<td>Total planetary albedo</td>
<td>0.0004</td>
<td>0.11%</td>
<td>Tu/Su</td>
<td>0.76</td>
<td>-</td>
</tr>
<tr>
<td>Clear-sky albedo</td>
<td>0.0004</td>
<td>0.15%</td>
<td>Fr/Mo</td>
<td>2.39</td>
<td>5 years</td>
</tr>
<tr>
<td>Cloud albedo</td>
<td>0.0018</td>
<td>0.43%</td>
<td>Th/Mo</td>
<td>0.68</td>
<td>-</td>
</tr>
<tr>
<td>OLR</td>
<td>0.231 W m$^{-2}$</td>
<td>0.10%</td>
<td>Tu/Su</td>
<td>0.93</td>
<td>-</td>
</tr>
</tbody>
</table>

To summarise the results of analysing global data, it can be said that ECHAM6-HAM2 is capable to simulate a clear weekly cycle in aerosol concentration, AOD, CDNC and likely the clear-sky albedo triggered by a weekly cycle in anthropogenic emissions. This confirms that a weekly cycle in emissions can lead to a clearly distinguishable first indirect effect. Significant results can be obtained after about 2 to 5 years of analysis time. For a second indirect effect or a thermodynamic effect no clear indicators were found, not even after 10 years of analysis time of global land data. Since there were no clear time consistent patterns observed in LWP, cloud cover or OLR and patterns with similar amplitudes for 6- and 8-year periods it is unlikely that making model simulations longer (e.g. 20 years) would change the results significantly.
Figure 4.2: Analysed patterns in the perturbed simulation (red) and the control simulation (grey) for cloud and radiation variables over global land after 10 years of analysis time period. Relative deviations are deviations from absolute weekly mean.
CHAPTER 4. RESULTS

4.3 Effect of weather situation filters

As frontal zones affect many meteorological variables they might cause noise in analysis. To reduce this noise and possibly get more distinct results over the focused region Europe, filters (as described in chapter 3.3) were applied to filter data which is affected by frontal zones respectively only use data with low influence of frontal zones. The results are summarized in table 4.3 for filtering whole timesteps (i.e. the weather situation) and table 4.4 for filtering single grid points at each timestep. Since the amplitude of weekly cycles mostly increases due to increasing noise with decreasing number of values and a significance test for extrema does not show influence of the filter on the control simulation, a relative indicator is used here. Therefore the relative peak-to-trough differences of perturbed and control simulation were compared. Additionally patterns were analysed if being time consistent. As weekly cycles in AOD, CDNC and clear-sky albedo were found in section 4.1 these parameters were used to verify if filtering weather situations leads to more distinct results.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Processed values</th>
<th>Processed days</th>
<th>Range disturbed / Range control</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>no filter</td>
<td>100 %</td>
<td>100 %</td>
<td>1.4</td>
<td>1.38</td>
</tr>
<tr>
<td>low large scale precip.</td>
<td>25.8 %</td>
<td>38.1 %</td>
<td>1.0</td>
<td>2.46</td>
</tr>
<tr>
<td>grad geopoth &lt; 100 gpm</td>
<td>21.7 %</td>
<td>29.1 %</td>
<td>2.5</td>
<td>2.93</td>
</tr>
<tr>
<td>grad geopoth &lt; 125 gpm</td>
<td>39.5 %</td>
<td>49.0 %</td>
<td>2.0</td>
<td>2.32</td>
</tr>
<tr>
<td>grad geopoth &lt; 150 gpm</td>
<td>57.0 %</td>
<td>65.4 %</td>
<td>1.1</td>
<td>2.77</td>
</tr>
<tr>
<td>omega &gt; 0 Pa s^{-1}</td>
<td>54.1 %</td>
<td>77.5 %</td>
<td>1.5</td>
<td>1.69</td>
</tr>
<tr>
<td>omega &gt; 0.01 Pa s^{-1}</td>
<td>37.7 %</td>
<td>59.3 %</td>
<td>1.4</td>
<td>0.87</td>
</tr>
</tbody>
</table>

Table 4.3: Summary of filters for selecting weather situations for analysis and results for AOD, CDNC and clear-sky albedo. Filters are marked as + (auspicious), o (no improvement) and – (negative).

For filtering whole timesteps the results are mixed. Using timesteps with almost no large scale precipitation improves results for CDNC but leads to high amplitudes in the control simulation. Filtering the data via the defined geopotential gradient mostly leads to more distinct differences between perturbed and control simulation, as mainly the amplitude of the weekly cycle in the control simulation decreases whereas the amplitude in the perturbed simulation decreases little. For using only timesteps with average subsidence (omega > 0) no positive results were found. Furthermore it has to be considered that using less data makes distortions more likely. Using much more rigorous filters than summarized in table 4.3 did lead to high noise and no improvements in results.
Grid point filters

<table>
<thead>
<tr>
<th>Filter</th>
<th>Processed values</th>
<th>Processed days</th>
<th>Range disturbed / Range control</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>no filter</td>
<td>100 %</td>
<td>100 %</td>
<td>1.4 / 1.38</td>
<td>1.4</td>
</tr>
<tr>
<td>no large scale precip.</td>
<td>73.2 %</td>
<td>100 %</td>
<td>1.4 / 1.33</td>
<td>o</td>
</tr>
<tr>
<td>$\omega &gt; 0 \text{ Pa s}^{-1}$</td>
<td>56.7 %</td>
<td>100 %</td>
<td>1.5 / 1.24</td>
<td>o</td>
</tr>
<tr>
<td>$\omega &gt; 0.1 \text{ Pa s}^{-1}$</td>
<td>16.1 %</td>
<td>99.7 %</td>
<td>2.5 / 2.33</td>
<td>+</td>
</tr>
</tbody>
</table>

Table 4.4: Summary of filters for selecting gridpoints with certain conditions for analysis and results for AOD, CDNC and clear-sky albedo. Filters are marked as + (auspicious), o (no improvement) and – (negative).

For filtering grid points at every timestep the results are more auspicious than for filtering whole timesteps. Using only data from grid points with no large scale precipitation also does not improve results significantly, but using only grid points with subsidience clearly reduces the amplitude of weekly cycles in the control simulation.

To summarize the effects of data filters it can be concluded that filtering timesteps via the defined gradient of geopotential and filtering grid points with subsidience significantly decreased noise in AOD, CDNC and clear-sky albedo which is probably due to reduced influence of frontal zones in data. It has to be noted here that filtering data via averaging and selecting values compared to a single constant also leads to focus on seasons as e.g. the defined geopotential gradient or omega show an annual cycle in area averaged values. Hence the attempt to reduce influence of frontal zones to examine a more general case might lead to a focus on seasons.
CHAPTER 4. RESULTS

4.4 Increased aerosol efficiency

As analysis of global land data showed a clear weekly cycle in CDNC but no weekly cycles due to further aerosol indirect effects, a 15-year simulation with a weekly cycle in anthropogenic emissions and increased aerosol efficiency was carried out to test if a highly increased amplitude and probably range of CDNC may lead to weekly cycles due to further indirect effects at all. Analysis was performed for European and global land data, all differences are peak-to-trough differences, percentage changes are relative to the average weekly mean. Summary of analysis results can be found in figure 4.3 and table 4.5, comprehensive plots for increasing analysed simulation time and comparison with 6- and 8-day periods can be found in appendix, figure A.3.

Aerosol concentrations show patterns similar to simulation with normal aerosol efficiency, indicating the model simulating similar conditions of aerosol life-cycles and concentration and providing the precondition for further indirect effects. CDNC shows a highly increased total mean value (+7.53 \cdot 10^{12}\%) and increased relative range of 24.6\% (+285\%) compared to the simulation with normal aerosol efficiency, but no clear weekly cycle.

For LWP, TCC, total planetary albedo, clear-sky albedo and cloud albedo increased absolute mean values were found, for OLR decreased values were found compared to the simulation with normal aerosol efficiency. The relative weekly range of LWP and OLR is clearly increased compared to the simulation with normal aerosol efficiency and the control simulation (which also uses normal aerosol efficiency), indicating increased CDNC leading to increased variable values due to more intense indirect effects. For other cloud and radiation variables a decreased relative weekly range was observed, supposing increased CDNC not having a large impact on weekly cycle in this variables. Only clear-sky albedo and LWP show consistent weekly cycles after different analysis time periods and a pattern as expected. However the relative range of these cycles is lower than the relative range of patterns in the control simulation.

In summary it has to be concluded that an increased aerosol efficiency leads to a highly increased CDNC in the model but without a distinct weekly cycle. Mean values of further cloud and radiation variables were clearly altered as expected for indirect aerosol effects, indicating the model simulating these indirect effects. As further cloud and radiation variables did not show distinct weekly cycles, it can be concluded that the model (in the here used configuration) currently can not confirm a weekly cycle in anthropogenic emissions lead to weekly cycles triggered by further indirect effects. As the parametrisation of cloud droplet nucleation in ECHAM6-HAM2 is a formula dependent on aerosol concentration but also vertical velocity it may be possible that noise in vertical velocity may be amplified and prevent a distinct weekly cycle in CDNC. Further examination of the unclear weekly pattern in CDNC should be provided as it is different than expected from analysis of simu-
lations with normal aerosol efficiency. Nevertheless increasing the aerosol efficiency could be useful for simulating generally stronger aerosol effects.

<table>
<thead>
<tr>
<th></th>
<th>Absolute range</th>
<th>Relative range</th>
<th>Day of max/min</th>
<th>Absolute mean change</th>
<th>Relative range change</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO$_2$ emissions</td>
<td>676 µg m$^{-2}$ day$^{-1}$</td>
<td>46.2%</td>
<td>weekdays/weekend</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SO$_2$ surf. conc.</td>
<td>0.534 µg m$^{-3}$</td>
<td>41.6%</td>
<td>Th/Su</td>
<td>-20.4%</td>
<td>-2.77%</td>
</tr>
<tr>
<td>SO$_4$ gas surf. conc.</td>
<td>0.0002 µg m$^{-3}$</td>
<td>26.6%</td>
<td>Tu/Su</td>
<td>-26.4%</td>
<td>+7.69%</td>
</tr>
<tr>
<td>AOD</td>
<td>0.0037</td>
<td>4.00%</td>
<td>Th/Mo</td>
<td>+44.7%</td>
<td>-36.2%</td>
</tr>
<tr>
<td>CDNC</td>
<td>1.41 $\cdot$ 10$^{12}$ cm$^{-3}$</td>
<td>24.6%</td>
<td>Su/Tu</td>
<td>+7.53 $\cdot$ 10$^{12}$%</td>
<td>+285%</td>
</tr>
<tr>
<td>LWP</td>
<td>0.223 mm</td>
<td>7.48%</td>
<td>Sa/Mo</td>
<td>+234%</td>
<td>+60.6%</td>
</tr>
<tr>
<td>Total cloud cover</td>
<td>0.0023</td>
<td>0.30%</td>
<td>Th/Mo</td>
<td>+20.8%</td>
<td>-56.6%</td>
</tr>
<tr>
<td>Total planetary albedo</td>
<td>0.0034</td>
<td>0.64%</td>
<td>Th/Mo</td>
<td>+33.0%</td>
<td>-39.7%</td>
</tr>
<tr>
<td>Clear-sky albedo</td>
<td>0.0006</td>
<td>0.26%</td>
<td>Fr/Mo</td>
<td>+4.37%</td>
<td>-35.6%</td>
</tr>
<tr>
<td>Cloud albedo</td>
<td>0.016</td>
<td>2.66%</td>
<td>Fr/Mo</td>
<td>+26.6%</td>
<td>-38.5%</td>
</tr>
<tr>
<td>OLR</td>
<td>0.365 W m$^{-2}$</td>
<td>0.17%</td>
<td>Th/Mo</td>
<td>-2.39%</td>
<td>+63.5%</td>
</tr>
</tbody>
</table>

Table 4.5: Summary of analysis results over European land for the simulation with increased aerosol efficiency. Values are for analysis after 15 years of simulation time, all differences are peak-to-trough differences, percentage changes are relative to the average weekly mean respectively relative to the simulation with normal aerosol efficiency after 10 years.
Figure 4.3: Analysed patterns in the perturbed simulation with increased aerosol efficiency (red) and the control simulation with normal aerosol efficiency (grey) for cloud and radiation variables over European land after 15 years of analysis time period. Relative deviations are deviations from absolute weekly mean.
5 Conclusions

In this study ECHAM6-HAM2 model simulations with a weekly cycle in anthropogenic emissions were analysed to examine if longer simulations than already performed by Quaas et al. [2009] would lead to further significant results about weekly cycles in indirect aerosol effects. For the focused region of Europe land areas distinct weekly cycles were only found in aerosol concentration. For AOD and CDNC consistent weekly cycles were observed, but with similar amplitude as the control simulation with constant emissions per week. For further aerosol indirect effects triggered by a weekly cycle in anthropogenic emissions no distinct indicators were found.

Extension of analysis area to global land and therefore including of regions where emissions are highest lead to distinct results about significant weekly cycles in aerosol concentration, AOD, CDNC and likely the clear-sky albedo. For further indirect aerosol effects no distinct indicators were found in global land data.

To reduce noise in European land data possibly caused by frontal zones in the mid-latitudes, it was tested if filtering data to situations with low influence of frontal zones would lead to significant results about CDNC, the clear-sky albedo and possibly further indirect effects. Comparing results of filtered simulations to unfiltered, including only grid-points with subsidence or including only timesteps with a low zonal gradient in geopotential height may be auspicious to reduce noise caused by frontal zones.

As results about simulations using normal aerosol efficiency did not provide conclusions about further indirect effects, a simulation with highly increased aerosol efficiency was analysed. Therefore a clear absolute increase but without distinct weekly cycles was found for CDNC, LWP, TCC and albedo variables, indicating the model simulating indirect aerosol effects but not confirming these effects showing distinct weekly cycles.

Finally it can be concluded that extending model simulations to 10 years currently can not confirm a weekly cycle in anthropogenic emissions lead to distinct further indirect effects except in CDNC. As the 15 year simulation with increased aerosol efficiency shows altered variable values but no such weekly cycles, it can be supposed that either the model can not simulate such cycles or positive results about weekly cycles in observation data may be accidental and not caused by a weekly cycle in anthropogenic emissions. Further understanding of underlying processes is needed to answer this question.

As this study can not provide further positive results on weekly cycles due to indirect aerosol effects than obtained by Quaas et al. [2009] it currently may be more auspicious to focus on other approaches to better quantify anthropogenic extend of aerosol effects. As there are e.g. positive results in models about distinguishable aerosol effects caused by anthropogenic pollution on shipping routes [Peters et al.,
2012], this approach currently seems to be more auspicious quantifying aerosol ef-
fefects than further investigation on less-understood and possibly accidental weekly
cycles in cloud and radiation variables.
Bibliography


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A Appendix

A.1 Complete plots for analysis over European land

SO₂ concentration

SO₄ gas concentration

AOD

CDNC

LWP
Figure A.1: Analysed patterns in the perturbed simulation (red) and the control simulation (grey) for cloud and radiation variables over European land after 3, 5 and 10 years of model simulation and patterns for hypothetical 6- and 8-day weeks after 10 years of model simulation. Relative deviations are deviations from absolute weekly mean.
A.2 Complete plots for analysis over global land

**SO₂ concentration**

- 3 years
- 5 years
- 10 years
- 6 day period
- 8 day period

**SO₄ gas concentration**

- 3 years
- 5 years
- 10 years
- 6 day period
- 8 day period

**AOD**

- 3 years
- 5 years
- 10 years
- 6 day period
- 8 day period

**CDNC**

- 3 years
- 5 years
- 10 years
- 6 day period
- 8 day period

**LWP**

- 3 years
- 5 years
- 10 years
- 6 day period
- 8 day period
Figure A.2: Analysed patterns in the perturbed simulation (red) and the control simulation (grey) for cloud and radiation variables over global land after 3, 5 and 10 years of model simulation and patterns for hypothetical 6- and 8-day weeks after 10 years of model simulation. Relative deviations are deviations from absolute weekly mean.
A.3 Plots, increased aerosol efficiency simulation

**SO$_2$ concentration**

- 3 years
- 5 years
- 15 years
- 6 day period
- 8 day period

**SO$_4$ gas concentration**

- 3 years
- 5 years
- 15 years
- 6 day period
- 8 day period

**AOD**

- 3 years
- 5 years
- 15 years
- 6 day period
- 8 day period

**CDNC**

- 3 years
- 5 years
- 15 years
- 6 day period
- 8 day period

**LWP**

- 3 years
- 5 years
- 15 years
- 6 day period
- 8 day period
Figure A.3: Analysed patterns in the perturbed simulation with increased aerosol efficiency (red) and the control simulation (grey) for cloud and radiation variables over European land after 3, 5 and 10 years of model simulation and patterns for hypothetical 6- and 8-day weeks after 10 years of model simulation. Relative deviations are deviations from absolute weekly mean.
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Kilian Franz Hermes