Aerosols and their seasonal variability - Are aerosols important for seasonal prediction?

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Abstract

This paper provides a short overview of aerosol particles in the atmosphere and their potential effects on weather and climate. Atmospheric aerosol particles display a large spatial and temporal variability and the aerosol con- centration is also strongly dependent on meteorological parameters such as clouds, precipitation and wind. In seasonal forecasting, aerosol particles have so far not been treated in great detail, and the importance of includ- ing temporal and spatial variations in the aerosol concentration is therefore not known. Some examples of the influence of changes in the atmospheric aerosol particle concentration on large-scale circulation, precipitation and surface temperature from climate-related applications are given here. It is shown that aerosol particles may affect tropical precipitation and thereby also extratropcial stationary waves and the surface temperature distribution. The atmospheric aerosol concentration may also influence large-scale circulation systems such as the Indian Monsoon, the Hadley circulation and the Walker circulation.

1 Introduction

An aerosol is a suspension of small solid and/or liquid particle in a gas (air). Aerosol particles can be both natural and anthropogenic with a size ranging from a few nanometers up to tenths of micrometers (Pöschl, 2005). Depending on the source, aerosol particles are typically divided into two categories; primary and secondary. Primary particles are either mechanically generated (wind-blown dust, sea salt, pollen) or emitted directly into the atmosphere through biomass burning, incomplete combustion of fossil fuels and volcanic eruptions. Secondary particles are formed through gas-to-particle conversion, e.g. sulfuric acid condensing into sulfate. The typical chemical components of an atmospheric aerosol are sulphate, nitrate, ammonium, sea salt, mineral dust, organic compounds and black carbon (soot). The atmospheric aerosol typically also contains water, where the water content is dependent on the chemical composition, the size of the aerosol and the relative humidity of the atmosphere.

Aerosol particles affect weather and climate, directly through scattering and absorbing solar radiation and indirectly through acting as cloud condensation nuclei and ice nuclei, thereby altering the micro- physical and radiative properties of clouds (cf. Figure 1). The global average anthropogenic aerosol effect has been estimated to be -1.2 $W\,m^{-2}$, but with a large uncertainty ranging from -0.4 to -2.7 $W\,m^{-2}$ (Forster et al., 2007). This means that anthropogenic aerosols may have masked some of the warming due to enhanced greenhouse gases during the 20th century. A number of potential effects of aerosol particles on cloud formation (e.g. aerosol effects on ice cloud formation) are also not included in the IPCC estimate.

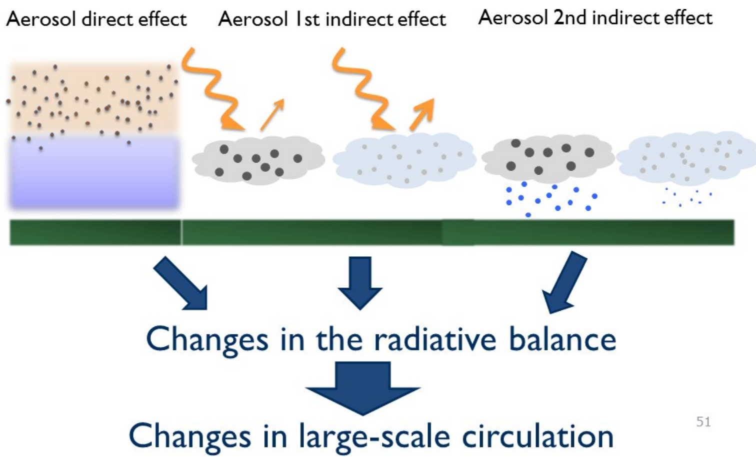

Figure 1: Illustration of aerosol direct and indirect effects. An increased amount of absorbing or scattering aerosols reduces the amount of radiation reaching the ground (left figure). An increased amount of aerosols results (for a constant liquid water content) in an increased number of droplets (middle figure) and a reduced precipitation efficiency (right figure).

There are a few important differences between aerosol particles and greenhouse gases and their respective climate effects:

- *The time evolution of the emissions*. The atmospheric greenhouse gas concentration has increased steadily during the 20th century, whereas the increase in anthropogenic aerosol particle emissions and aerosol precursors is non-linear Lamarque et al. (2010).
- *The strong coupling between aerosols and meteorology*. Aerosol particles can affect weather and climate, but changes in meteorological parameters (winds, temperature, cloudiness, precipitation) are also very important for the distribution of atmospheric aerosols. For example, the most impor- tant removal process of aerosol particles from the atmosphere is precipitation scavenging.
- *The residence time in the atmosphere*. Aerosol particles only stay in the atmosphere for days or weeks resulting in a more uneven distribution pattern compared to greenhouse gases (cf. Figure 2).

- *The location and type of aerosol emissions has changed*. Until 1970-1980, most of the anthro- pogenic aerosols were emitted in Europe and North America. During the last 30-40 years, emis- sion sources have shifted to the tropics and more absorbing aerosol particles (soot) are emitted Lamarque et al. (2010).

These factors imply that the radiative forcing pattern due to anthropogenic aerosols have been highly unevenly distributed in space and time during the 20th century. In addition, due to the short atmospheric residence time, changes in aerosol particle emissions result in an almost immediate response of the radiative forcing pattern.

2 Aerosol particles and their effect on circulation and precipitation

As anthropogenic aerosols exert a highly asymmetric forcing on the climate system, it gives reason to believe that the response to the aerosol forcing will also be highly asymmetric. However, although the net effect of increased aerosol concentrations is a global cooling, the resulting spatial distribution of temperature change does not necessarily show a strong resemblance of the radiative forcing pattern (e.g. Boer and Yu, 2003). To explain the difference, dynamical effects, caused by the inhomogeneous radiative forcing of aerosols, have to be taken into account (cf. Figure 1). The dominance of anthropogenic aerosol emissions in the northern hemisphere has been shown to cause a more or less general hemispheric-wide temperature change (Bollasina et al., 2011; Ming and Ramaswamy, 2011, 2009; Wang, 2007; Allen and Sherwood, 2010; Chung, 2005). As a response to this altered inter-hemispheric temperature gradient, tropical convective precipitation anomalies are generated due to a shift of the ITCZ (Inter-Tropical Convergence Zone). In addition to the zonally symmetric response, a few studies have also documented effects of aerosols on the climatological stationary wave pattern (Ming et al., 2011; Rodwell and Jung, 2008; Allen and Sherwood, 2010). Stationary planetary waves are features of the circulation which could explain the occurrence of anomalies far from the location of an initial perturbation. Latent-heat release in tropical deep convective clouds is a major diabatic heat source in the atmosphere. Tropical heating is also well-known to excite waves propagating into the extratropics (e.g. Held et al., 2002).

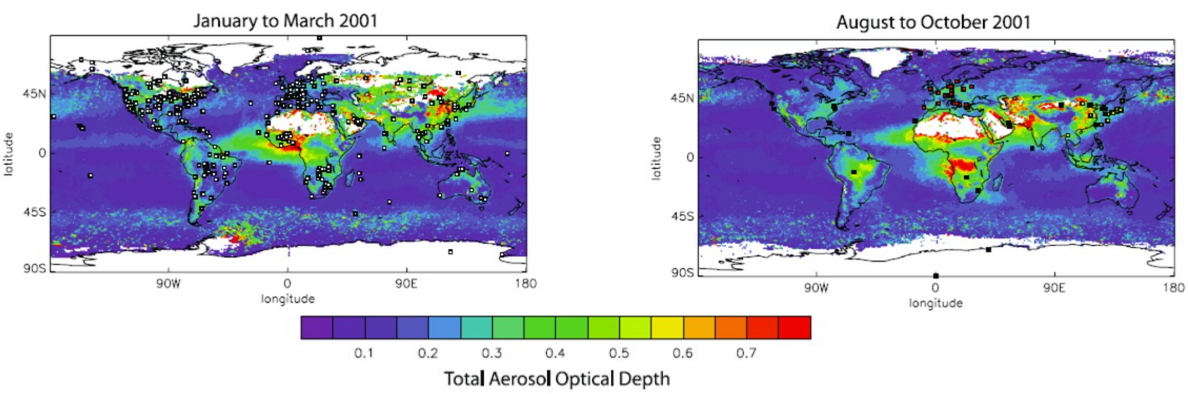

Figure 2: Aerosol optical depth (AOD) at 550 nm as determined by the MODIS instrument for the January to March 2001 mean (left panel) and for the August to October 2001 mean (right panel). From Forster et al. (2007).

The importance of considering changes in aerosol concentrations in seasonal forecasting is not well known. Rodwell and Jung (2008) concluded that when a more realistic aerosol climatology was introduced into the ECMWF Integrated Forecasting System, the local medium-range forecast skill was improved and seasonal-mean errors (in e.g. wind and temperature) were reduced throughout the globe. Boer (2009) showed that trends in several climate variables (surface temperature, 850hPa temperature and 500hPa geopotential) were stronger in the NCEP reanalysis data than in their deterministic forecasts (from the Canadian Meteorological Centre) and suggested that this may be an effect of not considering changes in greenhouse gas concentrations and aerosol particles in their seasonal forecasts. In the following, some examples are given regarding the potential importance of aerosol particles in influencing large-scale circulation, temperature and precipitation patterns.

2.1 Aerosol particles and the weakening of the South Asian summer monsoon

During the recent years, there have been a number of studies showing the potential influence of anthropogenic aerosols on the South Asian summer monsoon. Most of these studies focus on the direct effect of increased amounts of soot particles and suggest that an increase in atmospheric soot concentrations increases the heating of the atmosphere, reduces the radiation at the ground and weakens the temperature gradient between the northern and southern Indian Ocean. This change in temperature gradient may in turn either displace and/or affect the strength of the monsoon (Lau and Kim, 2006; Meehl et al., 2008; Ramanathan et al., 2005). Wang et al. (2009) also examined the direct effect of anthropogenic soot aerosols on the Indian summer monsoon, but pointed out that it is the change in moist static energy in sub-cloud layers (induced by the anomalous warming of the soot) that may alter the location and the strength of the monsoon.

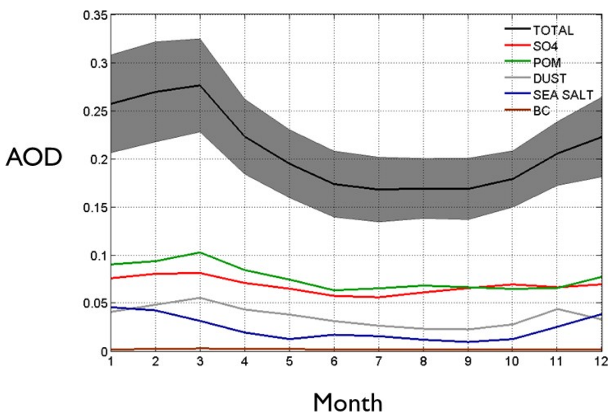

Figure 3: Simulated monthly mean AOD over Asia (10-70° N, 50-120° E) using the CAM-Oslo model coupled to a slab ocean. 40 years of simulation is used for the analysis and the gray shaded area shows the year-to-year variability in AOD.

The tropical circulation (in particular its zonal component) is expected to weaken in response to a warmer climate, e.g. due to enhanced atmospheric greenhouse gas concentrations. The reason is that the global mean precipitation, controlled by the atmospheric energy balance, cannot increase as fast as the lower tropospheric water vapor concentration (thermodynamical scaling argument, e.g. Held and Soden, 2006). Bollasina et al. (2011) concluded that the same type of scaling argument is valid for the cooling induced by anthropogenic aerosols, i.e. that an increase in aerosol concentrations slows down the tropical (zonal) circulation. Their study did not only focus on soot aerosols, but considered all types of aerosols and both aerosol direct and indirect forcing. In their model simulations, Bollasina et al. (2011) also noted a slowdown of the tropical atmospheric meridional overturning circulation, which was caused by the inhomogeneous aerosol-induced forcing of the southern and northern hemisphere. In other words, Bollasina et al. (2011) argued that a decrease of the Indian monsoon precipitation was to be considered as a global-scale circulation adjustment to an asymmetrical forcing.

Figure 3 displays the simulated annual variability of aerosol optical depth (AOD) over Asia using the CAM-Oslo model (Seland et al., 2008) coupled to a slab ocean. For the pre-monsoon month of May, the AOD may vary between 0.15 and 0.24, i.e. it may deviate from the monthly mean by approximately 25%. The large year-to-year variability may important for simulating the correct location and magnitude of the Indian summer monsoon.

2.2 Aerosol particles and changes in extra-tropical stationary wave patterns

As illustrated in the previous subsection, aerosol particles, through their direct and indirect effects, have a potential of altering the location and strength of tropical precipitation [cf. also](Chen and Ramaswamy, 1996; Ramaswamy and Chen, 1997; Chung et al., 2002; Rotstayn and Lohmann, 2002; Wang, 2004; Allen et al., 2012). Lewinschal et al. (2012) examined the role of aerosol-induced tropical precipitation changes in modifying northern hemisphere wintertime (DJF) stationary waves. The fully coupled ocean-atmosphere general circulation model EC-Earth (Hazeleger et al., 2010) was forced with aerosol concentrations representing pre-industrial (1850) and present-day values (2000), respectively. Only aerosol direct effects were considered which resulted in a global average radiative forcing and temperature response of -0.13 $W\,m^{-2}$ and -0.005 K, respectively. Figure 4 shows that the simulated temperature response pattern bears little resemblance with the radiative forcing pattern. However, when comparing the change in geopotential at 300 hPa with the 2m temperature response, the correlation was found to be rather high (0.5 using data between 0 and 70° N). Lewinschal et al. (2012) demonstrated that the main features of the wave pattern of EC-Earth could be replicated by a linear, baroclinic model forced with latent heat changes corresponding to the anomalous convective precipitation generated by EC-Earth. In other words, the tropical latent heat release was shown to be an effective means of generating stationary wave trains that propagate into the extratropics. These results corroborate the findings by Ming et al. (2011).

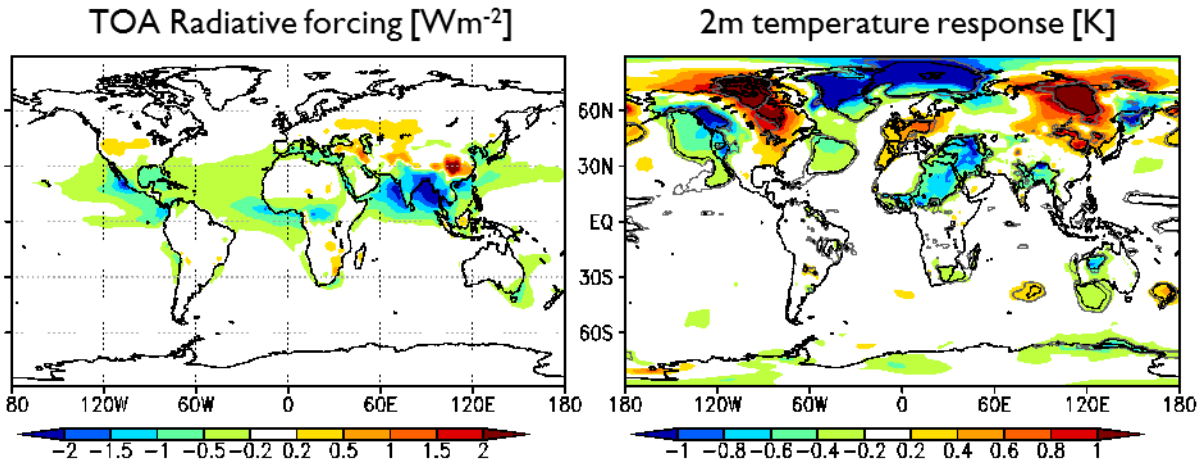

Figure 4: Simulated (EC-Earth) DJF top-of-the-atmosphere (TOA) radiative forcing and 2-m temperature response comparing present-day and pre-industrial aerosol concentrations. An average over 40 years of simulation is considered. Gray contours indicate statistical significance at the 90% confidence level using a 2-sided Student's t-test. From Lewinschal et al. (2012)

3 Aerosol particles and the large-scale surface temperature distribution

The results of Lewinschal et al. (2012), as well as earlier studies by e.g. Boer and Yu (2003), displaying a poor agreement between the pattern of aerosol forcing and temperature response, provokes the question: are local effects of aerosol particles on surface temperature possible to distinguish at all? Several studies have indicated a relation between clear-sky surface solar radiation (SSR) and aerosol particle concentrations, but finding an anthropogenic aerosol signal in all-sky SSR and surface temperature has provided more difficult (Zubler et al., 2011; Folini and Wild, 2011; Kambezidis et al., 2012). One issue with the study by Lewinschal et al. (2012), as well as with several of the modeling studies mentioned earlier, is that only direct aerosol effects were considered and that the interaction between aerosols and meteorology were treated in a very simplified manner. Since the 1970's, there has been a rapid change in the magnitude and spatial distribution of anthropogenic aerosol particle and precursor emissions with a significant decrease over e.g. Europe and North America and a substantial increase over large parts of Asia (Lamarque et al., 2010). To examine if the shift in aerosol emissions between 1970 and present day results in a clear fingerprint in the modeled atmospheric circulation and temperature change pattern, the global climate model CAM-Oslo (Seland et al., 2008) was utilized. CAM-Oslo includes a comprehensive module of the atmospheric aerosol cycle as well as parameterizations of the direct and indirect effects of aerosol particles on radiation, cloud reflectivity and precipitation.

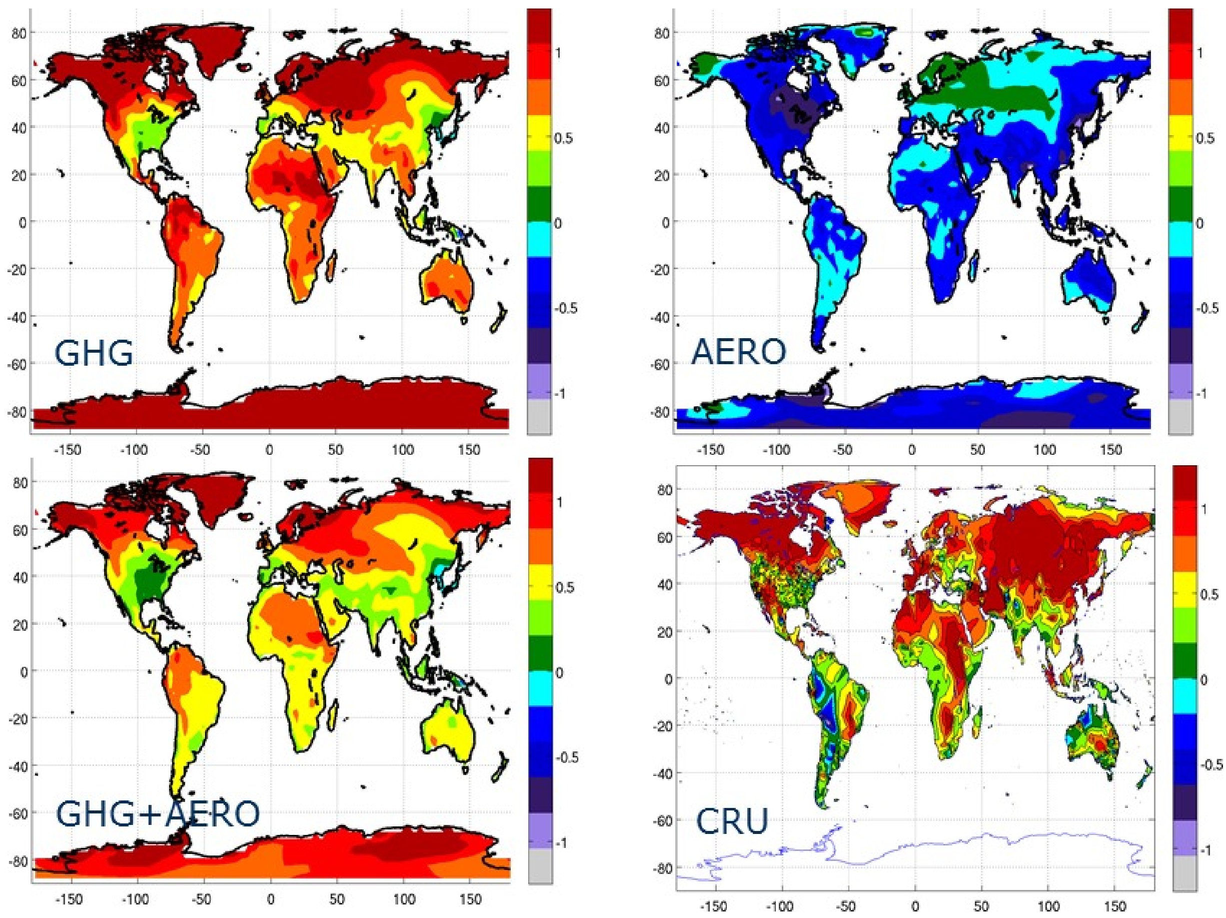

Figure 5: Simulated (CAM-Oslo) surface temperature change (K) comparing an average of 40 years of equilibrium simulations for the years 2000 and 1970. The simulations include changes in greenhouse gas concentrations (GHG), aerosol emissions (AERO) and both greenhouse gas concentrations and aerosol emissions (GHG+AERO), respectively. The observed (CRUTS3.1) surface temperature change, comparing averages over the periods 1995-2004 and 1965-1974, is also displayed.

Figure 5 displays the simulated surface temperature change over land comparing the year 2000 and 1970 for different versions of the CAM-Oslo model (including or excluding greenhouse gas and aerosol emission changes). Observations from the CRUTS3.1 record (Mitchell and Jones, 2005) are also shown for comparison. Focusing on the northern hemisphere, were the aerosol effects should be most pronounced, the simulated pattern of surface temperature change is very similar in all simulations. The spatial cor- relation (r) between the simulation including only changes in greenhouse gas emissions (GHG) and the one including only changes in aerosol particle emissions (AERO) is 0.38 for the northern hemisphere. The patterns are most similar over Europe (r=0.78), whereas there is a larger discrepancy over Asia (r=0.55) and North America (r=0.16). The northern hemisphere spatial correlation comparing the simulation GHG with the simulation including changes in both greenhouse gas emissions and aerosol particle emissions (GHG+AERO) is very high (r=0.96). However, there are some notable differences, for ex- ample over Southern Asia where the temperature increase is substantially lower in GHG+AERO than in GHG. Nevertheless, the three simulations GHG, AERO and GHG+AERO illustrate why an aerosol effect on surface temperature may be difficult to distinguish in long-term observations. In CAM-

Oslo, it appears as the mean response of the climate system to an enhanced forcing more or less directly projects onto the pre-existing natural modes of variability (Palmer, 1999) and/or that the surface temperature response to aerosol forcing is mostly governed by local feedbacks (Boer and Yu, 2003).

4 Conclusions

Aerosol particles in the atmosphere display a high temporal and spatial variability, i.e. there is a possibility for fast, relatively localized, changes in forcing and temperature response. During the 20th century, it is likely that changing aerosol particle concentrations have affected large-scale circulation systems such as the Indian monsoon, the Hadley circulation and the Walker circulation. Changes in the aerosol particle concentration and composition may also affect (directly and indirectly) tropical precipitation (location and intensity), generating wave trains propagating into the extratropics. The resulting change in extratropical stationary waves may in turn influence the surface temperature distribution.

Although the examples given here are on time scales relevant for climate applications, the underlying processes should also be valid for the time scales of seasonal prediction. In general, anthropogenic aerosol effects on weather and climate are poorly known. Including a more realistic treatment of aerosol particles in a seasonal forecasting system may not only improve the seasonal forecast, but it may also provide us with important information regarding the climate effects of aerosols.

Acknowledgments

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