Visibility measurements in De Bilt and Schiphol.

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"Cleaner air in Europe brings better views, more sunshine and warmer temperatures"

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Grand Canyon "hazy" Desert View at sunset. Will this view improve in the future? © A.J. van Beelen

Content

1. Introduction.

1.1 Introduction.

This report describes and compares the visibility measurements at two locations in the Netherlands. The World Meteorological Organization (WMO) defines visibility as "the greatest distance at which a black object of suitable dimensions (located on the ground) can be seen and recognized when observed against the horizon sky during daylight or could be seen and recognized during the night if the general illumination were raised to the normal daylight level" (*WMO, 1992a*).

In the past, visibility was "measured" by an actual observer looking at targets located at a certain distance. This is a somewhat subjective way of defining visibility, because one observer might have a better vision than another. A way of standardizing these observations is commonly used to increase objectivity. More recently, visibility has also been measured with transmisso- and scatterometers. These measurements are more objective, but still one has to correct them to be able to be comparable to what the "standard" human eye can see. Some more details about how visibility is actually obtained will be discussed in this report.

So why do we measure the visibility? Visibility is of great importance for aeronautical purposes, especially during take off and landing. Also other means of transportation have great interest in visibility. Dense fog can lead to serious traffic accidents, and advance warnings can make drivers aware of the danger and save lives.

The frequency of low visibility events has been observed to change. For example, *Vautard et al. (2009)* observed a substantial decrease in low visibility and foggy days in Europe between 1978 and 2006. This study however will focus on days with large visibility. Though this might seem of little importance (who cares if the visibility is 20 or 30 km?) at first, it is important to keep in mind that if the visibility is reduced, this will imply that sunlight is scattered or absorbed, with possibly large (regional) effects on climate (e.g. "global dimming"), such as temperature, sunshine duration and cloudiness, but also precipitation and evaporation. Besides meteorological consequences, a change in surface solar radiation can also have a large effect on the biosphere. All life is ultimately dependent on solar radiation and water, and changes in both can have profound effects.

Visibility is roughly determined by the aerosol (small suspended particles from both natural and anthropogenic sources) burden and humidity near the surface. More aerosols will decrease the visibility. High (> 90%) relative humidity can lead to water absorption of hygroscopic aerosols, increasing their diameters by as much as a factor four and thus decreasing visibility (a "haze"). Relative humidity near saturation will lead to condensation of water vapor and foggy conditions, reducing visibility even further. Precipitation will also strongly reduce visibility. The frequency of high visibility days could well be a better proxy for aerosol changes, because it is less influenced by changes in relative humidity and precipitation.

In an article in Meteorologica *Van Delden (2009)* noted that there seemed to be a large increase in the frequency of high (>30 km) visibility days since 1985 at de Bilt, the Netherlands. This study compares measurements conducted at the site of the Dutch national weather center (KNMI) in de Bilt, located in the center of the Netherlands, with measurements made at Schiphol, the largest airport in the Netherlands, approximately 40 km away. We will see if the same results are obtained for Schiphol. Also, we will take a quick look into a few parameters (e.g. humidity, wind direction, aerosol concentrations) which might have caused the visibility changes and see if we can find a response (e.g. changes in average temperature, temperature range, cloudiness, sunshine duration) to this event, consistent with basic physical assumptions. Finally, we will also take a look at how the measurements have actually been obtained at de Bilt and Schiphol. It would be rather inconvenient to attribute visibility changes to changes in atmospheric optics when they are actually caused by man made optics (e.g. glasses, different instruments).

1.2 Hypothesis.

In this study we will present the visibility measurements of de Bilt and Schiphol, the Netherlands. In an earlier study by *Van Delden (2009)* a significant increase in the frequency of days with visibility larger than 30 km was found at de Bilt. We propose that these results are significant, and not caused or biased by changes in the measurement procedure, but an actual physical result of changes in aerosol concentrations from human emissions in Europe. Hereby, we try to show that visibility changes near the surface can be used well as a proxy for changes in aerosol concentrations near the surface. We will also see if we can find a response to these changes in other variables, such as temperature, large enough to emerge through natural variability of the two individual stations. We have analyzed only two stations in the Netherlands, so more research needs to be done to see if this result is viable for a larger area.

2. Theory.

2.1 Introduction to aerosol effects.

This study focuses on visibility measurements at two different sites in the Netherlands. Visibility can be used as a proxy for the aerosol burden near the surface. So why are changes in aerosol burden so important? Well, it was recently discovered that aerosols play an important but very uncertain part in the Earth's climate system. In the late 1980s Atsumu Ohmura and several others discovered that the surface solar irradiance ("solar radiation at the surface") was decreasing (e.g. *Ohmura and Lang, 1989*). In the early 1990s it was discovered that in spite of increasing global temperatures, evaporation was actually decreasing, giving another indication of globally decreasing surface solar radiation. This reduction in surface solar radiation was called *global dimming*, and might have been responsible for the mid 20th century dip in global warming (see for example the discussion in *Wild et al., 2007*). What are the effects of aerosols on climate? This is generally considered as one of the biggest uncertainties in our understanding of the climate system. There are many ways in which aerosols can influence the climate.

Aerosols can change the surface radiation by absorption and scattering (the *direct aerosol effect*), or lead to changes in cloud formation by heating of certain atmospheric layers (*semi-direct aerosol effect*) from absorption of solar radiation, and aerosols can indirectly influence climate due by changing cloud properties (*indirect aerosol effect*), increasing the clouds' reflectance (albedo) and lifetime, because aerosols can be used as cloud condensation nuclei (*Twomey et al., 1984*). Long term decreases in evaporation might also influence the important water vapor feedback, which amplifies the effect of global warming.

Aerosols usually have limited lifetime, as they will be removed from the troposphere by precipitation (*wet deposition*) and sedimentation by gravity (*dry deposition*). The smallest aerosols (fine aerosols) tend to have longest lifetimes, because they can only be removed after growing by coagulation. Largest aerosol effects will be found locally, but there is a considerable amount of evidence of aerosols having a global effect on climate, for example see the review of "global dimming", *Wild (2009)*. Though the largest mass fraction (~85 %) of aerosols is of natural origin, anthropogenic aerosols are usually fine aerosols, which have longest lifetimes. The observed dominant tropospheric aerosol variations have been attributed to human activities. *Figure 1* shows the aerosol concentrations in rural and urban areas.

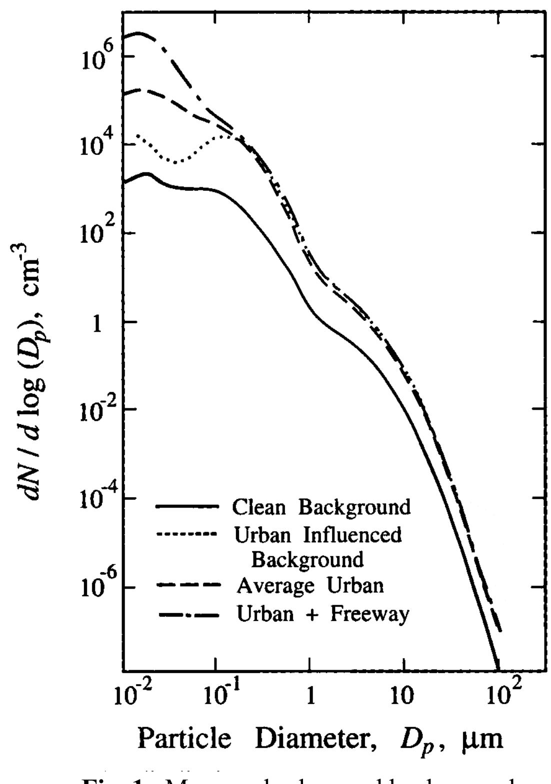


Fig. 1. Measured urban and background aerosol concentrations as function of diameter. Source: *Seinfeld and Pandis, (1998).*

Near cities and industries, human aerosols can dominate the total aerosol concentration, especially the fine part of the distribution.

Fine (anthropogenic) aerosols (also called particulate matter (PM)) can enter the human respiratory system and cause serious health issues (e.g. *Pope et al., 2002; WHO, 2006*). Changes in aerosol concentrations can also have a large effect on the biosphere. All life is dependent on solar radiation, and changes in solar radiation also affect the hydrological cycle (changes in evaporation and precipitation, e.g. *Roderick and Farquhar, 2002*) and photosynthesis. Both can also have a large effect on agriculture (e.g. *Stanhill and Cohen, 2001*). Besides radiation effects, human aerosol emissions can lead to acid deposition "acid rain" which can have a devastating effect on ecosystems.

It has recently been discovered that global dimming has reversed to a modest *global brightening*, i.e. increasing surface solar radiation (n.b. it is actually more correct to speak of a reduced global dimming) especially in the more developed parts of the world (*Wild, 2009*). This might have been caused by less heavy industry and recent environmental measures. This study focuses on visibility measurements. Visibility can be used as a proxy for aerosol concentrations (e.g. *Wang et al., 2009*), which has the advantage over surface radiation measurements that it is much less affected by changes in cloud cover. Here, we have specifically focused on changes in the frequency of high visibility days. It can be argued that this is a better proxy for changes in aerosol burden than low visibility days or average visibility, because it is less sensitive to small changes in relative humidity and effects of precipitation. Large visibility changes occur when relative humidity approaches saturation, and high visibility usually occurs at low relative humidity and in the absence of precipitation, where relative humidity and precipitation are not so much limiting factors.

2.2 Decadal trends in surface solar radiation: global dimming.

During the late 1980s and early 1990s many studies (e.g. review by *Wild, 2009*) showed that though worldwide temperatures were generally increasing, the surface solar radiation (SSR) had decreased about 8 W m^{-2} globally since 1960 (estimates strongly vary between studies). Somehow, much less sunshine was reaching the ground. On a local scale, even stronger decreases were found, for example a decrease of 15 W m^{-2} in surface solar radiation was determined from measurements in Germany between 1964 and 1990 (*Liepert et al., 1994*). In some other studies even more dramatic decreases have been found in some places where the surface solar radiation decreased up to 30 % in only a few decades. These results shocked many scientists. What had caused this "global dimming"?

Extraterrestrial variations (e.g. external solar variability) are an order of magnitude smaller as the observed changes in SSR, so this can not have been the cause. Changes in water vapor would have to be too large to explain the variation. A 10% increase in atmospheric water vapor decreases SSR by less than 1 W m^{-2}. Changes in SSR from water vapor concentrations are thus likely also one order of magnitude smaller than the observed changes in SSR. This leaves clouds and aerosols as possible dominant causes for the observed decadal SSR variability, for both global dimming and brightening (*Wild, 2009*). Clouds measurements over the past decades have shown controversial trends, although there are some indications for increased optical thickness during the global dimming period. This might actually be an indication for what is thought to be the most dominant reason for decadal SSR variations: changes in aerosol concentrations by anthropogenic emissions.

The dimming was most pronounced in highly populated areas. Substantial changes in SSR could be linked to changes in local pollution sites, strongly suggesting that besides possible indirect aerosol effects on clouds, the direct aerosol effect might be the dominant cause of global dimming and brightening. Several studies have recently found that the atmospheric transmission measurements showed a similar pattern than that of SSR. A somewhat more detailed discussion on the sources and size distribution of aerosols will be given later in this chapter.

2.3 Global brightening.

Already at the time when most studies concerning global dimming were published in the 1990s, there were already some indications of a reversal from a dimming to a brightening trend. Recent studies (e.g. *Wild et al., 2005*) have shown that this partial recovery from global dimming, "global brightening" has continued, though not everywhere, and not as strong as it had been declining in de decades before. Specific trends and their spatial extent are still somewhat controversial. Some argue that global brightening and dimming might actually be much more regional than global (e.g. *Alpert et al., 2005*) as has been proposed by others. *Wang et al. (2009)* conclude that visibility has only increased in Europe since the mid-1980s, but substantially declined in most other parts of the world (e.g. East and South Asia, South America, Africa and Australia), indicating that global dimming by the direct aerosol effect is still dominating globally, possibly pointing towards changes in cloud properties as the dominant contributor to the recent brightening.

However, *Wild et al. (2005)* conclude that surface solar radiation increases worldwide since 1990, especially outside the tropics in the northern hemisphere. Largest brightening trends were found in more developed areas, such as in Europe, where brightening started around 1985. They find a shift in the atmospheric transparency of cloud free days from pyrheliometer measurements, showing a decrease in atmospheric transmission until early 1980s and an increase afterward. This may be related to a decrease in aerosol concentrations from clean air regulations reducing SO_2 emissions (*Stern et al., 2006; Streets et al., 2006*), as no trend was found in natural sources between 1980 and 2006 (*Streets et al., 2009*). BSRN (Baseline Surface Radiation Network, *Ohmura et al., 1998*) high quality radiation measurements since 1992, nearly all show an increase in radiation. Also estimates of the surface solar radiation from satellites show a reverse in trend to an increase since 1990 (e.g. *Pinker et al., 2005*). Cloud and earthshine studies have both shown similar trends, including decreasing cloudiness and albedo, presenting further evidence for (global) brightening.

During the "global brightening" period surface solar radiation increased at several sites by about 2 W m^{-2} per decade between 1986 and 2000 (*Wild et al., 2008*), though how this estimate translates to a global average is highly uncertain (see also *Wild (2009)* and references therein). This can be considered as a partial recovery from global dimming. The period in which this occurs is somewhat different for each region, but roughly between 1985 until 2007 most studies found a significant upward trend in surface solar radiation. Global brightening after the late 1980s was most pronounced in Europe, Japan, the US, and the majority of the sites in Australia. In Europe a linear decline of 3.1 W m^{-2} per decade was found for the period 1971 – 1986, but an increase of 1.4 W m^{-2} per decade for the brightening period 1987 – 2002 (*Norris and Wild, 2007*).

However in India, parts of Africa and South America, the trend remained negative (dimming). In China, a renewed dimming trend seems to occur after 2000 after stabilization in the 90s. Also in Japan and Antarctica the brightening trends have leveled off, indicating that global dimming might return. Satellite measurements show an increase in derived SSR from 1983 to 2001. There are indications for a decrease between 1999 and 2004, somewhat consistent with a slowdown of the brightening after 2000 from the surface SSR measurements. There is also some evidence of "early brightening" during 30s and 40s until

1950 when it reached a maximum. In most places, currently (around the year 2000) the SSR is still lower than in the 1960s.

It can be concluded that surface solar radiation is subject to decadal variations, predominately caused by human aerosol emissions. There is robust evidence for a period of global dimming roughly between 1960 and 1990, and a partial recovery afterward. The latter is not observed everywhere but predominately in developed countries, and already there are signs of a renewed global dimming, predominately caused by fast growing industries, for example in China and India.

2.4 Dimming, brightening and climate.

Why are these trends in solar surface radiation so important? This section will shortly present some effects of the observed decadal variation in surface solar radiation caused by human aerosol emissions via scattering and absorption of sunlight and changing cloud properties. Here, we will focus on the surface temperature, before taking a look at emissions and measured aerosol changes and present the relation with visibility, the main focus of this study. In *Wild et al. (2007)* a discussion of possible and observed effects is presented. Some of its content and that of other articles will be discussed here. It should be kept in mind that much of this section can be considered somewhat controversial. The effects of aerosols on climate are still very much uncertain. A wide variety of observations of atmospheric changes have been assigned to aerosols, but other studies tend to dispute this, or more often the magnitude and global extent of aerosol variations caused by human emissions.

It is generally recognized that dimming masked the anthropogenic global warming (AGW) signal before 1980s, but has decreased since then (*Wild et al., 2007*). Speculations have arisen that the current warming (1970s to early 2000) has been caused by global brightening, but on the other hand that global dimming has lead to an underestimation of the climate sensitivity. The temperature rise between 1960 and 1980s has been roughly one order of magnitude less than the rise between 1980 and 2000 (*figure 2a*). This generally corresponds with the observed dimming and brightening periods.

The contribution of thermal (long wave) and solar radiation on temperature can be analyzed by looking at the differences between night and day. At night, radiative cooling is mostly determined by the capacity of the atmosphere to absorb and re-emit thermal radiation, while during the day solar radiation has its strongest effect on daytime heating. An analysis of the trends of daily minimum and maximum temperature might therefore have the potential to distinguish between solar and thermal radiation effects. *Wild et al. (2007)* found that globally, the maximum temperature declined between 1958 and 1985. The minimum temperature however still showed a positive trend during this period, consistent with increasing radiative forcing from AGW. Using this method, there are indications that global dimming might have damped the global land surface temperature rise in this period by 60 – 70 %. During the global brightening period between 1985 and 2002, a significant increase in both the daily minimum and maximum temperatures were found. The maximum temperature trend was still a bit less than that of the minimum temperatures, indicating that there might still be some global dimming.

The difference between the daily minimum and maximum temperature, the *diurnal temperature range* (DTR) might be a good indicator for the temperature changes described above. The DTR shows a marked negative trend (-0.15°C /decade) during the global dimming era (1958 – 1985), leveling of to only -0.03°C/decade during the global brightening area (1985 – 2002). The variation of DTR throughout the dimming and brightening eras can be seen in *figure 2b*.

It might be tempting to contribute most of the recent global warming to global brightening. However, *Wild et al. (2007)* conclude that the global insolation is still lower than in 1960, and that global land temperatures have risen 0.8°C since then. The BSRN radiation measurements show increasing downward thermal radiation, consistent with climate models. Besides temperature effects, another important climate effect is that of aerosols on the water cycle. Elevated aerosol concentrations can limit evaporation, inhibit precipitation from clouds and stabilize the atmosphere, leading to increasing droughts.

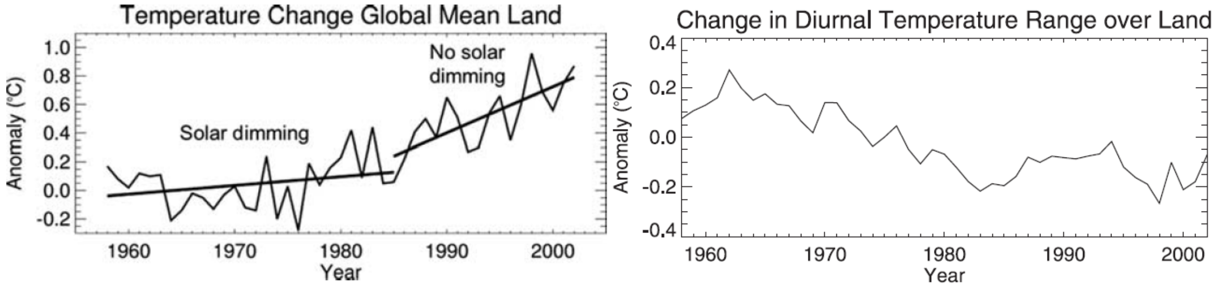


Fig. 2. (**a**) Left: The CRU global mean land surface temperature; and (**b**) right: the change in diurnal temperature range over land. Taken from *Wild et al. (2007)*.

In the previous sections some evidence for substantial decadal changes in the amount of solar radiation reaching the Earth's surface (global dimming and brightening) was presented. These changes have not only become evident in direct measurements of surface solar radiation (SSR) and diurnal temperature range as described here, but also for example in sunshine duration, pan evaporation, planetary albedo, estimates of anthropogenic emissions and ice core records. From all these data sets a reasonably consistent picture of a widespread dimming of SSR between the 1950s and 1980s arises. Recently, a reversal to brightening occurred in some areas especially in the developed world, but there are signs of renewed dimming on a global scale. These SSR variations left a remarkable imprint on the 20th century temperature records. Natural variations in aerosol concentrations had no significant trend during these periods, which indicates that it is likely anthropogenic of origin. Several other studies have traced the dominant aerosol signal back to anthropogenic sources, and showed a world wide effect of these emissions. A much more complete description can be found for example in a review by *Wild, (2009)*. In this study it will be determined if the variations in surface solar radiation and aerosols can also be found in visibility measurements.

2.5 Changes in human aerosol emissions.

In this section we will present historic estimates and observations of aerosol (predominately SO_2 and black carbon (BC)) emissions. The focus will be on European emissions, because they will have largest influence on the visibility in the Netherlands. *Streets et al. (2006)* use the IMAGE (*RIVM, 2001*) and estimates of fuel use trends per world region to determine the emission trends between 1980 and 2000. This period is roughly coincident with the transition from the dimming to brightening period described in earlier sections. Their results are presented in *figure 3*.

It can be seen clearly that in the developed countries (upper panels) both SO_2 and BC emissions decrease throughout the period. In contrary, in developing countries emissions show an increasing trend, especially in Asia, though in absolute terms the emissions in developed countries is still much larger in 2000. Also, note how the break-up of the former USSR and the resulting economic decline lead to much lower emissions in that region and a slow but relatively steady decline in European OECD countries (*) from environmental regulations. How do these emission trends translate to changes in the anthropogenic fraction of aerosols in the Netherlands? This is of course very difficult to determine, as it is, besides many other factors, dependent on the distance from the emission sources and wind direction. Many studies have shown that aerosols are strongly (but not at all fully) determined by regional sources. The National Institute for Public Health and the Environment (*MNP, 2005a*) has determined that on average, 45 % of the total aerosol concentration, represented by the total particle mass of particles with diameter less than 10 µm (particulate matter, PM_{10}), in the Netherlands is of anthropogenic origin, and roughly 2/3rd is from sources outside the Netherlands. The natural fraction contributes about 55% to the PM_{10} and consists mostly of sea salt and surface dust.

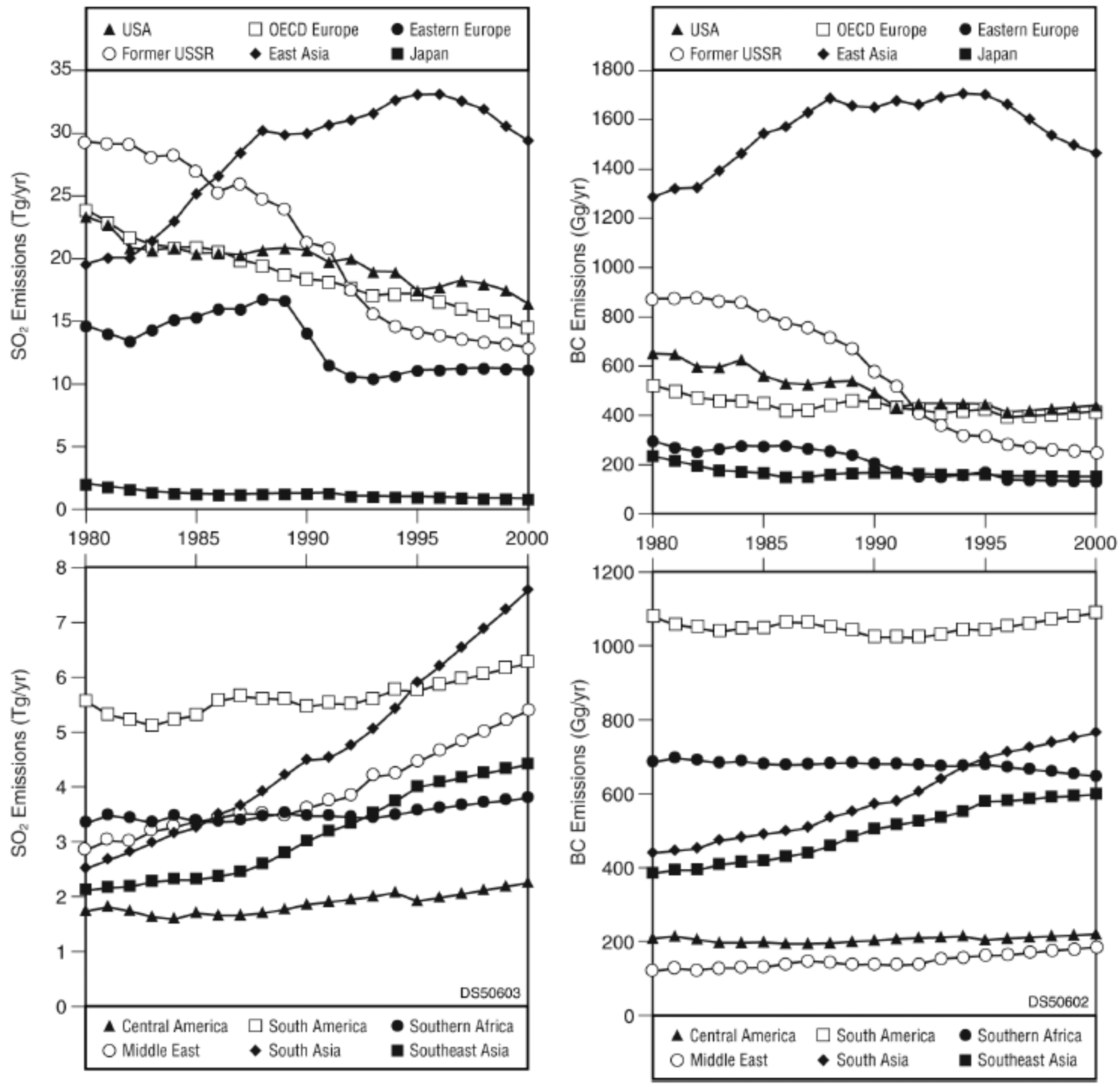


Fig. 3. Trends in SO2 (left) and Black Carbon (BC) emissions (right), 1980–2000, by world region: industrialized regions (upper), developing regions (lower). Source: *Streets et al. (2006)*.

(*) OECD Europe: Austria, Belgium, Denmark, Germany, France, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

The fine aerosol fraction is much stronger dominated by anthropogenic sources and can travel greater distances than larger particles which are predominately of natural origin. The residence time of sulfate aerosols is in the order of a few days, while for larger particles such as sea salt this is in the order of a day or less. The signature of sulfate aerosols can be found up to a few thousand km in optical depth measurements, and can be an order of magnitude larger than the background concentration up to a thousand km from its source. The dominant source for sulfate aerosols are human emissions, around 1990 about 94 % of the sulfate emissions originated from anthropogenic sources (*Charlson et al. (1992)* and references therein). Also the scattering efficiency per unit mass concentration is an order of magnitude larger for sub-micrometer sulfate aerosols than for super-micrometer sized dust. In contrary to dust, sulfate aerosols are strongly hygroscopic, and their diameter tends to become twice as large under relative humidity values between 70 – 80% commonly found in the atmosphere. These properties make the sulfate aerosol the most dominant scattering aerosol in the atmosphere. Though sulfate emissions are relatively small compared to natural emissions, the aerosol optical depth of sulfate aerosols is about 30 % (*Streets et al. 2006*). The optical depth of black carbon is only a few percent and is thus much less important, but its powerful absorption properties can have large effects on the atmosphere.

In this study we are interested in finding the cause of the observed visibility changes in the Netherlands. If we assume that changes in visibility are predominately driven by changes in aerosols, we need to make a rough estimate of the dominant long term changes in aerosol concentrations in the Netherlands. Though the contribution of emissions to the aerosol content in the Netherlands can only be determined by measurements, which only have a very short time span, or modeled, which is outside the scope of this experiment, a qualitative description can hopefully derived from the results of *Streets et al. (2006)*, *Stern (2006)*, and more recent emission estimates and PM_{10} measurements in Europe and the Netherlands from RIVM reports. We will assume that changes in the OECD or West European emissions dominate changes in aerosol concentrations in the Netherlands, especially during westerly winds, and that emissions from Eastern Europe and the former USSR might also contribute during easterly winds.

In the OECD countries, a general decrease in SO_2 emissions of about 40 % can be found between 1980 and 2000 (*figure 3*). A much larger decrease (>50%) occurs during the collapse of the former USSR which started around 1985. Emissions in Eastern Europe declined strongly during the fall of the Berlin Wall in 1989.

The RIVM and MNP in the Netherlands (e.g. *MNP, 2005a*) report a 50 % decrease in PM_{10} emissions between 1990 and 2003, and a 66% decrease in SO_2 emissions in the EU-25 countries between 1990 and 2002 (*EEA ECT/ACC, 2004*). These numbers are quite somewhat larger than the emission changes obtained by *Streets et al. (2006)*, and much closer to the estimates of *Stern (2006)*, as can be seen in *figure 4*, though trends are relatively similar to the ones obtained by Streets et al. Measurements of the PM_{10} concentration in the Netherlands between 1992 and 2008 are presented in *figure 5*, and can be used to illustrate more recent changes in surface aerosol concentrations.

Generally decreasing trends can be found in recent (1995 – 2003) estimates of PM_{10} emissions of several countries surrounding the Netherlands (*MNP, 2005a*, not shown), although there are signs of a leveling off in the early 2000s. The trend after 2000 is not statistically significant (*RIVM, 2008*). The measured PM_{10} concentration (*figure 5*) shows more variation associated with weather conditions such as wind direction, speed and long dry spells (e.g. a peak in 1996 and 2003, both characterized by long periods of anomalous weather patterns in the Netherlands). It is estimated that weather conditions can lead to yearly fluctuations of about 5 µg (*MNP, 2005a*).

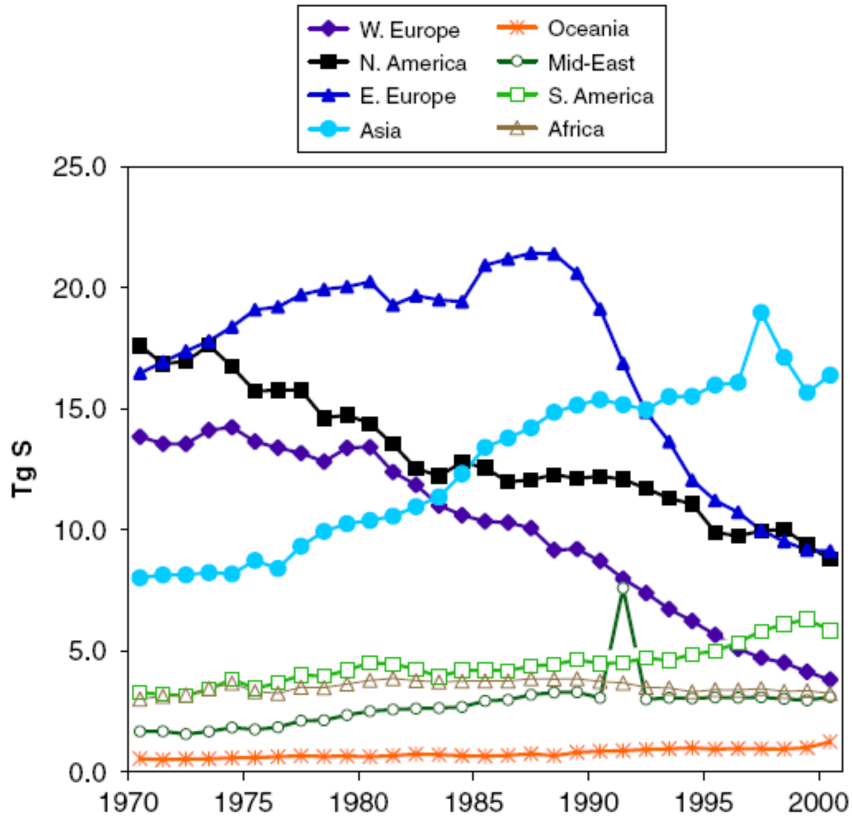


Fig. 4. Estimates of sulphur emissions per region, 1970 – 2000. Source: *Stern (2006)*

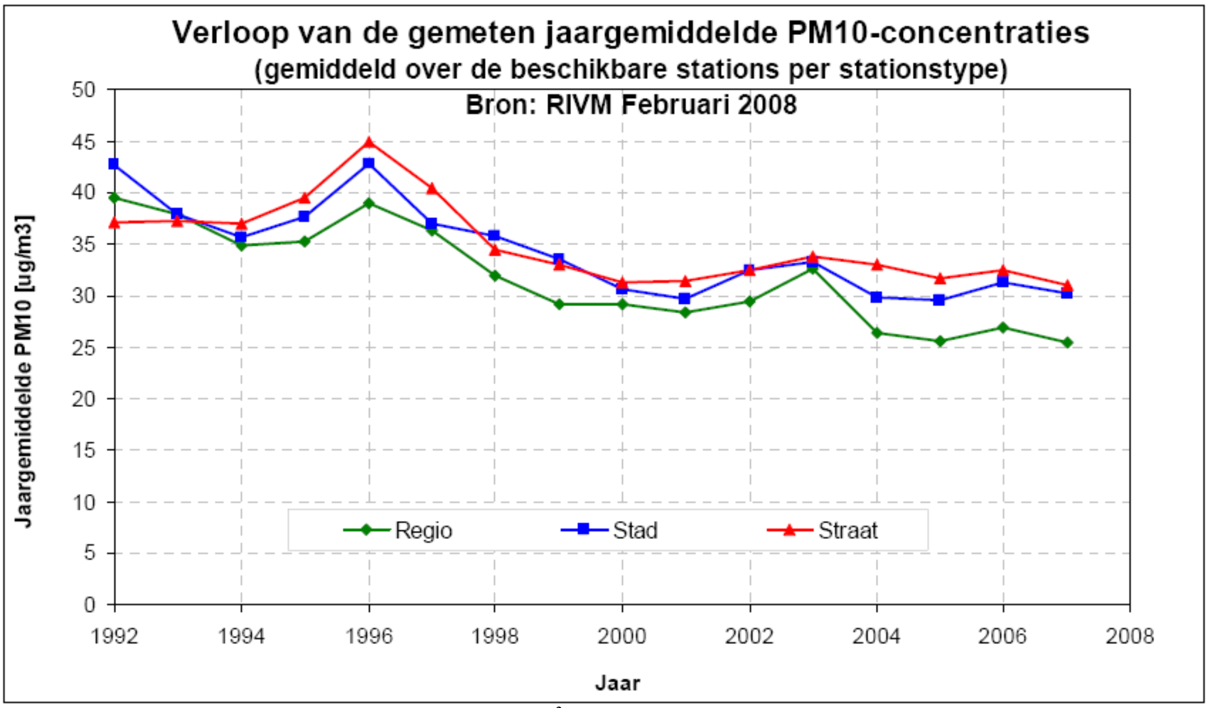


Fig. 5. Yearly averaged PM_{10} concentrations ($\mu g/m^3$) for stations located in rural (green) areas, cities (blue) and (busy) streets (red). Source: *RIVM, 2008*.

It is rather difficult to get a hold on the exact changes in emissions and aerosol concentrations because of the large uncertainties, different measuring techniques and periods reported in the literature. Though it seems likely that SO_2 emissions and sulfate aerosols which form from it can explain a large fraction of the variations in aerosol depth, other aerosols and meteorological factors such as relative humidity, wind direction and speed, stability (mixing) and several others can also contribute to it. The measured particulate matter concentrations presented here do not give any information about the distribution of aerosol types and their relative scattering abilities, nor about regional and short term variability. Still, the general picture which emerges from the available data is that emissions show a slow general decline since 1980, which rapidly increases around 1985 only to level off again in the early 2000s. *Stern (2006)* for example concludes that SO_2 emissions peaked in Western Europe between 1970 and 1980, in Eastern Europe somewhat later. The same picture arises from measurements done on several locations in the Netherlands. Optical depth measurements in Germany and Switzerland also showed trends consistent with the emission and PM_{10} trends; a very large decrease in aerosol optical depth of more than 60 % occurred between 1986 and 2005, most of early during this period and leveling off near the end of the period (*Ruckstuhl et al., 2008*). We will see if these variations are also reflected in the visibility measurements.

2.6 Visibility trends over Europe.

Now that changes in aerosols have been described, it would be interesting to look at the visibility measurements and see how they have been evolving during the dimming and brightening periods. It is to be expected that the visibility will be correlated with the aerosol concentrations near the surface, though meteorological influences might also play a significant role (e.g. *Sloane, 1987*). Several studies (e.g. *Ferman et al., 1981*) have found that sulfate aerosols account for over 50 % of the visibility reduction, and can be a good indicator of long term (sulfate) aerosol changes (*Trijonis, 1984*).

Gomez and Smith (1987) for example argue that the frequency of "very good visibility" days (defined as days where the visibility exceeds 19 km) in summer is a good indicator for long range transportation of air pollution. This simple method has been used in this and other studies too. Several other studies have also shown good correlations with aerosol (SO_2) emissions, and visibility changes can often be linked to economical events and environmental policies. In the United Kingdom, *Doyle and Dorling (2002)* found that in the United Kingdom, visibility increased after 1973 due to the oil crisis and implementation of environmental policies in the UK. Aerosols outside the UK were found to have much less influence than from sources inside the UK.

In a much larger study, using many stations located all over Europe *Vautard et al. (2009)* found a decline of fog, mist and haze over the past 30 years. They determined that the frequency of low visibility conditions declined in all season and for all visibility ranges between 0 and 8 km. This decline was spatially and temporally correlated with trends in SO_2 emissions, suggesting a significant contribution to air quality improvements. Besides visibility trends, also (much smaller) negative trends in cloud cover were discovered. Most substantial changes occurred in West-Central and Eastern Europe. A similar study was done by *Oldenborgh et al. (2010)*. Focusing on the effect of changes in aerosol emissions and atmospheric circulation on dense foggy days, they also found a significant decline which was spatially and temporally correlated with SO_2 emissions. The decline of days with low visibility started in De Bilt in 1985. No significant trend was found before this date. The decline started in different years at different stations (*figure 6*), which is another indication (besides spatial correlation) that local aerosol emissions dominate visibility changes. In heavily industrialized areas (e.g. Rotterdam), the number of fog days showed a linear decline.

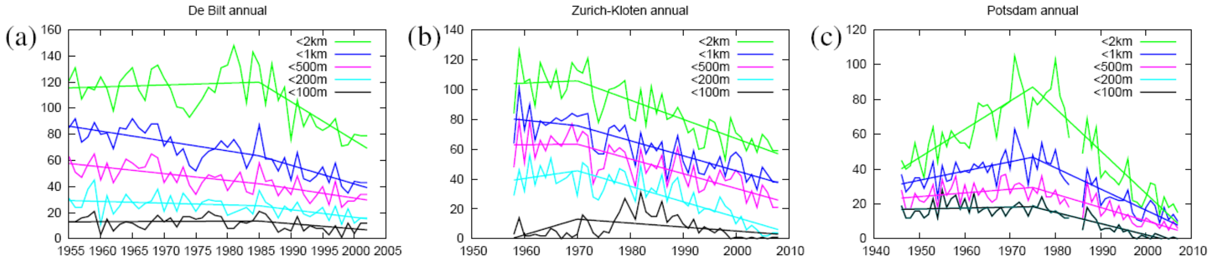


Fig. 6. The number of days with visibility less than 100 m, 200 m, 500 m, 1 km and 2 km at (**a**) De Bilt (The Netherlands), (**b**) Zürich Airport (Switzerland) and (**c**) Potsdam (Germany). The straight-line fits include a break-point estimated from the 5 km visibility. Source: *Oldenborgh et al. (2010)*

2.7 Meteorological influences on visibility.

In previous sections, we have mainly focused on the relation between aerosols and visibility. However, many studies have shown that atmospheric circulation and relative humidity can also have a significant effect on visibility. Atmospheric circulation determines the transport of aerosols via wind direction and speed. It also determines the removal of aerosols from wet deposition by precipitation. The stability of the lower atmosphere determines the height of the well mixed boundary layer, in which most of the aerosols reside. Circulation changes dominate interannual variability, but on the long term trends other factors such as aerosol emissions and land use changes (e.g. trends in urbanization area) are more important (*Oldenborgh et al., 2010*).

It is well known that relative humidity (RH) strongly influences visibility. When relative humidity reaches saturation values, visibility is dramatically reduced to less than a few hundred meters, also known as a “fog”. However, well before RH values reaches saturation, visibility can be reduced by what is called a “haze”. This actually occurs because many aerosols are hygroscopic, taking up water at humidity values below saturation. The sulfate aerosol, which is predominately formed from anthropogenic SO_2 emissions and has become one of the most contributing scatterer in the atmosphere, can become much larger under these conditions. When RH reaches 90%, the diameter of the sulfate aerosol is increased so that its scattering efficiency is increased by a factor five! *Figure 7* presents a scatterplot of measurements obtained by *Malm and Day (2001)* of the ratio between dry and wet scattering as a function of relative humidity f(RH) of aerosols in the Great Smoky mountains. Note the rapid increase of scattering when RH becomes larger than 80%. This indicates that visibility will likely be much more sensitive to relative humidity changes when relative humidity is high, than when it is low.

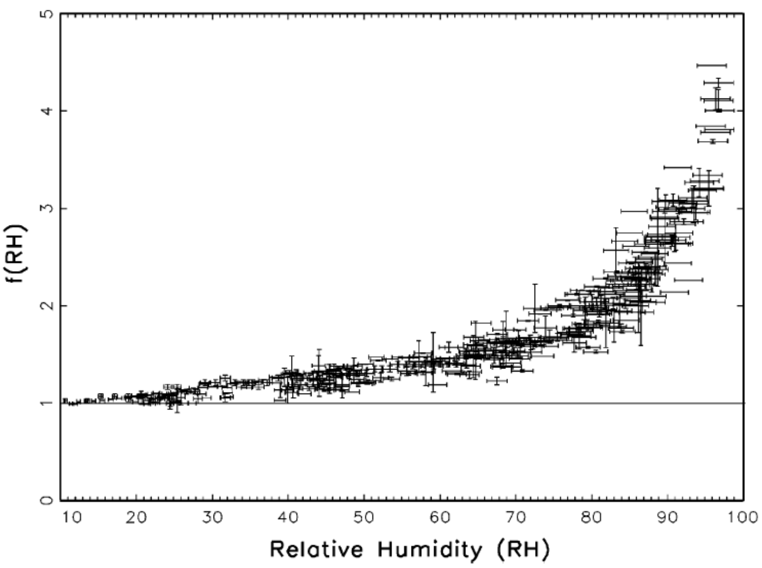


Fig. 7. Left: Scatterplot of all f(RH) measurements versus relative humidity. Source: *Malm and Day (2001)*.

3. Methodology.

3.1 Introduction to atmospheric visibility.

This chapter gives an overview of the general visibility theory, how it is visually obtained and its uncertainties as explained in *Horvath (1981)* and *WMO (2008)*. In later sections we will present information about visibility measurements obtained by instruments (from the KNMI "handbook of measurements", *KNMI, 2005*), station history and specific issues with visibility measurements in de Bilt and Schiphol (if it can be obtained from the KNMI "climate desk"). The WMO gives the following definition of visibility:

Visibility, meteorological visibility (by day) and meteorological visibility at night are defined as the greatest distance at which a black object of suitable dimensions (located on the ground) can be seen and recognized when observed against the horizon sky during daylight or could be seen and recognized during the night if the general illumination were raised to the normal daylight level.

How is the visibility obtained?

The presence of atmospheric particles always causes a reduction in visibility. When looking at a distant target, its appearance is altered in such a way that the contrast between the target and the background atmosphere decreases with increasing distance. This occurs when light is scattered towards the observer from the air between the target and the observer. This light "adds" with the light travelling from the target towards the observer, decreasing its contrast with the background atmosphere or horizon. The distance at which the contrast drops below the contrast threshold of the human eye, and the target becomes barely visible, is defined as the *visibility*. If the illumination, the scattering function, intrinsic brightness of the target and extinction coefficient of the atmosphere are known the contrast change can be determined. The distance at which the contrast of a target against the background atmosphere becomes equal to the contrast threshold of the human eye is called "visibility". However, these parameters are known only incompletely, as they may vary with the distance from the observer. Therefore the visibility calculated from these parameters available at the observer's location may vary from that of the actually observed visibility, as well as the visibilities using different targets in different directions. Under controlled conditions in a laboratory, it has been shown that visibility can be determined with accuracy of a few percent.

Several factors influence the visibility of a human observer. Firstly, a target might not be perfectly black, i.e. the intrinsic brightness of different targets may vary. Lighter colored objects are usually less well visible against a bright background. Objects in their own shadow are usually dark enough to be used for accurate visibility estimates, and the intrinsic brightness of lighter targets can be estimated by comparing them to nearby model surfaces.

The extinction coefficient may vary in the atmosphere, and the observed visibility is an average of this though the atmosphere between the target and the observer. Inhomogeneous illumination between the target and its background can lead to increasing or decreasing visibility of the target. A 20 % higher visibility can be obtained if there are clouds shading the area between the observer and the target, and sunshine behind the target, but generally shading by clouds will lead to deviations in the order of 5% (*Horvath, 1981*).

Also, the contrast threshold of the human eye can differ between observers. Dusk or darker conditions also limit the human observer's ability to see contrast. The extinction coefficient of aerosols in the atmosphere decreases with increasing wavelength, so red objects are better visible than blue or green objects. Targets with a small angular size (less than a few arc-minutes) are less visible than larger targets.

Due to these varying factors, it can be shown that it would be desirable to determine a standard visibility. This can be obtained from the measured visibility, by inclusion of correction factors for contrast and inhomogeneous illumination. A “standard” visibility may be estimated by using a relatively simple equation. However, when obtaining actual observations, the conditions often deviate from the “standard”, and corrections have to be included. Let us explain a few important basic parameters described in the previous section, and introduce the basic visibility theory and equations. This section is modified from *WMO (2008)*.

The basic equation for visibility measurements is the Bouguer-Lambert law (*equation 1*)

$$F = F_0 e^{-\sigma x} \qquad \textbf{(1)}$$

where F is the luminous flux (in lumen) received after a path length x in the atmosphere, and F_0 is the flux at x = 0. The *extinction coefficient*, σ is here defined as the proportion of luminous flux lost by a collimated beam, emitted by a source (2700 K) travelling though a unit path length of the atmosphere. The *transmission factor* (T) is defined as

$$T = F/F_0 \qquad \textbf{(2)}$$

This factor is for example measured in *transmissometers*, an instrument used for visibility measurements. If we combine equation 1 and 2, we can write

$$T = F/F_0 = e^{-\sigma x} \qquad \textbf{(3)}$$

From this equation we can derive the equation for the *Meteorological Optical Range* (MOR). This is a physical variable in which the limitations of the human eye and the *background luminosity* (L_b) do not play a role. This is the visibility measured by instruments, or determined from human visibility observations. In order to make the MOR comparable to the human visibility, a transmission factor of 0.05 has been chosen. Then, the path length (x) needed to obtain this transmission factor is equal to the MOR, so that T becomes

$$T = 0.05 = e^{-\sigma . MOR} \qquad \textbf{(4)}$$

The MOR can now be related to the extinction coefficient:

$$MOR = \frac{1}{\sigma} \ln\left(1/0.05\right) \approx 3/\sigma \qquad \textbf{(5)}$$

which may be rewritten in terms of the transmissometer baseline (x) and the transmission factor (T) so that the MOR can be directly calculated from transmissometer measurements.

$$P = \frac{x \ln\left(0.05\right)}{\ln\left(T\right)} \qquad \textbf{(6)}$$

When the visibility it determined by an observer during daylight, who looks at dark targets against a bright background (i.e. the horizon), the visibility is determined by the contrast between the target and the background. This *contrast of luminance* (C) is:

$$C = \frac{B_T - B_H}{B_H}, \qquad \textbf{(7)}$$

where B_T is the brightness (or luminance, the luminous intensity (I) per unit area in cd m^{-2}) of the target and B_H the brightness of the horizon. The smallest contrast which can be seen by the eye of an observer is called the contrast threshold ε.

The *intrinsic contrast* C□ of an object is the contrast of a target (relative to the atmosphere) at zero distance. At some distance V of the observer, the apparent contrast of a target against its background (atmosphere) becomes equal to ε. This distance equals the visibility (V) and is presented in *equation 8*.

$$V = \frac{1}{\sigma}\left(\ln|\varepsilon| - \ln|\bar{C}|\right), \qquad \textbf{(8)}$$

where σ is again the extinction coefficient. V is equal to the MOR, when the target is black viewed against the horizon (C□ = -1) and the apparent contrast is equal to the contrast threshold (0.05). This equation (8) is a version of the *Koschmieder visibility formula*, though at that time (1924) a contrast threshold of 0.02 was used.

Keep in mind that in this equation it is assumed that the contrast threshold of the human eye is 0.05 (recommended today by the WMO) and the target that we are looking at is an ideally black target, for which C□ = -1. In the range of normal illumination for daylight conditions the contrast value is independent of the brightness of the background. For conditions deviant from the above, corrections can often be applied.

For a non-black target for example, the ratio of the visibility of a non-back target V_N and a black target V_B is given by *equation 9*,

$$\frac{V_N}{V_B} = \frac{1 - \ln|\bar{C}|}{\ln|\varepsilon|}. \qquad \textbf{(9)}$$

For a non-black target, |C□| < 1, so visibility is reduced for all targets which are either darker than the horizon, or have a brightness up to a maximum value of twice the brightness of the horizon. Corrections for a non-black target can be easily made by measuring its intrinsic contrast.

Other assumptions that have been made in the Koschmieder visibility formula are that the extinction coefficient is constant along the path of sight and that the amount of light scattered by a volume element in the path of sight is proportional to its volume and extinction coefficient, and is also constant along this path. Both assumptions are invalid when the aerosol concentration changes along the path length or when clouds lead to inhomogeneous illumination of the path of sight. However, taking several measurements in multiple directions reduces the error substantially. An interesting discussion of these problems is presented in *Horvath (1981)*. In spite of these uncertainties, usually reliable and accurate visibility data can be obtained from suitable targets during daylight conditions.

However, how are visibility observations made during the night, or at dusk? Observations done at night are not so simply related to the MOR. These observations are usually done by looking at light sources preferably of known intensity (usually 100 Cd, which roughly corresponds to 100 W) and or distance. The distance at which a light can be seen at night is not only related to the MOR, but also on the illuminance at the observer's eye from all other light sources. What is the relation between the MOR and the observed visibility at night? The following section closely follows the explanation of the *WMO (2008)*.

We will start a short derivation of the MOR from an equation proposed by Allard in 1876, the law of attenuation of light from a point source of known intensity (I) as a function of distance (x) and extinction coefficient (σ). The illuminance (E) of a point light source is given by *equation 10*.

$$E = I \cdot x^{-2} \cdot e^{-\sigma x} \tag{10}$$

When the light is only barely visible, $E = E_t$ and we can rewrite the equation as a function of the extinction coefficient.

$$\sigma = \frac{1}{x} \ln\left(\frac{I}{x^2 E_t}\right) \tag{11}$$

If we now substitute equation (5) into equation (11) we find for the MOR

$$MOR = \frac{x \ln\left(1/0.05\right)}{\ln\left(I/x^2 E_t\right)} \tag{12}$$

Note that an observer preferably needs to know the intensity of the light (I), the distance between the observer and the light (x) which can only barely be observed and an estimate of the amount of background light or ambient luminance (E_t), e.g. twilight, moonlight or complete darkness. The *WMO (2008)* proves more specific details of how day and night visibility observations should be carried out.

During daylight, the *WMO (1990)* states that the MOR determined from observed visibility is about 15 % higher than from observations made with instruments at an identical location. The interquartile range of differences between the observer and instruments was about 30 % of the measured MOR. This yields a standard deviation of 22 %, assuming a Gaussian distribution. At night, the MOR determined from observed visibility was generally 30% higher than measured by instruments, with an interquartile range of 35 to 40% of the measured MOR. When the visibility is not identical in all directions, the smallest range is taken.

3.2 Visibility measurements at de Bilt and Schiphol.

3.2.1 Introduction.

Now that we know the basics of how the visibility observations are carried out by humans, it would be interesting to find out how exactly the measurements were obtained at de Bilt and Schiphol. Are observations done by humans or instruments? What instruments are used? How do they work? Did the method change during the period? This section will try to provide answers to these questions. Most of the information can be found in the "handbook of observations” of the Royal Netherlands Meteorological Institute (*KNMI, 2005*) and the WMO chapter on visibility (*WMO, 2008*).

3.2.2 Instrumentation.

Visibility can be measured using several instruments. Most important are the transmissometer and the scatterometer. The transmissometer determines the transmissivity or transmission factor (T) of the atmosphere, from which the extinction coefficient (σ) of the air and thus the MOR can be calculated. For operational meteorological purposes in the Netherlands the *Vaisala Mitras* transmissometer is used.

Transmissometers are usually used for low visibility ranges, such as between 10 and 3000 m. *Figure 8* shows a schematic model of a transmissometer setup, including a background luminance meter (for measuring the background luminance, L_b).

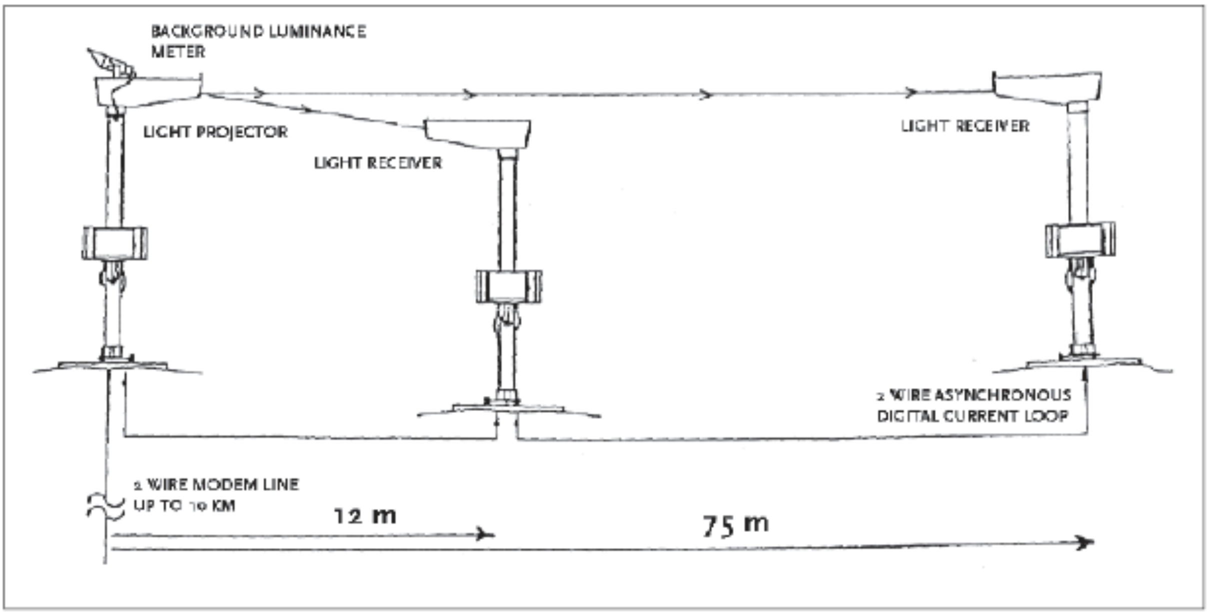


Fig. 8. A schematic of the transmissometer set up. The light projector and background luminance meter can be seen left, and both light receivers in the center and right side. Source: *KNMI (2005)*

The transmissometer consists of a light source sending out short pulses (visible/infrared) with an extremely high and constant intensity. A parallel light bundle is produced and directed towards one or more light receivers located at a certain distance (e.g. at 12 and 75 m respectively). These sensors determine the received light intensity and relate this to the intensity of the outgoing pulse of the source. The receiver located at a smaller distance can be used to accurately measure the extinction of low visibility conditions, and one at larger distance can be used during clearer conditions. The light source is located at 2 (synoptic stations) or 2.5 (aeronautic stations) meters above the surface. This is slightly deviant from the WMO norm (1.5 m), but it is to be expected that the obtained measurements will have uncertainties well within the requirements (*KNMI, 2005*). Usually also a background luminance meter is placed on the transmissometer.

The uncertainty of the transmissometer is dependent on the measured transmission coefficient, which is dependent on both the extinction coefficient of the atmosphere and the relative distance between sender and receiver. To make sure that the uncertainty stays within the required limits, often more receivers are used at several distances from the source. The technical specifications are presented in *table 2*. *Figure 9* is a picture of a transmissometer located at Schiphol.

Fig. 9. A transmissometer set up located at Schiphol, the Netherlands. Right: projector and background luminance meter; Left: two light receivers. Source: *KNMI, 2005*.

A scatterometer can also be used for visibility measurements. Scatterometers are usually much more accurate for longer visibility ranges. The scatterometer determines the scattering in the atmosphere from which the extinction coefficient and MOR can be determined. There are two types of scatterometers used in the Netherlands, the *HSS 402B* and *Vaisala FD12 P* scatterometers, but the HSS will be phased out in favor of the Vaisala.

Figure 10 presents a picture and a schematic of the Vaisala present weather sensor (PWS) which includes a scatterometer. It can also discriminate between precipitation particles. The sensor has a light source which sends out infrared (875 nm) pulses at a frequency of 2.3 kHz. The sender and receiver are placed at an angle of 33° (see figure 10) with each other, so that a volume (V) of about 10^{-4} m^3 (or about 0.1 liter) of the atmosphere at 1.50 m altitude above the surface is sampled. The atmosphere contains several types of particles (aerosols, water droplets, precipitation) which scatter the light from the sender in all directions, of which a part is detected by the receiver. A 33° scattering angle is used, because in this configuration the scattering signal is least sensitive to the type of scattering particles in the sample. The *scatter coefficient* (b) measured by the scatterometer is given in *equation 13*.

$$b = \frac{2\pi}{\Phi_v}\int_0^{\pi} I(\phi)\sin(\phi)\,d\phi \qquad \textbf{(13)}$$

where Φ_v is the flux entering the volume of air (sample volume, V), and I(Φ) is the intensity of the light scattered in direction Φ with respect to the incident beam.

Note that for accurate determination of b it would be necessary to measure and integrate the scattered light over all directions. However, the instruments measure over a limited angle only and rely on a high correlation between the integral over this region to the integral over all directions. Another assumption which is made is that the visibility is only limited by scattering. In reality it might also be limited by absorption, but the contribution of absorption to visibility is usually negligible according to the *WMO (2008)*. Using this assumption, the scattering coefficient becomes equal to the extinction coefficient, from which the MOR can be calculated. The technical specifications of the HSS and Vaisala scatterometers are presented in *table 2*. The accuracies of the transmissometer and the scatterometer are compared in *WMO (1992b)*.

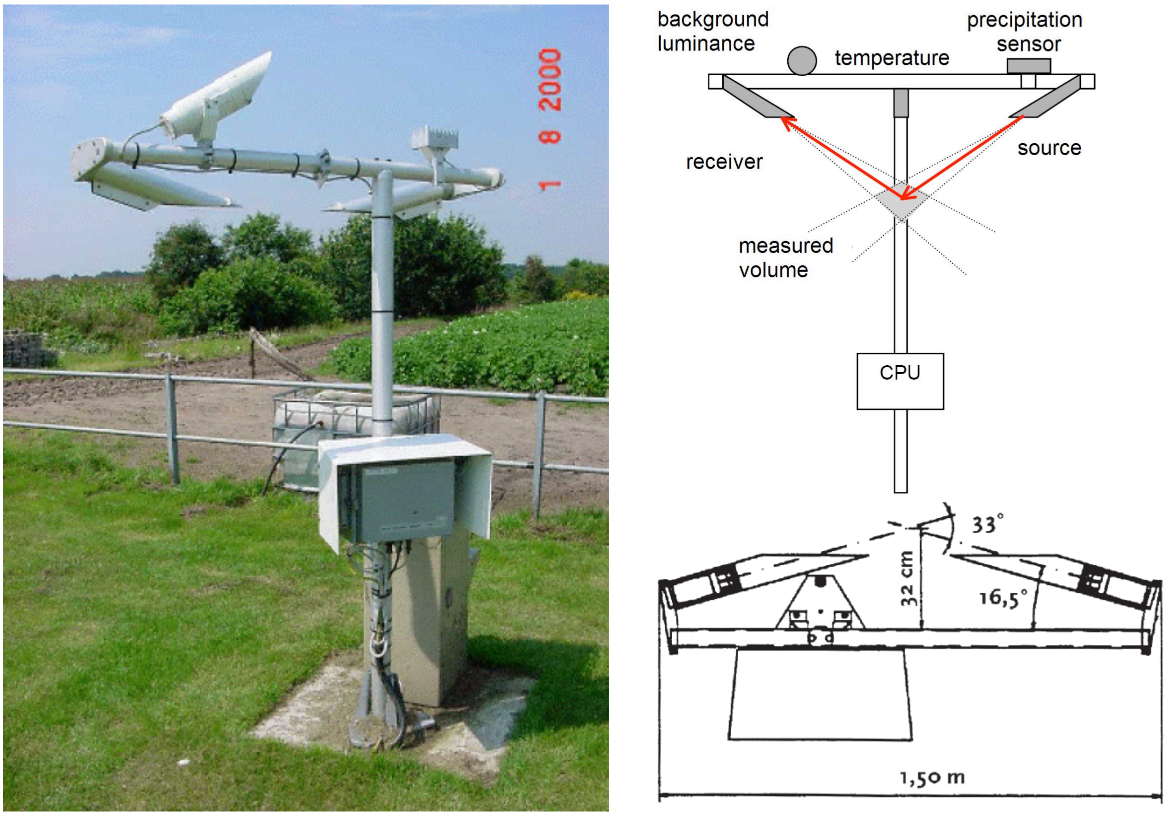


Fig. 10. The Vaisala FD12P present weather sensor (including scatterometer) and a schematic drawing of its most important features. Source: *KNMI, (2001)*: left & upper right (adapted); *KNMI (2005)*: below, right.

A background luminance sensor is located on both the transmisso- and scatterometers. The visibility of a light source (e.g. for night visibility) is dependent on the sensitivity of the human eye, the contrast between the light source at a certain distance and the luminance ("brightness") of all background light. Also for the determination of the (runway) visual range, an estimate of the background luminance is needed. In section 3.1 the luminance threshold E_t was introduced. This parameter can be calculated from the measured background luminance (L_B) using equation 14.

$$E_T = 10^{-6.666+0.05725l+0.0004997l^2}$$

where $l = 10 \cdot {}^{10}\log\left(L_B\right)$. Technical specifications of the background luminance sensor together with the other instruments can be found in *table 3*, and a close up picture of the scatterometer with a background luminance sensor located at De Bilt is presented in *figure 11*.

Fig. 11. A close up of the scatterometer, including a background luminance meter (left, pointing slightly upward) at de Bilt. Note the precipitation detector in the right side of the image. Source: *KNMI (2005)*.

Name	Vaisala Mitras	Vaisala FD12 P	HSS 402B
Type	Transmissometer	Scatterometer/PWS	Scatterometer/PWS
Range	10 m – 3 km	10 m – 50 km	10 m – 150 km
Resolution	1 m	1 m	1 m
Accuracy	10% - 20%	10% (10 m – 10 km)	< 5% (10 m – 10 km)
		20% (10 km – 50 km)	< 10% (10 m – 50 km)
		30% (precipitation)	50 % (>50 km)
Measuring frequency	every 12 s	every 12 s	every 12 s

Table 2. Transmisso- and scatterometer specifications.

Background luminance sensor	Vaisala FD12 P	HSS 402B
Range	10 – 30 000 Cd m^{-2}	3 – 10 000 Cd m^{-2}
Resolution	1 Cd m^{-2}	3 Cd m^{-2}
Accuracy	10%	10%
Field of View	7°	7°
Measuring frequency	every 12 s	every 12 s

Table 3. Background luminance sensor specifications.

3.2.3 Maintenance and placement.

It is of the utmost importance that the instruments are well maintained and calibrated. Especially transmissometers are extremely sensitive to dirt accumulating on the sensors. Scatterometers are much less susceptible to pollution of the sensors, and have become

increasingly popular due to their greater range, smaller size and easy maintenance. Modern instruments described above have a sensor which measures the pollution of the senders and receivers. A nice and amusing example of unexpected things which can come up while the instruments are operational can be found here:
http://www.knmi.nl/cms/content/80452/spinrag_en_zichtmeting (in Dutch only).

All instruments are calibrated in field and cleaned on a regular basis, usually twice a year (*KNMI, 2005*). The instruments are based on a level surface and the sensors are kept out of direct sunshine (facing north). They are placed far away from sources of pollutants, aerosols, and bodies of water, because the latter influence the humidity and thus the visibility. They are placed over 100 m from obstructions and at least 5 m from water (lakes, ponds, etc).
The transmissometer is calibrated using optical filters to simulate certain visual ranges. The scatterometer is calibrated using scatterplates with known extinction coefficient, which have been calibrated against a reference transmissometer. The scatterometers are also calibrated against a standard transmissometer located at the KNMI site in the Bilt. Much more information can be found in the handbook of measurements (*KNMI, 2005*).

3.2.4 Uncertainties and resolution.

The *KNMI (2005)* presents the following uncertainties in the MOR. The measurements we used in this study (also called synoptic visibility) have a certain resolution, which decreases when the visibility increases. Both can be found in *table 3*. Always the lower boundary is reported, e.g. a visibility of 350 m is reported as 300 m.

MOR	Uncertainty	MOR (SYNOP)	Resolution
0 – 600 m	50 m	0 – 100 m	10 m
600 – 1500 m	10%	100 – 5000 m	100 m
Above 1500 m	20%	5 km – 30 km	1 km
		30 – 100 km(*)	5 km

Table 3. The uncertainty and resolution for given (synoptic) MOR ranges used in this study. (*) 100 km is the maximum reported synoptic visibility.

3.2.5 Frequency and recording of measurements.

The visibility measurements from instruments are done continuously. However, also 12 seconds averages are available. Reported one minute visibility values are averages of all five 12 s averages in the minute before the reported time (e.g. the reported value at 14:00:00 is actually the average of MOR(13:59:12, 13:59:24, 13:59:36, 13:59:48 and 14:00:00). When visibility is reported every 10 minutes, only the latest 1 minute average is presented. Note that this is not the average of the previous 10 minutes! In *KNMI (2005)* it is reported that internationally there is a trend towards reporting the actual 10 minute averages, however it is not specified when this will be done in the Netherlands and where. The background luminosity is also measured, and presented using an identical procedure. Extrema are calculated from the 12 s averages. If we assume for example that the visibility is recorded every 10 minutes, then the maximum or minimum visibility recorded is the maximum or minimum 12 s average visibility recorded during the previous 10 minutes.

Hourly values generated for the SYNOP visibility (code VV) are the 1 minute averages generated between 11 and 10 minutes before the hour. The WMO requires that it is determined this way somewhere between 15 and 2 minutes before the hour.

3.3 Methodology changes between 1955 and 2010 at the Bilt and Schiphol.

We have obtained our data from the KNMI website. However, very little specific information was available about the methodology. On the internet and in the literature a lot of general information is available, so that we have a good idea how this is done in general. It is difficult to precisely determine the method used for the determination of the synoptic visibility (code: VV), partly because there are quite a few products available. However, in order to avoid reporting spurious or biased results arising from changes in methodology and instrumentation we need specific information about the station history, so we contacted the KNMI for more information. Somewhat to my surprise this was not easily obtainable, and they had to forward our questions to an expert in this field. About two weeks later I received an email from Dr. R. Leander that they were also trying to obtain specific information about the visibility data sources for a research project they were working on. He wrote to me in an email that there were no corrections applied to the visibility record. Before the transition to automatic weather stations the visibility was obtained by a human observer. During the transition period the visibility below 3 km was determined by instruments, but visibility ranges greater than this were still obtained by a human observer. Measurements done by instruments determine the atmospheric extinction, which is something different than the visibility obtained by a human observer. He would contact me as soon as more detailed information as soon as it became available to him, which hasn't occurred yet at the time of writing. Besides the KNMI, I have also contacted Dr. J. van der Meulen about these issues, but have not (yet) received a response.

I have found some signs which point to the year 2001 as the year in which the automatic weather stations became operational. The most obvious example which is documented in the peer review is that of *Oldenburgh et al. (2010)*. They report that they found six stations which showed very obvious breaks in a visual inspection of the time series, which included De Bilt (but not Schiphol?). They report that this break coincided with the introduction of automatic weather stations in 2001, and that they left out the data between 2002 and 2006 for all Dutch data. The *KNMI (2001)* reports that the AVW ("automatic visual observations") stations became operational at November 1, 2001, which seems to correspond with the findings of Oldenburgh et al.

The author of this report hopes that the KNMI will soon provide more specific details concerning the visibility measurements so that it can still be incorporated in this document. This also clearly demonstrates the need for proper documentation of all observations, which is especially important for all climate related research.

3.4 Methodology of this project.

This section will shortly describe the methodology of this project. The measurements were downloaded from the KNMI website: http://www.knmi.nl/klimatologie/daggegevens/download.html/. The daily observations of De Bilt (260) and Schiphol (240) were selected. All data analysis was done and plots were made using the Python scripting language (http://www.python.org/) along with numpy/scipy (http://numpy.scipy.org/) and matplotlib (http://matplotlib.sourceforge.net/) numerical and plotting packages.

In this project we have chosen to look at the daily maximum visibility, which is available since 1955 for both stations. More specifically, we calculated the number of days in a year with a maximum visibility greater than some threshold (*equation 14*). We have taken 30 km and 19 km as a threshold, the latter being a simple but good indicator for the transport of anthropogenic aerosol (*Doyle and Dorling, 2002*). Data coverage was generally very well; in only a few years one or two days were missing. These days were omitted, and the amount of days in a year was adjusted accordingly when calculating the number of days as a fraction of the corresponding year. This should not lead to any significant errors. The visibility data was then separated into two classes: days with a continental wind regime (daily average wind directions between 90 and 180 degrees, i.e. between east and south) and a maritime wind regime (all remaining directions). The number of days in a year having a visibility greater than some specific threshold were separated into the maritime and continental classes, and then calculated as a fraction of each class, by dividing through the total amount of maritime or continental days in a year. The yearly fraction of days (F) of a class (i.e. maritime or continental) can be calculated by

$$F_{class} = \frac{N\left(VV_{\max,class} > \tau\right)}{N_{class}} \qquad \textbf{(14)}$$

where $N(VV_{max,class} > \tau)$ is the amount of days in a class with a maximum visibility (VV_{max}) larger than a threshold (τ) and N_{class} is the total amount of days in a class for each year. Plots of this fraction of days in a year with a visibility larger than some threshold in each class showed some very interesting things. These plots were then compared to the estimates of aerosol emissions by *Streets et al. (2006)* and the PM_{10} measurements from the RIVM.

In order to see if the wind regime has changed during the years, also the fractions of maritime and continental days per year were plotted for each station. Besides aerosols and wind direction, also the relative humidity determines the visibility, so also plots of the average relative humidity and the fraction of high humidity days per year were made for each station. Several other plots were made to investigate the results of visibility changes, such as on the average temperature, the diurnal temperature range, sunshine duration and cloudiness.

Fig. 12. A scatterometer with a background luminance meter at Beek, The Netherlands. Source: *KNMI, 2005*.

4. Results & discussion.

4.1 Visibility at de Bilt and Schiphol.

In recent years, several studies have looked into visibility changes (e.g. *Vautard et al. 2009; Wang et al., 2009; Oldenborgh et al., 2010*). However, they have mostly looked into changes of average or low visibility conditions. *Doyle and Dorling (2002)* did also study the frequency of high visibility days in the United Kingdom, and concluded (also based on earlier studies) that changes in the frequency of days with visibility larger than 19 km were a good indicator of changes in aerosol concentrations, and could be linked well to emission changes. *Delden (2009)* analyzed the frequency of days during which the visibility was larger than 30 km, for both maritime and continental wind regimes. This methodology has also been used in this report, and we will take a look at the > 19 km visibility days as well.

Figure 13 presents a scatterplot of the yearly fraction of high (>30 km) visibility (VV_{max}) days in De Bilt. The results are separated into continental and maritime wind regimes. Five year moving averages and least-squares trendlines have also been shown to better illustrate the changes. It can be seen that the fraction of days with maximum visibility larger than 30 km remained relatively constant between 1955 and 1985, but has rapidly increased since then. The maritime fraction seems to be a leveling off since 2000, which might have been aided by the transition from human observers to automatic weather stations in 2001. Human observers generally report 15% higher visibility than instruments (*WMO, 1990*). However, the continental fraction does not seem to level off, and still shows a strong trend towards greater visibility. It can be seen that the visibility of days with a maritime wind regime ("maritime days") is generally larger than of continental days. However, recently the continental fraction has become equal or larger than the maritime fraction. This can be expected because on maritime days, a lot of sea salt aerosols are present in the air, which add to the aerosol burden limiting the visibility. Continental air masses can have much lower concentrations of aerosols, as long as they are not polluted by anthropogenic aerosols. Blowing dust and forest fires can limit the visibility in continental air, but these are relatively rare events in Western Europe.

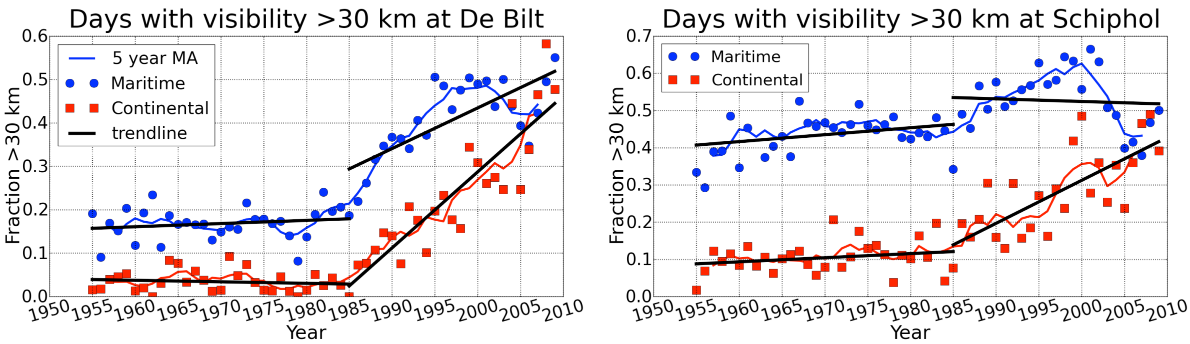


Fig. 13. The relative amount of days in a year with a maximum visibility larger than 30 km (very high visibilities) for continental and maritime wind regimes at De Bilt (left) and Schiphol (right). Five year moving averages (MA) and least-squares trendlines have been drawn illustrate the changes.

Is the observed clearing of the air at De Bilt some local phenomenon? Let's compare it to Schiphol, which is the largest airport in the Netherlands. It is likely that the measurements at

Schiphol have been conducted with great care because of its importance to air traffic. *Figure 13* also shows the measurements at Schiphol.

Again, we see a similar picture, visibility is relatively stable until 1985, and shows a rapid increase afterward. (N.b. the scale is slightly larger.) However, there are also some notable differences. Generally, the increase in visibility is somewhat smaller than at De Bilt, especially for the maritime fraction, which actually peaks around 2000, and strongly decreases after that. It is interesting to see what might have caused this peak and dip (physical processes or changes in instrumentation), which is predominately visible in the maritime fraction. Hardly any levelling off can be found in the continental fraction and recently again the continental visibilities have become equal to the maritime visibilities.

The maritime visibilities were until recently generally larger than in De Bilt, probably because Schiphol is located closer to the North Sea, and thus less contaminated by anthropogenic pollution. However, also the continental visibilities were slightly larger, which could be caused by many reasons such as different methodology or instruments, but also because near Schiphol there is much more open farm- and grassland than near De Bilt, which is surrounded by urban regions and forests. Recently, continental visibilities at Schiphol have become equal to De Bilt. Also note that the yearly variation of continental visibilities has increased substantially since around 1985, but that this does not seem to occur for the maritime visibilities.

What has caused this significant clearing of the air? *Figure 14* shows the fraction of days with a maximum visibility larger than 19 km, which can be used well as a proxy for the aerosol concentration.

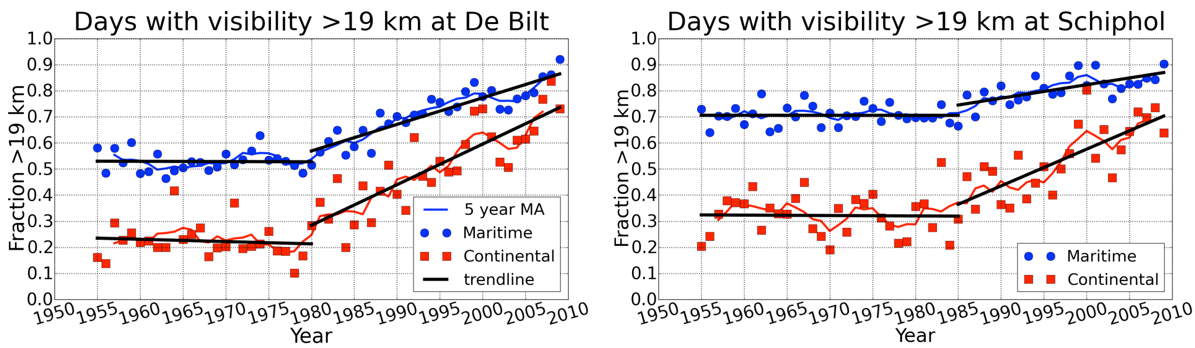


Fig. 14. Fraction of maritime and continental days on which a maximum visibility larger than 19 km (high visibility days) was observed in De Bilt (left) and Schiphol (right). Again a 5 year moving average and trendlines were drawn to highlight the changes.

We can clearly see a positive trend after 1980 in de Bilt, which started about 5 years earlier than in the previous graph of very high visibilities. This is maybe not so surprising; you might expect to see increases in high visibility days occurring before significant increases in very high visibility days if the aerosol burden of the atmosphere decreases. At Schiphol however, a significant positive trend only occurs after 1985. The visibility increases are again smaller at Schiphol than at de Bilt, and smaller for maritime than for continental wind regimes. Though the maritime and continental fractions tend to converge, they have not yet become equal, in contrary to the very high visibility fractions displayed in *figure 13*. Again, the continental visibility fraction shows a lot more interannual variation than the maritime fraction.

The positive visibility trends tend to level off somewhat after 2000, but less than for the very high visibility days. The graphs show an interesting dip between 2000 and 2005, which corresponds well with the suspected transition to AWS (in 2001). However, it also corresponds well with the measured peak of PM_{10} concentrations (*figure 5*). This minimum also seems to occur a few years earlier than the minimum in very high visibility days in the previous graphs. Both the very high and high visibility graphs seem to have a peak in the years 1999 and 2000, predominately in the continental regime. It would be interesting to determine the cause of this "millennium peak".

The increase in visibility days corresponds very well with the decrease in low visibility days found in *Vautard et al. (2009)* and *Oldenborgh et al. (2010)*, and quite well with the dimming and brightening periods discussed in *Wild (2009)*. The marked increase in visibilities seems to have occurred later (1973 versus 1985) in the Netherlands than in the United Kingdom (*Doyle and Dorling, 2002*). How do the visibility changes compare to the emission estimates in Europe (*figure 3* and *4*), recent measurements of PM_{10} in the Netherlands (*figure 5*) and the dimming and brightening periods (*figure 2*)? The West European (WE) estimates of sulfur emissions (*Stern, 2006*) are remarkably similar to our high visibility days (that is, actually the inverse trends). The WE emissions are relatively constant between 1970 and 1980, and show a rapid and relatively constant decline of about 65% between 1980 and 2000 up to the end of the analysis period (2000). This has a very close inverse relationship with the high visibility days in the Netherlands. Personally, I would have expected that the East European emissions would also have a large influence on our visibility. They slowly increase up to 1989, and show a dramatic decline afterwards, leveling off towards the end of the period. This is not clearly reflected in the visibility measurements, though it cannot be ruled out that the emission decline in Eastern Europe has also contributed to the recent visibility trends. This is an interesting result, because it indicates that visibility is mostly affected by regional sources. It can be concluded that the emissions of sulfur in Western Europe dominate the long term trends in high visibility days. Visibility trends in the Netherlands also do not relate very well to the long term emissions of the larger European region, which peaked around 1980, and only decreased to 1955 values in 1995 (*Smith, 2001*). Total European emission trends however do relate very well to the Potsdam, (Eastern) Germany visibility graphs of *Oldenborgh et al. (2010)*. That station, being much closer to the major East European industries, does seem to be affected by both West and East European emissions. Worldwide sulfur emissions peaked between 1980 and 1990 and also show a weaker relation with the visibility measurements at De Bilt and Schiphol. These conclusions are in agreement with the findings of *Doyle and Dorling (2002)*, who reported that visibility seemed to be predominately influenced by local emission variations.

Besides these long term trends, the fraction of high visibility days also shows shorter term variability ("dips" and "bumps"). For the period 2000 – 2009 we don't have any emission estimates. However, we do have measurements of aerosol concentrations (PM_{10}, *RIVM, 2008*). These measurements are a composite of an increasing amount of stations in the Netherlands, and show a relatively homogeneous downward trend, which levels off after 2000. The trend becomes insignificant after 2000, which can possibly explain the absence of a significant rise in the maritime fraction of very high visibility days, however it might be more likely that the increase in visibility has been limited by moisture and background sea salt aerosols because maritime air usually contains more moisture and sea salt than continental air. The continental visibility continues to rise rapidly though during this time, showing hardly any signs of a trend break. There does not seem to be an obvious relation between the aerosol concentration and the short term variations of the visibility (such as the peak around 2000 and the dip in the maritime fraction around 2005), but correlating the concentrations with the high visibility days might give more insight. The PM_{10} peaks occurring around 1996 and 2003 do correspond well with anomalous weather patterns in the Netherlands such as the cold winter in 1996 and extremely hot summer in 2003, and might provide interesting case studies for future research. Besides that, it might be interesting to correlate emission estimates and PM_{10} measurements with the high visibility days.

4.2 *Visibility and changes in wind regime.*

The visibility measurements were separated into maritime and continental wind regimes, in order to investigate the visibility changes in both classes. The atmospheric circulation (wind speed and direction) determines the transport of aerosols and can influence relative humidity. The separation into maritime and continental regimes is a crude way of isolating visibility changes from aerosol emissions and circulation variations, and gives some information about the emissions in the region where the air comes from. Schiphol generally has a greater amount of maritime winds than the Bilt (*figure 15*), but the differences are very small, and seem to have a slow and somewhat chaotic decadal variation with a minimum around 1965 and after 2005 and a maximum around 1990. Though yearly variations are fairly large and the data shows some longer term variations, hardly any trend can be observed during the full analysis period. De Bilt shows a minor and insignificant decline. It can be concluded that is not likely that changes in the wind regime have caused the increase in visibility since 1985. However, the separation into only two regimes is a rather crude method of looking at circulation changes, and a more detailed study might provide interesting details of the aerosol source regions and its temporal changes.

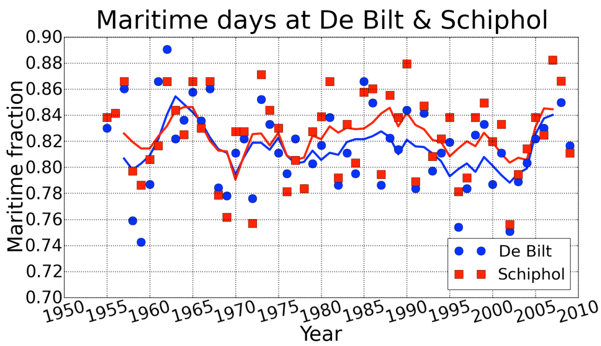


Fig. 15. (left) The yearly fraction of maritime days in De Bilt and Schiphol. Five year moving averages have been included (blue = De Bilt, red = Schiphol).

4.3 *Visibility and changes in relative humidity.*

Besides the aerosol concentrations also relative humidity influences the visibility. High relative humidity values can significantly limit the visibility by increasing the scattering efficiency of sulfate aerosols (a "haze") and fog formation. *Figure 16* presents the average relative humidity and the fraction of days with an average humidity below 80%. Other values have been tested, but showed similar changes. A relative humidity larger than 80% reduces the sulfate aerosol scattering efficiency by about a factor two or more (*figure 7*).

There are no major trends in the yearly average relative humidity, though Schiphol does have a significant decline between 1985 and 2009, and a significant increase in days with average humidity smaller than 80%. This weak downward trend in relative humidity is somewhat surprising. It can be caused by many things, both natural and anthropogenic, for example better drainage of the surrounding landscape. However, De Bilt does not show this at all, but does have the larger visibility increases than Schiphol. This inconsistency with what you might expect becomes even larger if we look at the relative humidity peaks and dips as well, and compare them with the visibility peaks and dips. The relative humidity has a relative maximum, and the amount of days with average RH <80% a relatively large minimum for both De Bilt and Schiphol, but the visibility has a large peak around the year 2000 for both stations! It is probably not useful to focus too much on these small interannual variations. Part of the dip after 2001 might also have been caused by changes in instrumentation, though the station history should be checked to be sure.

Though short term variability (i.e. hours, days) of relative humidity is very large and can have a profound effect on the visibility, our (limited) analysis shows that it is not likely that the observed minor long term relative humidity changes have had a major effect on the occurrence of high visibility days. It can be concluded that it is likely that the yearly average humidity does not vary enough to be the dominant cause of the increase of high visibility days. The current analysis is insufficient to explain the short term variations of the high visibility days.

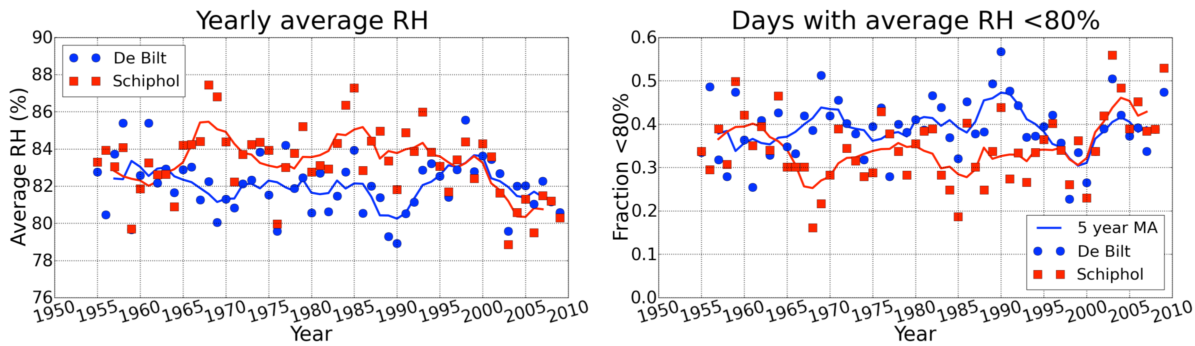


Fig. 16. (Left) Yearly average relative humidity (RH) and (right) the yearly fraction of days with daily average relative humidity smaller than 80 %. A five year moving average has been drawn to demonstrate the changes.

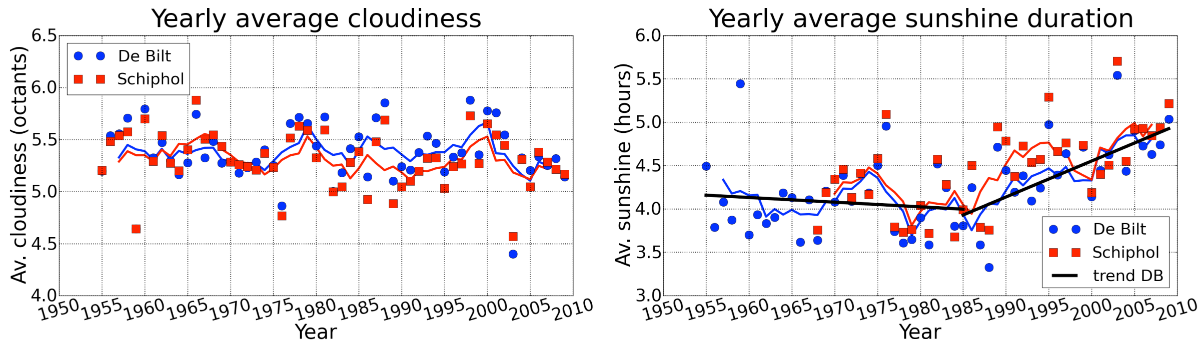
4.4 Visibility changes, cloudiness and sunshine duration.

A decrease in aerosol concentration would lead to better visibility ("direct effect") and a decrease in cloudiness (indirect aerosol effect), so we would expect a decrease in cloudiness when we have a long term positive trend in high visibility days. However, it is probably not that simple, because cloud microphysics is not very straightforward. For example, especially in (heavily) polluted air such as in the Netherlands, it is not completely clear if and when aerosols become the limiting factor on cloud formation. In heavily polluted areas the semi-direct aerosol effect might actually lead to decreasing cloudiness, especially in the presence of high concentrations of absorbing black carbon. Due to the introduction of air filters, the amount of black carbon has reduced substantially in more recent decades. The combination of these effects on cloudiness is currently difficult to derive, but very important for the earth's energy budget, because of the large refractive ability of clouds (high albedo) and its influence on long wave radiation. To make things worse, surface based observations of cloudiness (here, i.e. the fraction (in octants) of the sky which is covered in clouds) are considered very much uncertain and somewhat subjective because they are often still being done visually. Let us now take a look at the changes in cloudiness between 1955 and 2009, presented in *figure 17*.

One thing that strikes out immediately is that the differences between Schiphol and De Bilt are relatively small. This gives some confidence in the data. Another interesting observation which really stands out is the years which are famous for their (summer) droughts, such as 1959, 1976 and 2003, the latter also especially for its extremely hot summer. The trend does not resemble that of high visibility days though, as the cloudiness remains rather constant.

The increasing cloudiness is not the only result of the indirect-aerosol effect. It can also change the optical depth and reflectance of the clouds. Other studies have shown that in Europe, the reflectance of clouds has changed during the period in which we find increasing visibility. *Krüger and Graßl (2002)* for example found from satellite measurements that cloud reflectance in Central Europe decreased by about 2% from the late 1980s to the late 1990s.

The trends in cloudiness are not in agreement with the yearly average sunshine duration (*figure 17*). Though the peaks and troughs in the graphs are clearly inversely related (as expected), the cloudiness stands out because it does not show the same trends as the sunshine duration. Sunshine only occurs during the day, so in order to eliminate the trends, night time cloud cover would have to change accordingly to eliminate the trends. This is not likely. The sunshine duration estimates* are much more certain than the cloud cover estimates, and can be used well as a proxy of daytime cloudiness. Hopefully we can assume that this correlates well with the total daily cloud cover. The trends of yearly average daily sunshine duration in both De Bilt and Schiphol show a quite similar pattern to the high visibility days, and are thus consistent with what we would expect from the indirect-aerosol effect. It should be noted that the yearly average daily sunshine duration is dominated by spring and summer variations, because of the longer day length. To eliminate this effect, it is better to calculate the sunshine duration as a fraction of the day length, which shows equivalent trends. This is a significant result. It is likely that the sunshine duration in the Netherlands has increased on average by almost 1 hour per day since 1985 or by about 8% of the daily maximum possible sunshine duration, possibly caused by significant decreases in aerosol concentrations by clean air regulations. Besides having cleaner air, it seems like we can also enjoy more sunshine!



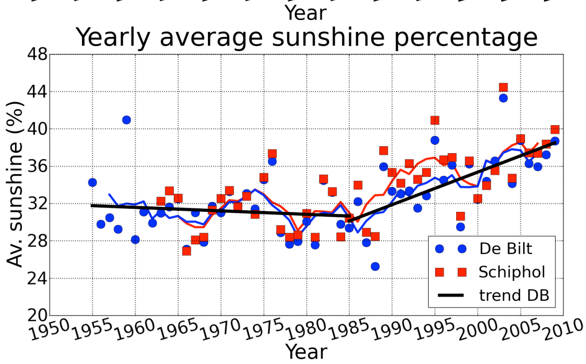


Fig. 17. The yearly average fraction of cloud cover (above left, in octants), the yearly average sunshine duration (above right, in hours per day) and the yearly average sunshine percentage (right, % per day) at De Bilt and Schiphol. Five year moving averages and trendlines (only for De Bilt) have been shown.

*The change from Campbell-Stokes to pyranometers occurred between 1991 and 1993 is not clearly visible in the yearly average sunshine duration. At Schiphol, data was missing during a large part of the summer of 1967 and the data before that date was left out for convenience.

4.5 Visibility changes and temperature.

Wild et al. (2007) studied the effect of dimming and brightening by aerosols on the Earth's global land surface temperatures. Using the CRU dataset they found a weak rising trend between 1955 and 1985 and a much stronger rising trend between 1985 and 2005. They concluded that these periods coincide well with the dimming and brightening periods, limiting global warming between 1955 and 1985 and possibly enhancing the temperature trend between 1985 and 2005. It would be interesting if a similar response can be found in the temperature records of De Bilt and Schiphol. The visibility trends correspond very well with the "global" dimming and brightening periods. This is probably somewhat coincidental; because we (and others) found some indications that the visibility trends are mostly determined by local aerosol emissions, which do not have to correlate well with the global emissions. For example, one could look at the visibility graph of Potsdam in Germany and Zürich in Switzerland by *Oldenborgh et al. (2010)*, which can be considered "nearby" from a global perspective, but have quite different visibility trends than the "global average" dimming and brightening periods.

Figure 18 presents the yearly average temperature in De Bilt and Schiphol, with the trendline between 1955 – 1985 and 1985 – 2009 of De Bilt. The trends show a strikingly similar pattern to the global averages, though they are larger by just over a factor of 2. Schiphol is slightly warmer than De Bilt, but the trends are almost equal. Can we now conclude from this correlation that the large recent temperature rise in the Netherlands is predominately caused by the changes in aerosol concentrations we derived from the visibility measurements? Though tempting, this might not be correct. We have not done a thorough analysis of other factors which might have caused the temperature change, which can be very subtle. Also, the fact that the global temperature trends beautifully coincide with the expected visibility changes in the Netherlands is actually somewhat inconvenient now. It makes it difficult to conclude if the recent temperature rise in the Netherlands is just the result of the global trends which have been amplified by some other unknown factors or that it is, like the visibility, predominately caused by local changes in aerosols. A quick look at the temperature record of Potsdam for example revealed a visually better correlation with changes in global temperatures, than changes in aerosol concentrations as derived from its visibility trends. However, though it might be very difficult or impossible to separate the individual contributions to the temperature trend of only two stations, there are several known physical mechanisms pointing towards a certain contribution of aerosol changes to the temperature trends. We have seen that the visibility and sunshine duration trends are quite similar, and this result (a decrease before 1985 and an increase after 1985 of sunshine resulting in a similar variation of short wave radiation) already hints at a contribution of aerosol driven changes in surface solar radiation to the temperature trend. Other observational studies have confirmed this variation in surface solar radiation. Recent studies (e.g. *Vautard et al., 2009*; *Oldenborgh et al., 2009* and references therein) have done a more thorough evaluation of what might have amplified the recent warming in Europe, and concluded that changes in atmospheric circulation and surface moisture content strongly contributed to the recent warming trend. On the contribution of aerosols on the temperature trends *Vautard et al. (2009)* conclude that the reduction in low visibility conditions could have contributed to 10 – 20 % of the recent daytime warming in Europe. *Oldenborgh et al. (2009)* conclude that the observed decrease of surface solar radiation in Western Europe of about 0.3 W m^{-2} per year (in summer) over 1970 – 1985 might have caused a 0.3 to 0.4 K cooling during this time, but that the contribution of this temporary dimming has only a small effect on the longer term average (1971 or 1950 – 2007), because dimming and brightening cancel each other to a large extent.

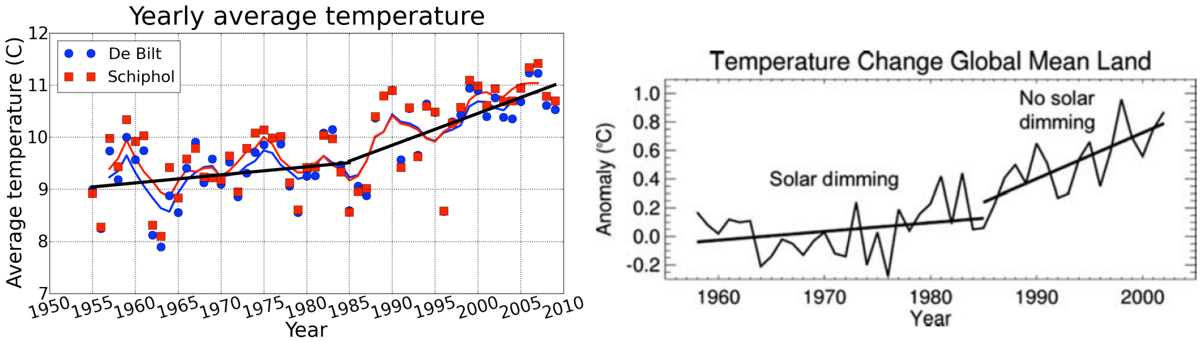


Fig. 18. The yearly average temperature in De Bilt and Schiphol (left). Five year moving averages and the trendline of De Bilt have been shown. Note that the temperature trends closely resemble the global temperature (right; shown again for comparison) and visibility changes.

It can be concluded that the visibility and yearly average temperature trends of De Bilt and Schiphol show a remarkably similar pattern. However, the latter is also strongly comparable to the variation of the global temperature trend. A more thorough analysis using many more stations is needed to analyze the contribution of aerosol changes, which were here estimated from visibility trends, on the temperature trends. Other studies have done a more comprehensive evaluation, and found a significant contribution of visibility and aerosol changes to the temperature trends in Europe.

4.6 Visibility changes and the diurnal temperature range.

Another indicator of the aerosol dimming and brightening periods is the diurnal temperature range. It is to be expected that if the surface solar radiation increases, in the absence of other changes, the day and night temperature differences become larger. We have seen that aerosol concentrations have decreased and visibility and sunshine duration have increases, so that we would expect increasing DTR between 1985 and 2009. *Figure 19* shows the DTR. Though there seems to be a general increase in DTR between 1970 and 1990 especially for Schiphol, we do not see a large or larger increase occurring between 1985 – 2009 for either De Bilt or Schiphol, in contrary to what you might expect and has generally been observed in other studies. *Makowski et al. (2008)* for example studied the DTR in Europe, and though they generally found a DTR variation which is consistent with the surface solar radiation and sulfur dioxide they did not find a significant trend in the Benelux. In Western Europe they found a reverse from decreasing to increasing DTR since 1970 and during the 1980s in Eastern Europe. The DTR trend at Schiphol is somewhat consistent with that of Western Europe, but not consistent with the changes of high visibility days. For De Bilt and Schiphol is likely that other factors have swamped the trend caused by changes in aerosols.

The yearly average DTR is probably dominated by changes in spring and summer, when large day to night differences often occur, and is likely very sensitive to changes of circulation, due to the nearby presence of the North Sea. It is probably also quite sensitive to changes in cloudiness and sunshine duration. Maritime winds greatly reduce the DTR of coastal stations, and its tempering influence can be observed far inland when winds are stronger. It can be seen by comparing the maritime fraction with the DTR (*figure 19*) that the DTR of Schiphol is influenced by this effect, especially after 1970. However, before 1970 a peak in maritime days does not seem to influence the DTR very much, as no trough can be found during this time. At De Bilt this effect is much weaker, but still no large influence of the aerosol effect on the DTR can be found here. The years 1959 and 2003 again show anomalous behavior, the DTR is much higher than in other years. However, 1976 does have a high DTR at all!

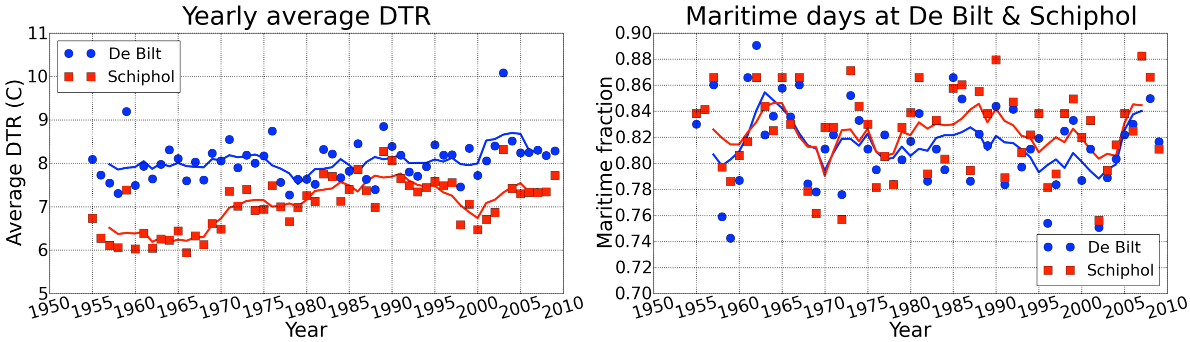


Fig. 19. Yearly average diurnal temperature range (DTR) (left) and the yearly fraction of maritime days shown again for comparison.

It can be concluded that the changes in yearly average DTR do not clearly show a relation with the visibility trends. DTR is probably influenced by circulation changes due to the nearby presence of the North Sea; to investigate this it might be illustrative to correlate the DTR with the fraction of maritime days or the wind direction in general.

5. Summary & Conclusions.

In this study we have presented the visibility measurements of de Bilt and Schiphol, the Netherlands. We have used a dataset of daily observations from the KNMI between 1955 and 2009. The daily maximum visibility measurements were separated in maritime and continental wind regimes using the daily average wind direction. The fraction of days with a maximum visibility larger than some threshold (i.e. 19 "high visibility days" and 30 km "very high visibility days") was then determined in each regime. In an earlier study by *Delden (2009)*, using an identical method a significant increase in the frequency of days with visibility larger than 30 km was found at de Bilt since 1985, after having been relatively constant between 1955 and 1985. These results were compared to visibility measurements at Schiphol, the largest airport in the Netherlands, and similar variations were observed.

We found that these changes are significant and not likely biased much by changes in the methodology of visibility measures. Strong indications were found that this is a physical result of changes in aerosol concentrations from human emissions in Western Europe, which has been confirmed by other studies. We have shown that the changes in the amount of high (>19 km) visibility days near the surface agree well with temporal changes of anthropogenic sulfur dioxide (aerosol) emissions in Western Europe, but less so with the emissions on larger scales (European, global), indicating that visibility is predominately influenced by local emissions. Recently, emission trends in Europe seem to have leveled, so the rise of high visibility days might halt in the near future. We have not seen strong evidence of this yet. The maritime very high visibility fraction has leveled recently, possibly becoming limited by sea salt aerosol instead of anthropogenic aerosols, as no signs of a leveling could be observed in the continental or high visibility fraction. Also, it was observed that recently, continental visibilities have surpassed maritime visibilities.

Besides aerosols, also changes in the atmospheric circulation and relative humidity might result in visibility trends. No long term changes in the wind regimes were observed, from which it can be concluded that it is not likely that this has caused the increase in visibility since 1985. However, the separation into only two wind regimes is a rather crude method of looking at circulation changes, and a more detailed study might provide interesting details of the aerosol source regions and its temporal changes.

A relative humidity larger than 80% reduces the aerosol scattering "efficiency" by about a factor two or more, so that long term changes in relative humidity might lead to visibility trends. There are no major tendencies in the yearly average relative humidity, though Schiphol does have a significant decline between 1985 and 2009, and a significant increase in days with average humidity less than 80%. However, De Bilt does not seem to have a significant humidity trend, but the observed visibility increases for this station are generally larger than at Schiphol. Though short term variability (i.e. hours, days) of relative humidity is very large and can have a profound effect on the visibility, our (limited) analysis shows that it is not likely that the observed minor long term relative humidity changes have had a major effect on the occurrence of high visibility days. It can be concluded that it is likely that the yearly average humidity does not vary enough to be the dominant cause of the increase of high visibility days. The current analysis was insufficient to explain the short term variations of the high visibility days.

Though there has been a gradual transition from human observers to automated weather stations, which likely occurred around 2001, this did not seem to bias the observed trends. However, the station history of Schiphol and De Bilt was not readily available from the KNMI. The author pleads for proper documentation of all observations and its availability, which is especially important for all climate related research.

We have also looked for a response to the visibility changes in other variables, such as cloudiness, sunshine duration and temperature, to see if they were large enough to emerge through the natural variability of two individual stations. We would expect changes in cloudiness and sunshine duration when the aerosol burden in the atmosphere decreases. This is known as the indirect aerosol effect. The trends in cloudiness were not in agreement with the visibility and yearly average sunshine duration. Though yearly average cloudiness showed peaks and troughs which were clearly inversely related to the sunshine duration (as expected), the cloudiness did not show corresponding trends. The trends of yearly average sunshine duration and percentage of day length in both De Bilt and Schiphol are likely more accurate, and did show a strikingly similar pattern as the changes of high visibility days, and are thus consistent with what we would expect from the indirect-aerosol effect. It should be noted that representation of yearly average daily sunshine duration is dominated by spring and summer variations, because of the longer day length in those seasons. To eliminate this effect, we also determined the sunshine duration as a percentage of the total possible daily sunshine duration or “day length”. Both methods showed significant increases of almost 1 hour per day or 8% of the maximum possible daily sunshine duration between 1985 and 2009, possibly caused by clean air regulations which have led to significant decreases in anthropogenic aerosol burden in the atmosphere.

The yearly average temperature trends of De Bilt and Schiphol show a remarkably similar pattern to changes in high visibility days as well. Increasing surface solar radiation, observed and linked to decreasing aerosol concentrations in other studies, is an obvious explanation for this result. However, the yearly average temperature trend is also very much comparable to the variation of the global temperature trend. At other stations in Europe showing a different visibility variation, it seemed like the temperature trends had a stronger correlation with the global temperature trend than with the visibility trends. A more thorough analysis using many more stations is needed to analyze the contribution of aerosol changes, here estimated from visibility trends, on the temperature trends. Other studies have done a more comprehensive evaluation, and found that though other factors (e.g. circulation changes) dominated the temperature trends, especially during shorter periods (e.g. 1985 – 2009), a significant contribution of visibility and aerosol changes to the temperature trends in Europe was found.

Other studies have noted that the difference between the daily minimum and maximum temperature, the diurnal temperature range (DTR) might be a good indicator of aerosol and visibility changes. However, we did not find a strong relation of the DTR with the visibility trends. DTR in the Netherlands is probably strongly influenced by atmospheric circulation changes due to the nearby presence of the North Sea; to investigate this it might be interesting to study the relation of the DTR with changes in cloud cover and especially with the wind speed and direction in coastal areas.

In this short project, we have analyzed only two stations in the Netherlands, and more research needs to be done to see our results are viable for a larger area. Our results indicate that the frequency of high visibility days can be used well as a proxy for changes of aerosol concentration. Many other studies have shown robust evidence of a large influence of aerosols on regional climate changes, though globally, the net effects are still poorly understood.

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